ADAPTING TO A CHANGING CLIMATE

2023 Current Environmental Issue STUDY RESOURCES

Part A

NCF-Envirothon 2023 New Brunswick

Adapting to a Changing Climate

Current Environmental Issue Study Resources – Part A

Table of Contents

Key Topic 1: Factors Contributing to a Changing Climate

1. Describe climate change and the process through which it occurs.
2. Outline the factors, both anthropogenic and natural, which influence climate and climate change.
3. Describe the major economic sectors that contribute to greenhouse gas (GHG) emissions.
4. Describe major energy sources and explain how each contributes to climate change.
5. Outline indicators of climate change.

Study Resources

Resource Title	Source	Located on
Basics of Climate Change	*US Environmental Protection Agency, 2019*	Pages 4-9
Causes of Climate Change	*Government of Canada, 2019*	Pages 10-12
VIDEO: Climate Change 2022: Impacts, Adaptation & Vulnerability – CLICK LINK	*Intergovernmental Panel on Climate Change (IPCC), 2020*	Page 30; 14 Minutes
Sector by sector: where do global greenhouse emissions come from?	*Our World in Data, Hannah Ritchie, 2020*	Pages 31-36
Energy and the Environment Explained	*US Energy Information Administration, 2021*	Pages 37-48

Please Note: Hyperlinks found in text are not considered required reading; however, included video links are required to watch.

Study Resources begin on the next page →

Basics of Climate Change

Learn about some of the key concepts related to climate change:

- The Greenhouse Effect
- Key Greenhouse Gases
- Other Greenhouse Gases
- Aerosols
- Climate Feedback

How is the Climate Changing in the United States?

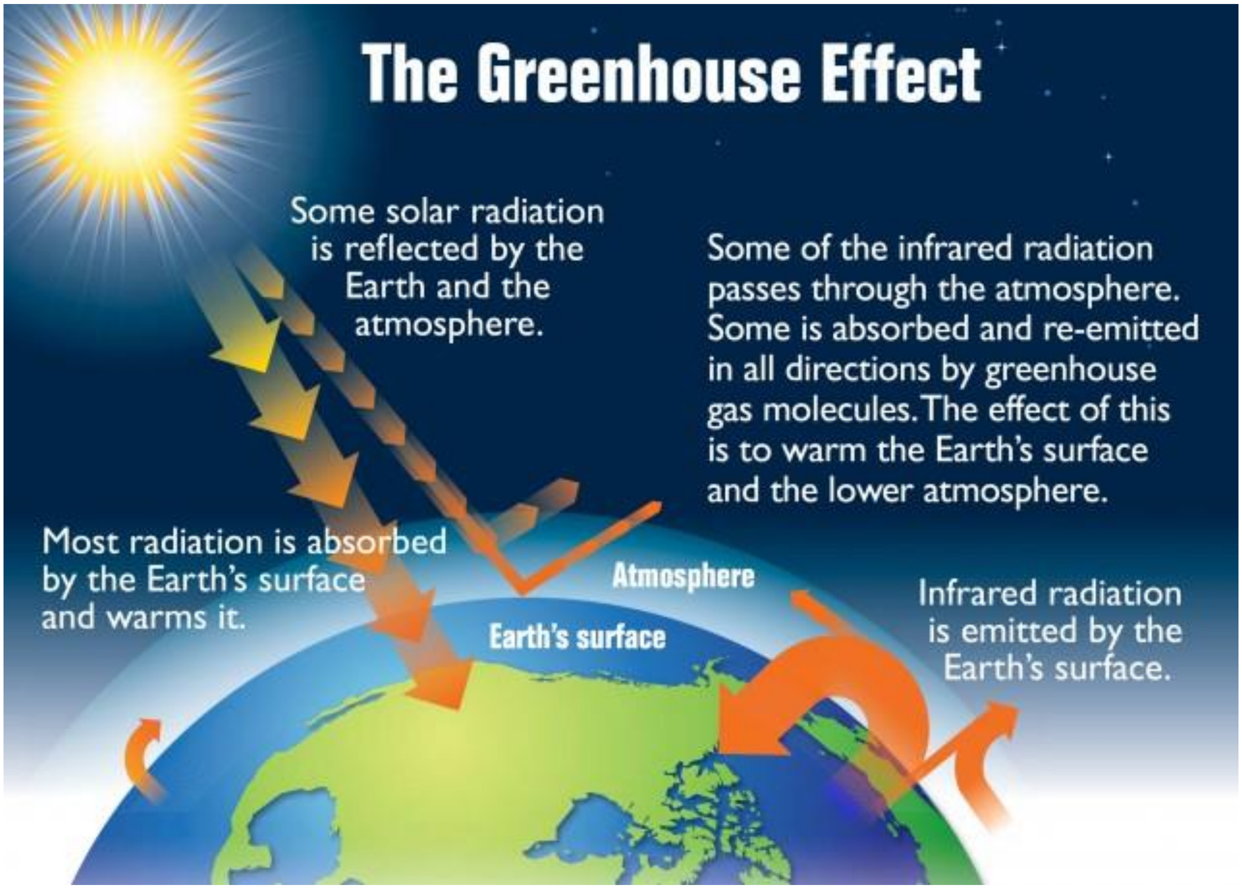
Observations across the United States and world provide multiple, independent lines of evidence that climate change is happening now. **Learn More About Climate Change Indicators** <https://epa.gov/climate-indicators> **>>**

The earth's climate is changing. Multiple lines of evidence show changes in our weather, oceans, and ecosystems, such as:

- Changing temperature and precipitation patterns <https://epa.gov/climate-indicators/weather-climate>.[1] [2]
- Increases in ocean temperatures, sea level, and acidity <https://epa.gov/climateindicators/oceans>.
- Melting of glaciers and sea ice <https://epa.gov/climate-indicators/snow-ice>.[3]
- Changes in the frequency, intensity, and duration of extreme weather events <https://epa.gov/climate-indicators/weather-climate>.
- Shifts in ecosystem characteristics <https://epa.gov/climate-indicators/ecosystems>, like the length of the growing season, timing of flower blooms, and migration of birds.

These changes are due to a buildup of greenhouse gases in our atmosphere and the warming of the planet due to the greenhouse effect.

The Greenhouse Effect



The greenhouse effect helps trap heat from the sun, which keeps the temperature on earth comfortable. But people's activities are increasing the amount of heat-trapping greenhouse gases in the atmosphere, causing the earth to warm up.

The earth's temperature depends on the balance between energy entering and leaving the planet's system. When sunlight reaches the earth's surface, it can either be reflected back into space or absorbed by the earth. Incoming energy that is absorbed by the earth warms the planet. Once absorbed, the planet releases some of the energy back into the atmosphere as heat (also called infrared radiation). Solar energy that is reflected back to space does not warm the earth.

Certain gases in the atmosphere absorb energy, slowing or preventing the loss of heat to space. Those gases are known as "greenhouse gases." They act like a blanket, making the earth warmer than it would otherwise be. This process, commonly known as the "greenhouse effect," is natural and necessary to support life. However, the recent buildup of greenhouse gases in the atmosphere from human activities has changed the earth's climate and resulted in dangerous effects to human health and welfare and to ecosystems.

Key Greenhouse Gases

Most of the warming since 1950 has been caused by human emissions of greenhouse gases.[4] Greenhouse gases come from a variety of human activities, including burning fossil fuels for heat and energy, clearing forests, fertilizing crops, storing waste in landfills, raising livestock, and producing some kinds of industrial products.

Carbon Dioxide

Carbon dioxide is the primary greenhouse gas contributing to recent climate change. Carbon dioxide enters the atmosphere through burning fossil fuels, solid waste, trees, and other biological materials, and as a result of certain chemical reactions, such as cement manufacturing. Carbon dioxide is absorbed and emitted naturally as part of the carbon cycle, through plant and animal respiration, volcanic eruptions, and ocean atmosphere exchange.

The Carbon Cycle

The carbon cycle is the process by which carbon continually moves from the atmosphere to the earth and then back to the atmosphere. On the earth, carbon is stored in rocks, sediments, the ocean, and in living organisms. Carbon is released back into the atmosphere when plants and animals die, as well as when fires burn, volcanoes erupt, and fossil fuels (such as coal, natural gas, and oil) are combusted. The carbon cycle ensures there is a balanced concentration of carbon in the different reservoirs on the planet. But a change in the amount of carbon in one reservoir affects all the others. Today, people are disturbing the carbon cycle by burning fossil fuels, which release large amounts of carbon dioxide into the atmosphere, and through land use changes that remove plants, which absorb carbon from the atmosphere.

Methane

Both natural and human activities produce methane. For example, natural wetlands, agricultural activities, and fossil fuel extraction and transport all emit methane.

Nitrous Oxide

Nitrous oxide is produced mainly through agricultural activities and natural biological processes. Fossil fuel burning and industrial processes also create nitrous oxide.

F-Gases

Chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, together called F-gases <https://epa.gov/ghgemissions/overview-greenhouse-gases#f-gases>, are often used in coolants, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants.

Global Warming Potential
Different greenhouse gases can remain in the atmosphere for different amounts of time, ranging from a few years to thousands of years. In addition, some gases are more effective than others at making the planet warmer. Learn more about Global Warming Potential (GWP) <https://epa.gov/ghgemissions/understanding-globalwarming-potentials>, a measure of climate impacts based on how long each greenhouse gas remains in the atmosphere and how strongly it absorbs energy.

Other Greenhouse Gases

Ground-Level Ozone

Ground-level ozone <https://epa.gov/ground-level-ozone-pollution> is created by a chemical reaction between emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight. In addition to trapping heat, ground-level ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Water Vapor

Water vapor is another greenhouse gas and plays a key role in climate feedbacks because of its heat-trapping ability. Warmer air holds more moisture than cooler air. Therefore, as greenhouse gas concentrations increase and global temperatures rise, the total amount of water vapor in the atmosphere also increases, further amplifying the warming effect.[5]

For more information on greenhouse gases, see Greenhouse Gas Emissions <https://epa.gov/ghgemissions>.

Aerosols

Aerosols in the atmosphere can affect climate. Aerosols are microscopic (solid or liquid) particles that are so small that instead of quickly falling to the surface like larger particles, they remain suspended in the air for days to weeks. Human activities, such as burning fossil fuels and biomass, contribute to emissions of these substances, although some aerosols also come from natural sources such as volcanoes and marine plankton.

Unlike greenhouse gases, the climate effects of aerosols vary depending on what they are made of and where they are emitted. Depending on their color and other factors, aerosols can either absorb or reflect sunlight. Aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect.

Not only can black carbon directly absorb incoming and reflected sunlight, but it can also absorb infrared radiation.[6] Black carbon can also be deposited on snow and ice, darkening the surface and thereby increasing the snow's absorption of sunlight and accelerating melt.[7] While reductions in all aerosols can lead to more warming, targeted reductions in black carbon emissions can reduce global warming. Warming and cooling aerosols can also interact with clouds, changing their ability to form and dissipate, as well as their reflectivity and precipitation rates. Clouds can contribute both to cooling, by reflecting sunlight, and warming, by trapping outgoing heat.

Climate Feedbacks

Climate feedbacks are natural processes that respond to global warming by setting or further increasing change in the climate system. Feedbacks that set the change in climate are called negative feedbacks. Feedbacks that amplify changes are called positive feedbacks.

Water vapor appears to cause the most important positive feedback. As the earth warms, the rate of evaporation and the amount of water vapor in the air both increase. Because water vapor is a greenhouse gas, this leads to further warming.

The melting of Arctic **sea ice** is another example of a positive climate feedback. As temperatures rise, sea ice retreats. The loss of ice exposes the underlying sea surface, which is darker and absorbs more sunlight than ice, increasing the total amount of warming. Less snow cover during warm winters has a similar effect.

Clouds can have both warming and cooling effects on climate. They cool the planet by reflecting sunlight during the day, and they warm the planet by slowing the escape of heat to space (this is most apparent at night, as cloudy nights are usually warmer than clear nights).

Climate change can lead to changes in the coverage, altitude, and reflectivity of clouds. These changes can then either amplify (positive feedback) or dampen (negative feedback) the original change. The net effect of these changes is likely an amplifying, or positive, feedback due mainly to increasing altitude of high clouds in the tropics, which makes them better able to trap heat, and reductions in coverage of lower-level clouds in the mid-latitudes, which reduces the amount of sunlight they reflect. The magnitude of this feedback is uncertain due to the complex nature of cloud/climate interactions.[8]

Government of Canada Gouvernement du Canada

Causes of climate change

What is the most important cause of climate change?

Human activity is the main cause of climate change. People burn fossil fuels and convert land from forests to agriculture. Since the beginning of the Industrial Revolution, people have burned more and more fossil fuels and changed vast areas of land from forests to farmland.

Burning fossil fuels produces carbon dioxide, a greenhouse gas. It is called a greenhouse gas because it produces a “greenhouse effect”. The greenhouse effect makes the earth warmer, just as a greenhouse is warmer than its surroundings.

Carbon dioxide is the main cause of human-induced climate change.

It stays in the atmosphere for a very long time. Other greenhouse gases, such as nitrous oxide, stay in the atmosphere for a long time. Other substances only produce short-term effects.

Not all substances produce warming. Some, like certain aerosols, can produce cooling.

What are climate forcers?

Carbon dioxide and other substances are referred to as climate forcers because they force or push the climate towards being warmer or cooler. They do this by affecting the flow of energy coming into and leaving the earth’s climate system.

Small changes in the sun’s energy that reaches the earth can cause some climate change. But since the Industrial Revolution, adding greenhouse gases has been over 50 times more powerful than changes in the Sun's radiance. The additional greenhouse gases in earth’s atmosphere have had a strong warming effect on earth’s climate.

Future emissions of greenhouse gases, particularly carbon dioxide, will determine how much more climate warming occurs.

What can be done about climate change?

Carbon dioxide is the main cause of human-induced global warming and associated climate change. It is a very long-lived gas, which means carbon dioxide builds up in the atmosphere with ongoing human emissions and remains in the atmosphere for centuries. Global warming can only be stopped by reducing global emissions of carbon dioxide from human fossil fuel combustion and industrial processes to zero, but even with zero emissions, the global temperature will remain essentially constant at its new warmer level. Emissions of other substances that warm the climate must also be substantially reduced. This indicates how difficult the challenge is.

What is climate change?

Climate change is a long-term shift in weather conditions identified by changes in temperature, precipitation, winds, and other indicators. Climate change can involve both changes in average conditions and changes in variability, including, for example, extreme events.

The earth's climate is naturally variable on all time scales. However, its long-term state and average temperature are regulated by the balance between incoming and outgoing energy, which determines the Earth's energy balance. Any factor that causes a sustained change to the amount of incoming energy or the amount of outgoing energy can lead to climate change. Different factors operate on different time scales, and not all of those factors that have been responsible for changes in earth's climate in the distant past are relevant to contemporary climate change. Factors that cause climate change can be divided into two categories - those related to natural processes and those related to human activity. In addition to natural causes of climate change, changes internal to the climate system, such as variations.

In ocean currents or atmospheric circulation, can also influence the climate for short periods of time. This natural internal climate variability is superimposed on the long-term forced climate change.

Does climate change have natural causes?

The Earth's climate can be affected by natural factors that are external to the climate system, such as changes in volcanic activity, solar output, and the Earth's orbit around the Sun. Of these, the two factors relevant on timescales of contemporary climate change are changes in volcanic activity and changes in solar radiation. In terms of the Earth's energy balance, these factors primarily influence the amount of incoming energy. Volcanic eruptions are episodic and have relatively short-term effects on climate.

Changes in solar irradiance have contributed to climate trends over the past century but since the Industrial Revolution, the effect of additions of greenhouse gases to the atmosphere has been over 50 times that of changes in the Sun's output.

Human causes

Climate change can also be caused by human activities, such as the burning of fossil fuels and the conversion of land for forestry and agriculture. Since the beginning of the Industrial Revolution, these human influences on the climate system have increased substantially. In addition to other environmental impacts, these activities change the land surface and emit various substances to the atmosphere. These in turn can influence both the amount of incoming energy and the amount of outgoing energy and can have both warming and cooling effects on the climate. The dominant product of fossil fuel combustion is carbon dioxide, a greenhouse gas. The overall effect of human activities since the Industrial Revolution has been a warming effect, driven primarily by emissions of carbon dioxide and enhanced by emissions of other greenhouse gases.

The build-up of greenhouse gases in the atmosphere has led to an enhancement of the natural greenhouse effect. It is this human-induced enhancement of the greenhouse effect that is of concern because ongoing emissions of greenhouse gases have the potential to warm the planet to levels that have never been experienced in the history of human civilization. Such climate change could have far-reaching and/or unpredictable environmental, social, and economic consequences.

Short-lived and long-lived climate forcers

Carbon dioxide is the main cause of human-induced climate change. It has been emitted in vast quantities from the burning of fossil fuels and it is a very long-lived gas, which means it continues to affect the climate system during its long residence time in the atmosphere. However, fossil fuel combustion, industrial processes, agriculture, and forestry-related activities emit other substances that also act as climate forcers. Some, such as nitrous oxide, are long-lived greenhouse gases like carbon dioxide, and so contribute to long-term climate change. Other substances have shorter atmospheric lifetimes because they are removed fairly quickly from the atmosphere. Therefore, their effect on the climate system is similarly short-lived. Together, these short-lived climate forcers are responsible for a significant amount of current climate forcing from anthropogenic substances. Some short-lived climate forcers have a climate warming effect ('positive climate forcers') while others have a cooling effect ('negative climate forcers').

If atmospheric levels of short-lived climate forcers are continually replenished by ongoing emissions, these continue to exert a climate forcing. However, reducing emissions will quite quickly lead to reduced atmospheric levels of such substances. A number of short-lived climate forcers have climate warming effects and together are the most important contributors to the human enhancement of the greenhouse effect after carbon dioxide. This includes methane and tropospheric ozone – both greenhouse gases – and black carbon, a small solid particle formed from the incomplete combustion of carbon-based fuels (coal, oil and wood for example).

Other short-lived climate forcers have climate cooling effects, most notably sulphate aerosols. Fossil fuel combustion emits sulphur dioxide into the atmosphere (in addition to carbon dioxide) which then combines with water vapour to form tiny droplets (aerosols) which reflect sunlight.

Sulphate aerosols remain in the atmosphere for only a few days (washing out in what is referred to as acid rain), and so do not have the same longterm effect as greenhouse gases. The cooling from sulphate aerosols in the atmosphere has, however, offset some of the warming from other substances. That is, the warming we have experienced to date would have been even larger had it not been for elevated levels of sulphate aerosols in the atmosphere.

Global climate indicators

Global climate indicators[1] reveal the ways in which the climate is changing and provide a broad view of the climate at the global scale. They are used to monitor the key components of the climate system and describe the most relevant changes in the composition of the atmosphere, the heat that arises from the accumulation of greenhouse gases (and other factors), and the responses of the land, ocean and ice to the changing climate. These indicators include global mean surface temperature, global ocean heat content, state of ocean acidification, glacier mass balance, Arctic and Antarctic sea-ice extent, global CO_2 mole fraction and global mean sea level and are discussed in detail in the sections below. Further information on the data sets used for each indicator can be found at the end of this report.

A variety of baselines are used in this report. For global mean temperature, the baseline is 1850–1900, which is the baseline used in the IPCC Special Report on Global Warming of 1.5 °C as an approximation of pre-industrial temperatures.[2] For greenhouse gases, pre-industrial concentrations estimated from ice cores for the year 1750 are used as baselines.

For other variables and for temperature maps, the WMO climatological standard normal 1981–2010 is used, where possible, as a base period for consistent reporting of surface measurements, satellite data and reanalyses. For some indicators, it is not possible to use this base period, either because there are no measurements in the early part of the period, or because a longer base period is needed to calculate a representative average. Where the base period used is different from 1981–2010, this is noted in the text or figure captions, and more details are given in the Data set details section.

TEMPERATURE

The global mean temperature for 2020 was 1.2 ± 0.1 °C above the 1850–1900 baseline (Figure 1), which places 2020 as one of the three warmest years on record globally. The WMO assessment is based on five global temperature data sets (Figure 1). All five of these data sets currently place 2020 as one of the three warmest years on record. The spread of the five estimates of the annual global mean ranges between 1.15 °C and 1.28 °C above pre-industrial levels (see the baseline definition in the Global climate indicators section). It is worth noting that the Paris Agreement aims to hold the global average temperature to well below 2 °C above

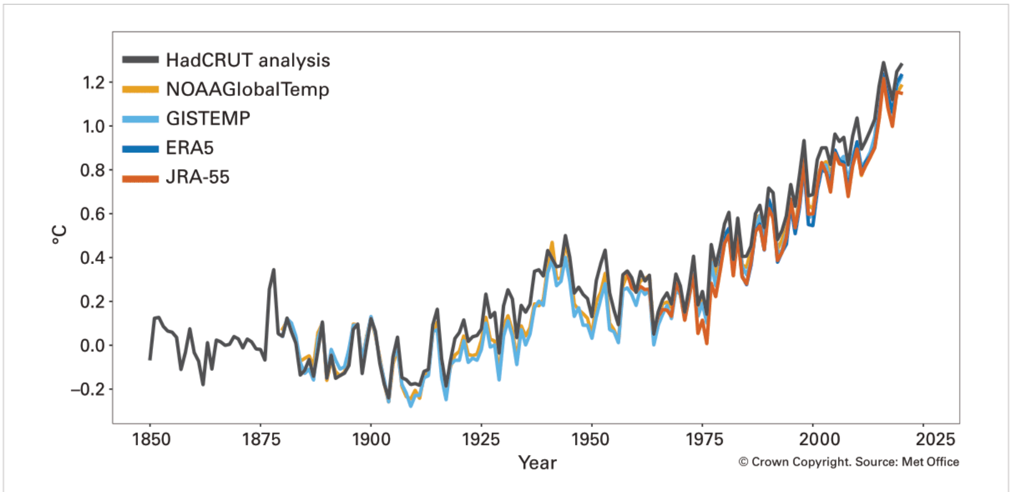


Figure 1. Global annual mean temperature difference from pre-industrial conditions (1850–1900) for five global temperature data sets. For details of the data sets and plotting, see Temperature data in the Data set details section at the end of this report.

[1] https://journals.ametsoc.org/view/journals/bams/aop/bamsD190196/bamsD190196.xml

[2] http://www.ipcc.ch/sr15/

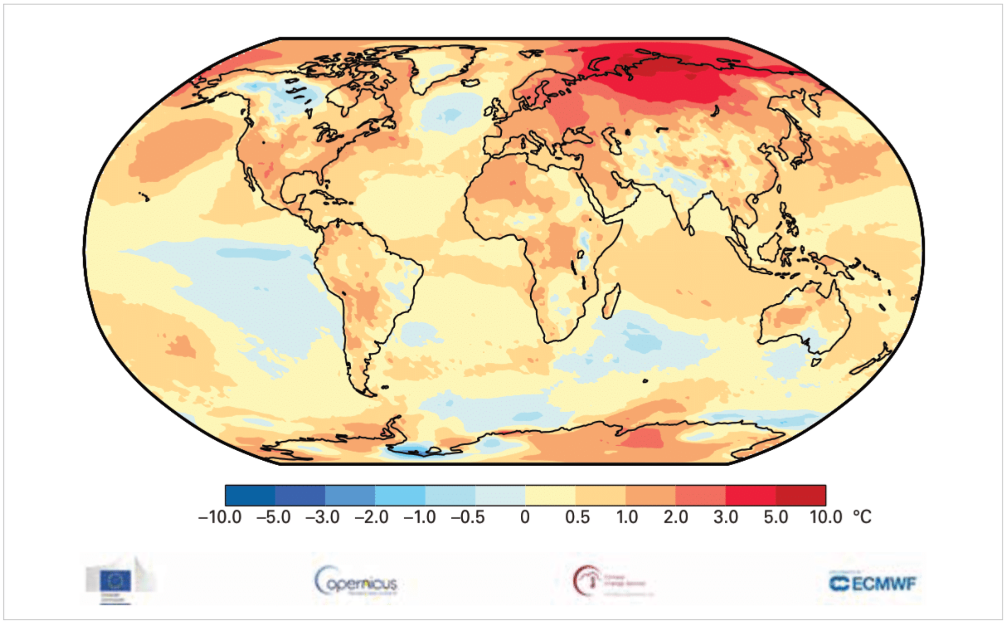


Figure 2. Temperature anomalies relative to the 1981–2010 long-term average from the ERA5 reanalysis for 2020. *Source:* Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts (ECMWF)

pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels[3]. Assessing the increase in global temperature in the context of climate change refers to the long-term global average temperature, not to the averages for individual years or months.

The warmest year on record to date, 2016, began with an exceptionally strong El Niño, a phenomenon which contributes to elevated global temperatures. Despite neutral or comparatively weak El Niño conditions early in 2020[4] and La Niña conditions developing by late September,[5] the warmth of 2020 was comparable to that of 2016.

With 2020 being one of the three warmest years on record, the past six years, 2015–2020, were the six warmest on record. The last five-year (2016–2020) and 10-year (2011–2020) averages were also the warmest on record.

Although the overall warmth of 2020 is clear, there were variations in temperature anomalies across the globe (Figure 2). While most land areas were warmer than the long-term average (1981–2010), one area in northern Eurasia stands out with temperatures of more than five degrees above average (see The Arctic in 2020). Other notable areas of warmth included limited areas of the south-western United States, the northern and western parts of South America, parts of Central America, and wider areas of Eurasia, including parts of China. For Europe, 2020 was the warmest year on record. Areas of below-average temperatures on land included western Canada, limited areas of Brazil, northern India, and south-eastern Australia.

Over the ocean, unusual warmth was observed in parts of the tropical Atlantic and Indian Oceans. The pattern of sea-surface temperature anomalies in the Pacific is characteristic of La Niña, having cooler-than-average surface waters in the eastern equatorial Pacific surrounded by a horseshoe-shaped band of warmer-than-average waters, most notably in the North-East Pacific and along the western edge of the Pacific from Japan to Papua New Guinea.

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[3] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[4] https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

[5] http://www.bom.gov.au/climate/enso/wrap-up/archive/20200929.archive.shtml

GREENHOUSE GASES AND STRATOSPHERIC OZONE

GREENHOUSE GASES

Atmospheric concentrations of greenhouse gases reflect a balance between emissions from human activities and natural sources, and sinks in the biosphere and ocean. Increasing levels of greenhouse gases in the atmosphere due to human activities have been the major driver of climate change since the mid-twentieth century. Global average mole fractions of greenhouse gases are calculated from in situ observations made at multiple sites in the Global Atmosphere Watch Programme of WMO and partner networks.

In 2019, greenhouse gas concentrations reached new highs (Figure 3), with globally averaged mole fractions of carbon dioxide (CO_2) at 410.5 ± 0.2 parts per million (ppm), methane (CH_4) at 1 877 ± 2 parts per billion (ppb) and nitrous oxide (N_2O) at 332.0 ± 0.1 ppb, respectively, 148%, 260% and 123% of pre-industrial (before 1750) levels. The increase in CO_2 from 2018 to 2019 (2.6 ppm) was larger than both the increase from 2017 to 2018 (2.3 ppm) and the average yearly increase over the last decade (2.37 ppm per year). For CH_4, the increase from 2018 to 2019 was slightly lower than the increase from 2017 to 2018 but still higher than the average yearly increase over the last decade. For N_2O, the increase from 2018 to 2019 was also lower than that observed from 2017 to 2018 and close to the average growth rate over the past 10 years.

The temporary reduction in emissions in 2020 related to measures taken in response to COVID-19[6] is likely to lead to only a slight decrease in the annual growth rate of CO_2 concentration in the atmosphere, which will be practically indistinguishable from the natural interannual variability driven largely by the terrestrial biosphere. Real-time data from specific locations, including Mauna Loa (Hawaii) and Cape Grim (Tasmania) indicate that levels of CO_2, CH_4 and N_2O continued to increase in 2020.

The IPCC Special Report on Global Warming of 1.5 °C found that limiting warming to 1.5 °C

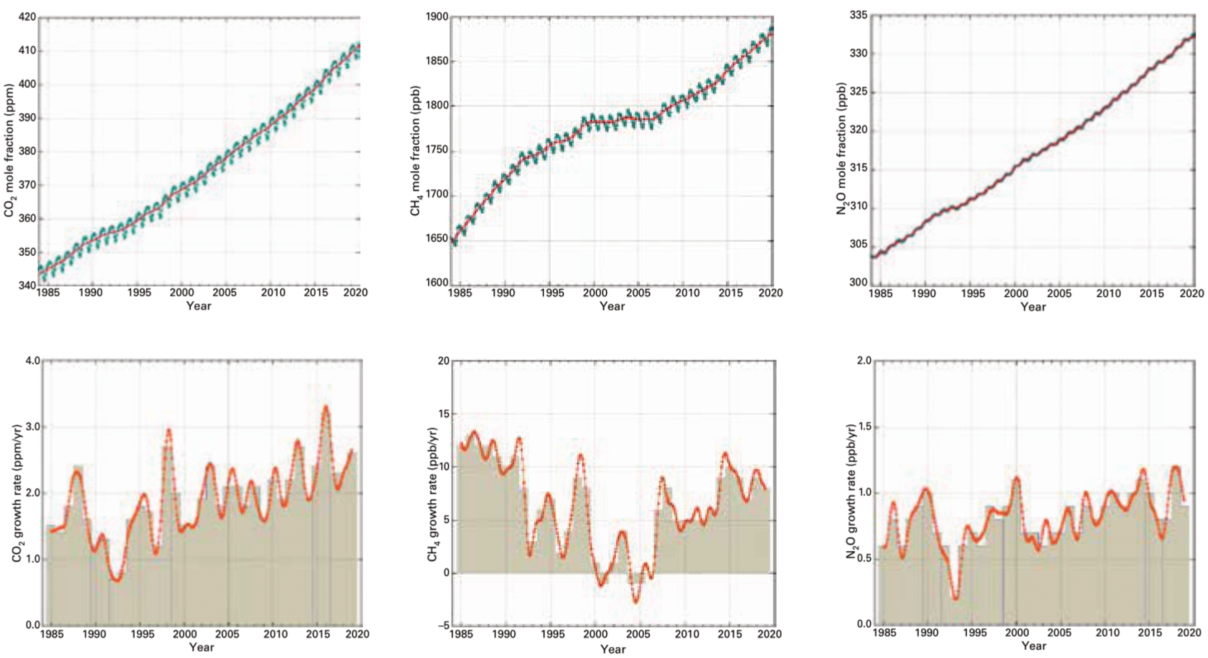

Figure 3. Top row: Globally averaged mole fraction (measure of concentration), from 1984 to 2019, of CO_2 in parts per million (left), CH_4 in parts per billion (centre) and N_2O in parts per billion (right). The red line is the monthly mean mole fraction with the seasonal variations removed; the blue dots and line show the monthly averages. Bottom row: The growth rates representing increases in successive annual means of mole fractions are shown as grey columns for CO_2 in parts per million per year (left), CH_4 in parts per billion per year (centre) and N_2O in parts per billion per year (right).
Source: WMO Global Atmosphere Watch

[6] Liu, Z. et al., 2020: Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. *Nature Communications*, 11(1): 5172, https://doi.org/10.1038/s41467-020-18922-7.

above pre-industrial levels implies reaching net zero CO_2 emissions globally by around 2050, with concurrent deep reductions in emissions of non-CO_2 forcers.

STRATOSPHERIC OZONE AND OZONE-DEPLETING GASES

Following the success of the Montreal Protocol, the use of halons and chlorofluorocarbons has been reported as discontinued, but their levels in the atmosphere continue to be monitored. Because of their long lifetime, these compounds will remain in the atmosphere for many decades, and even if there are no new emissions, there is still more than enough chlorine and bromine present in the atmosphere to cause the complete destruction of ozone in Antarctica from August to December. As a result, the formation of the Antarctic ozone hole continues to be an annual spring event, with the year-to-year variation in its size and depth governed to a large degree by meteorological conditions.

The 2020 Antarctic ozone hole developed early and went on to be the longest-lasting and one of the deepest ozone holes since ozone layer monitoring began 40 years ago (Figure 4). The ozone hole area reached its maximum area for 2020 on 20 September at 24.8 million km^2, the same area as was reached in 2018. The area of the hole was closer to the maxima observed in 2015 (28.2 million km^2) and 2006 (29.6 million km^2) than the maximum that was reached in 2019 (16.4 million km^2) according to an analysis from the National Aeronautics and Space Administration (NASA). The unusually deep and long-lived ozone hole was driven by a strong and stable polar vortex and very low temperatures in the stratosphere.

At the other end of the Earth, unusual atmospheric conditions also led to ozone concentrations over the Arctic falling to a record low for the month of March. Unusually weak "wave" events in the upper atmosphere left the polar vortex relatively undisturbed, preventing the mixing of ozone-rich air from lower latitudes. In addition, early in the year, the stratospheric polar vortex over the Arctic was strong, and this, combined with consistently very low temperatures, allowed a large area of polar stratospheric clouds to grow. When the sun rises after the polar winter, it triggers chemical processes in the polar stratospheric clouds that lead to the depletion of ozone. Measurements from weather balloons indicated that ozone depletion surpassed the levels reported in 2011 and, together with satellite observations, documented stratospheric ozone levels of approximately 205 Dobson Units on 12 March 2020. The typical lowest ozone values previously observed over the Arctic in March are at least 240 Dobson Units.

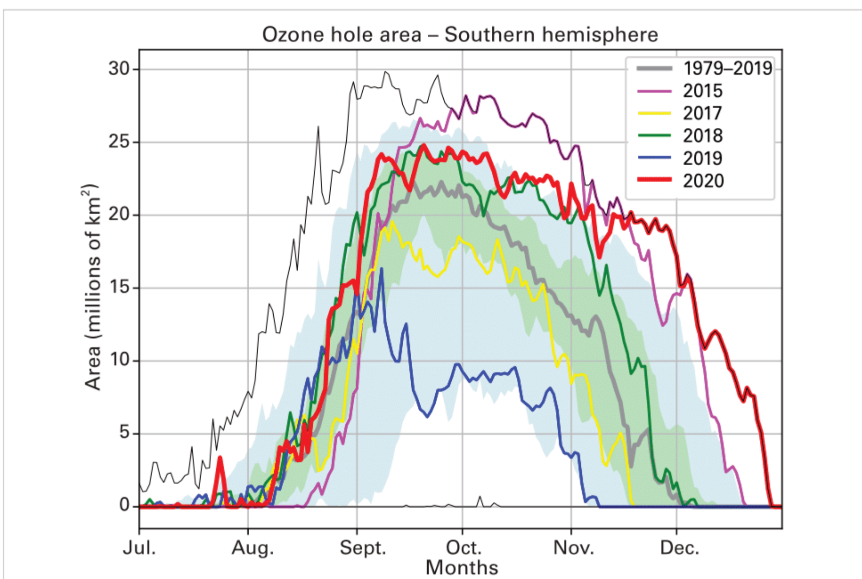

Figure 4. Area (millions of km^2) where the total ozone column is less than 220 Dobson units. 2020 is shown in red, and the most recent years are shown for comparison as indicated by the legend. The thick grey line is the 1979–2019 average. The blue shaded area represents the 30th to 70th percentiles, and the green shaded area represents the 10th and 90th percentiles for the period 1979–2019. The thin black lines show the maximum and minimum values for each day in the 1979–2019 period. The plot was made at WMO on the basis of data downloaded from NASA Ozone Watch (https://ozonewatch.gsfc.nasa.gov/). The NASA data are based on satellite observations from the OMI and TOMS instruments.

OCEAN

The majority of the excess energy that accumulates in the Earth system due to increasing concentrations of greenhouse gases is taken up by the ocean. The added energy warms the ocean, and the consequent thermal expansion of the water leads to sea-level rise, which is further increased by melting ice. The surface of the ocean warms more rapidly than the interior, and this can be seen in the rise of the global mean temperature and in the increased incidence of marine heatwaves. As the concentration of CO_2 in the atmosphere rises, so too does the concentration of CO_2 in the oceans. This affects ocean chemistry, lowering the average pH of the water, a process known as ocean acidification. All these changes have a broad range of impacts in the open ocean and coastal areas.

OCEAN HEAT CONTENT

Increasing human emissions of CO_2 and other greenhouse gases cause a positive radiative imbalance at the top of the atmosphere – the Earth Energy Imbalance (EEI) – which is driving global warming through an accumulation of energy in the form of heat in the Earth system.[7,8,9] Ocean heat content (OHC) is a measure of this heat accumulation in the Earth system as around 90% of it is stored in the ocean. A positive EEI signals that the Earth's climate system is still responding to the current forcing[10] and that more warming will occur even if the forcing does not increase further.[11]

Historical measurements of subsurface temperature back to the 1940s mostly rely on shipboard measurement systems, which constrain the availability of subsurface temperature observations at the global scale and at depth.[12] With the deployment of the Argo network of autonomous profiling floats, which first achieved near-global coverage in 2006, it is now possible to routinely measure OHC changes to a depth of 2000 m.[13,14]

Various research groups have developed estimates of global OHC. Although they all rely more or less on the same database, the estimates show differences arising from the various statistical treatments of data gaps, the choice of climatology and the approach used to account for instrumental biases.[9,15] A concerted effort has been established to provide an international assessment on the global evolution of ocean warming,[16] and an

[7] Hansen, J. et al., 2005: Earth's Energy Imbalance: Confirmation and Implications. *Science,* 308(5727): 1431–1435, https://doi.org/10.1126/science.1110252.

[8] Intergovernmental Panel on Climate Change, 2013: *Climate change 2013: The Physical Science Basis*, https://www.ipcc.ch/report/ar5/wg1/.

[9] von Schuckmann, K. et al., 2016: An imperative to monitor Earth's energy imbalance. *Nature Climate Change,* 6(2): 138–144, https://doi.org/10.1038/nclimate2876.

[10] Hansen, J. et al., 2011: EEarth's energy imbalance and implications. *Atmospheric Chemistry and Physics*, 11(24): 13421–13449, https://doi.org/10.5194/acp-11-13421-2011.

[11] Hansen, J. et al., 2017: Young people's burden: requirement of negative CO_2 emissions. *Earth System Dynamics*, 8(3): 577–616, https://doi.org/10.5194/esd-8-577-2017.

[12] Abraham, J.P. et al., 2013: A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics*, 51(3): 450–483, https://doi.org/10.1002/rog.20022.

[13] Riser, S.C. et al., 2016: Fifteen years of ocean observations with the global Argo array. *Nature Climate Change*, 6(2): 145–153, https://doi.org/10.1038/nclimate2872.

[14] Roemmich, D. et al., 2019: On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array. *Frontiers in Marine Science*, 6, https://doi.org/10.3389/fmars.2019.00439.

[15] Boyer, T. et al., 2016: Sensitivity of Global Upper-Ocean Heat Content Estimates to Mapping Methods, XBT Bias Corrections, and Baseline Climatologies. *Journal of Climate*, 29(13): 4817–4842, https://doi.org/10.1175/JCLI-D-15-0801.1.

[16] von Schuckmann, K. et al., 2020: Heat stored in the Earth system: where does the energy go? *Earth System Science Data*, 12(3): 2013–2041, https://doi.org/10.5194/essd-12-2013-2020.

update of the entire analysis to 2019 is shown in Figure 5 and Figure 6.

The 0–2 000 m depth layer of the global ocean continued to warm in 2019, reaching a new record high (Figure 5), and it is expected that it will continue to warm in the future.[17] A preliminary analysis based on three global data sets suggests that 2020 exceeded that record. Heat storage at intermediate depth (700–2 000 m) increased at a comparable rate to the rate of heat storage in the 0–300 m depth layer, which is in general agreement with the 15 international OHC estimates (Figure 6). All data sets agree that ocean warming rates show a particularly strong increase over the past two decades. Moreover, there is a clear indication that

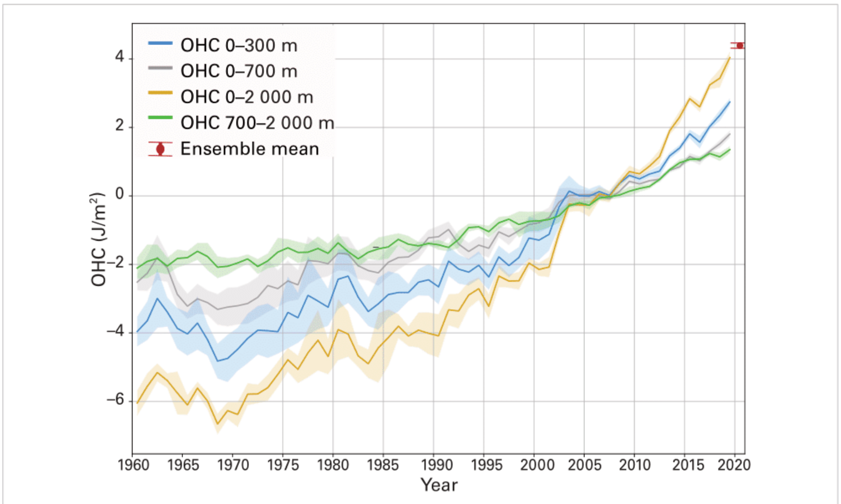

Figure 5. 1960–2019 ensemble mean time series and ensemble standard deviation (2-sigma, shaded) of global OHC anomalies relative to the 2005–2017 climatology. The ensemble mean is an outcome of a concerted international effort, and all products used are listed in Ocean heat content data and in the legend of Figure 5. Note that values are given for the ocean surface area between 60°S–60°N and limited to the 300 m bathymetry of each product. *Source:* Updated from von Schuckmann, K. et al., 2016 (see footnote 9). The ensemble mean OHC (0–2000 m) anomaly (relative to the 1993–2020 climatology) has been added as a red point, together with its ensemble spread, and is based on Copernicus Marine Environment Monitoring Service (CMEMS) (Coriolis Ocean Dataset for Reanalysis (CORA)) products (see Cheng et al., 2017 and Ishii et al., 2017 in Ocean heat content data).

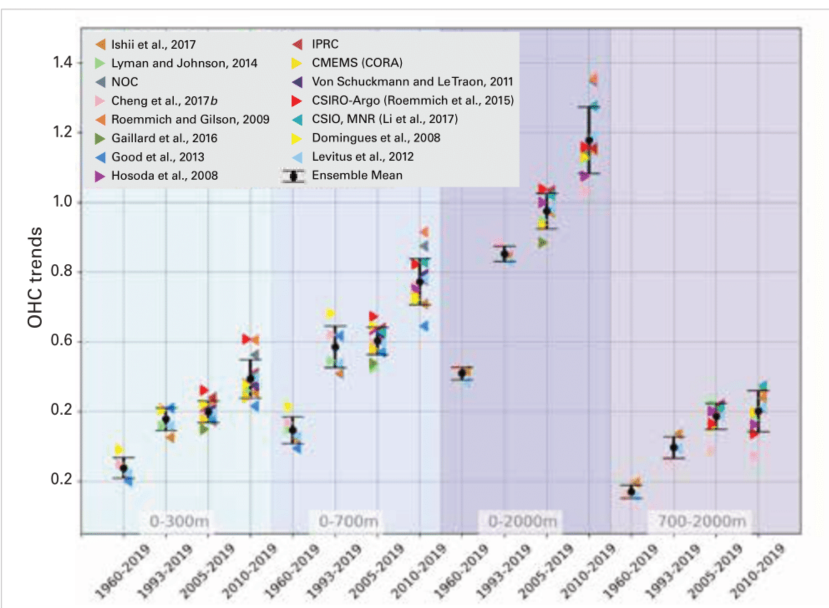

Figure 6. Linear trends of global OHC as derived from different temperature products (colours). References are listed in Ocean heat content data. The ensemble mean and standard deviation (2-sigma) is given in black. The shaded areas show trends from different depth layer integrations: 0–300 m (light turquoise), 0–700 m (light blue), 0–2 000 m (purple) and 700–2 000 m (light purple). For each integration depth layer, trends are evaluated over four periods: historical (1960–2019), altimeter era (1993–2019), golden Argo era (2005–2019), and the most recent period of 2010–2019. *Source:* Updated from von Schuckmann, K. et al., 2016 (see footnote 9).

[17] Intergovernmental Panel on Climate Change, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, https://www.ipcc.ch/srocc/.

heat sequestration into the ocean below 700 m depth has occurred over the past six decades and is linked to an increase in OHC trends over time. Ocean warming rates for the 0–2 000 m depth layer reached rates of 1.2 (0.8) ± 0.2 Wm^{-2} over the period 2010–2019. Below 2 000 m depth, the ocean also warmed, albeit at the lower rate of 0.07 ± 0.04 Wm^{-2} from 1991 to 2018.[18]

SEA LEVEL

On average, since early 1993, the altimetry-based global mean rate of sea-level rise has amounted to 3.3 ± 0.3 mm/yr. The rate has also increased over that time. A greater loss of ice mass from the ice sheets is the main cause of the accelerated rise in global mean sea level.[19]

Global mean sea level continued to rise in 2020 (Figure 7, left). A small decrease during the northern hemisphere summer was likely related to La Niña conditions in the tropical Pacific. Interannual changes of global mean sea level around the long-term trend are correlated with El Niño–Southern Oscillation (ENSO) variability (Figure 7, right). During La Niña events, such as that which occurred in late 2020 and the strong La Niña of 2011, shifts in rainfall patterns transfer water mass from the ocean to tropical river basins on land, temporarily reducing global mean sea level. The opposite is observed during El Niño (for example, the strong 2015/2016 El Niño). In 2020, exceptional rainfall across the African Sahel and other regions may also have contributed to a temporary slowing in sea-level rise as flood waters slowly found their way back to the sea. However, by the end of 2020, global mean sea level was rising again.

At the regional scale, sea level continues to rise non-uniformly. The strongest regional trends over the period from January 1993 to June 2020 were seen in the southern hemisphere: east of Madagascar in the Indian Ocean; east of New Zealand in the Pacific Ocean; and east of Rio de la Plata/South America in the South Atlantic Ocean. An elongated eastward pattern was also seen in the North Pacific Ocean. The strong pattern that was seen in the western tropical Pacific Ocean over the first two decades of the altimetry record is now fading, suggesting that it was related to short-term variability. Regional sea-level trends are dominated by variations in ocean heat content.[17] However, in some regions, such as the Arctic, salinity changes due to freshwater input from the melting of ice on land play an important role.

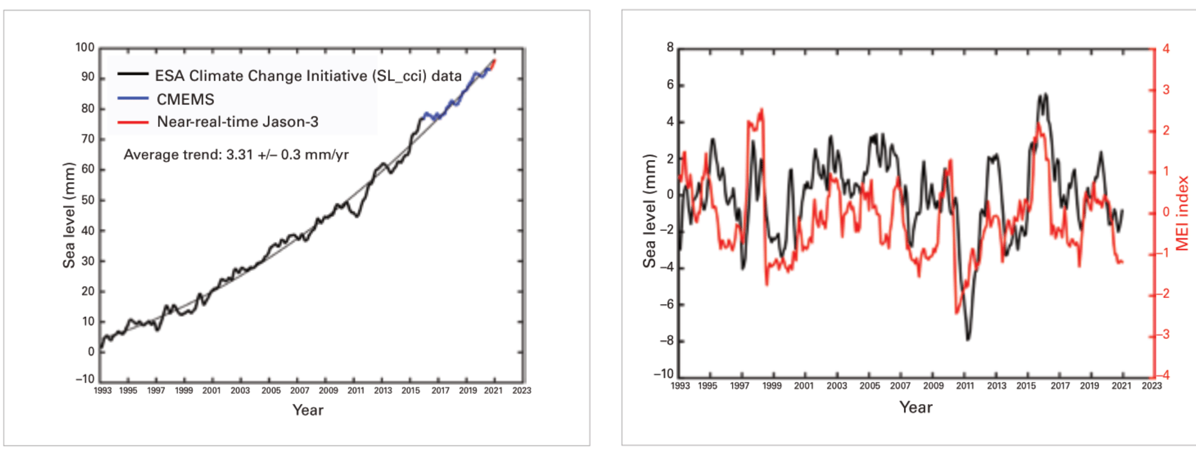

Figure 7. Left: Satellite altimetry-based global mean sea level for January 1993 to January 2021 (last data: 21 January 2021). Data from the European Space Agency Climate Change Initiative Sea Level project (January 1993 to December 2015, thick black curve), data from CMEMS (January 2016 to November 2020, blue curve) and near-real-time altimetry data from the Jason-3 mission beyond November 2020 (red curve). The thin black curve is a quadratic function that best fits the data. Right: Interannual variability of the global mean sea level (with the quadratic function shown in the left-hand panel subtracted) (black curve and left axis) with the multivariate ENSO index (MEI) (red curve and right axis).

[18] Update from Purkey, S.G. and G.C. Johnson, 2010: Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *Journal of Climate*, 23(23): 6336–6351, https://doi.org/10.1175/2010JCLI3682.1.

[19] WCRP Global Sea Level Budget Group, 2018: Global sea-level budget 1993–present. *Earth System Science Data*, 10(3): 1551–1590, https://doi.org/10.5194/essd-10-1551-2018.

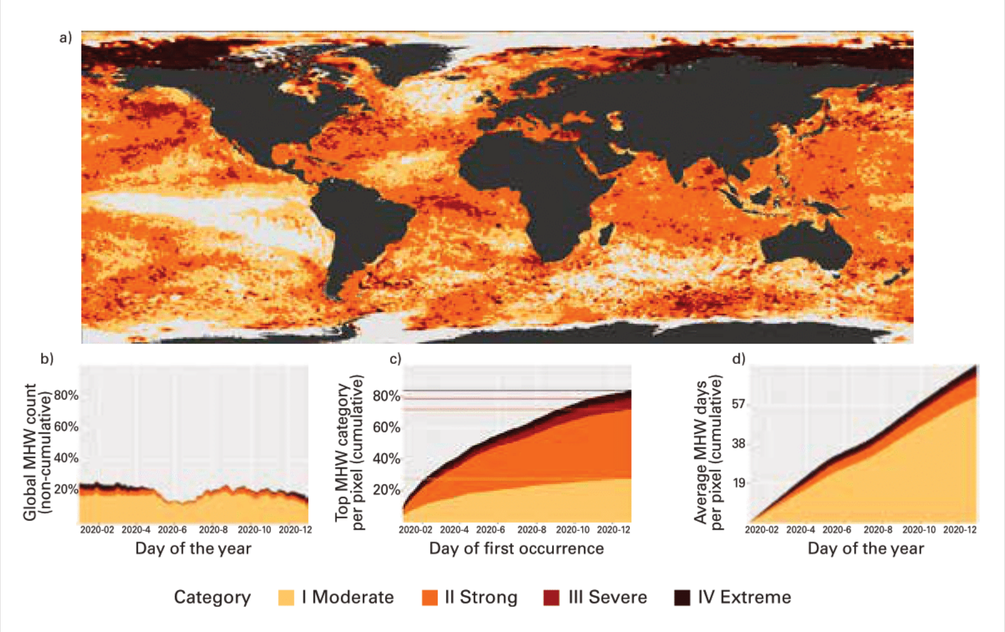

Figure 8. (a) Global map showing the highest MHW category (for definitions, see Marine heatwave data) experienced at each pixel over the course of the year (reference period 1982–2011). Light grey indicates that no MHW occurred in a pixel over the entire year; (b) Stacked bar plot showing the percentage of ocean pixels experiencing an MHW on any given day of the year; (c) Stacked bar plot showing the cumulative percentage of the ocean that experienced an MHW over the year. Note: These values are based on when in the year a pixel first experienced its highest MHW category, so no pixel was counted more than once. Horizontal lines in this figure show the final percentages for each category of MHW; (d) Stacked bar plot showing the cumulative number of MHW days averaged over all pixels in the ocean. Note: This average is calculated by dividing the cumulative number of MHW days per pixel for the entire ocean by the overall number of ocean pixels (~690 000). *Source:* Robert Schlegel

MARINE HEATWAVES

As with heatwaves on land, extreme heat can affect the near-surface layer of the oceans. This situation is called a marine heatwave (MHW), and it can cause a range of consequences for marine life and dependent communities. Satellite retrievals of sea-surface temperature can be used to monitor MHWs. An MHW is categorized here as moderate, strong, severe or extreme (for definitions, see Marine heatwave data).

Much of the ocean experienced at least one 'strong' MHW at some point in 2020 (Figure 8a). Conspicuously absent are MHWs in the Atlantic Ocean south of Greenland and in the eastern equatorial Pacific Ocean. The Laptev Sea experienced a particularly intense MHW from June to December. Sea-ice extent was unusually low in that region, and adjacent land areas experienced heatwaves during the summer (see The Arctic in 2020). Another important MHW to note in 2020 was the return of the semi-persistent warm region in the North-East Pacific Ocean. This event is similar in scale to the original 'blob',[20,21] which developed around 2013, with remnants lasting until 2016.[22] Approximately one fifth of the global ocean was experiencing an MHW on any given day in 2020 (Figure 8b). This percentage is similar to that of 2019, but less than the 2016 peak percentage of 23%. More of the ocean experienced MHWs classified as 'strong' (45%) than 'moderate' (28%). In total, 84% of the ocean experienced at least one MHW during 2020 (Figure 8c); this is similar to the percentage of the ocean that experienced MHWs in 2019 (also 84%), but below the 2016 peak (88%).

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[20] Gentemann, C.L. et al., 2017: Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, 44(1): 312–319, https://doi.org/10.1002/2016GL071039.

[21] di Lorenzo, E. and N. Mantua, 2016: Multi-Year Persistence of the 2014/15 North Pacific Marine Heatwave. *Nature Climate Change*, 6: 1042–1047, https://doi.org/10.1038/nclimate3082.

[22] Schmeisser, L. et al., 2019: The Role of Clouds and Surface Heat Fluxes in the Maintenance of the 2013–2016 Northeast Pacific Marine Heatwave. *Journal of Geophysical Research: Atmospheres*, 124(20): 10772–10783, https://doi.org/10.1029/2019JD030780.

OCEAN ACIDIFICATION

The ocean absorbs around 23% of the annual emissions of anthropogenic CO_2 into the atmosphere,[23] thereby helping to alleviate the impacts of climate change.[24] However, the CO_2 reacts with seawater, lowering its pH. This process, known as ocean acidification, affects many organisms and ecosystem services, threatening food security by endangering fisheries and aquaculture. This is particularly a problem in the polar oceans. It also affects coastal protection by weakening coral reefs, which shield coastlines. As the pH of the ocean declines, its capacity to absorb CO_2 from the atmosphere decreases, diminishing the ocean's capacity to moderate climate change. Regular global observations and measurements of ocean pH are needed to improve the understanding of the consequences of its variations, enable modelling and prediction of change and variability, and help inform mitigation and adaptation strategies.

Global efforts have been made to collect and compare ocean acidification observation data. These data contribute towards achieving Sustainable Development Goal (SDG) 14.3 and can be used to determine its associated SDG Indicator 14.3.1: "Average marine acidity (pH) measured at agreed suite of representative sampling stations". They are summarized in Figure 9 (left) and show an increase of variability (minimum and maximum pH values are highlighted) and a decline in average pH at the available observing sites between 2015 and 2019. The steady global change (Figure 9, right) estimated from a wide variety of sources, including measurements of other variables, contrasts with the regional and seasonal variations in ocean carbonate chemistry seen at individual sites. The increase in the amount of available data highlights the variability and the trend in ocean acidification, as well as the need for sustained long-term observations to better characterize the natural variability in ocean carbonate chemistry.

DEOXYGENATION

Since 1950, the open ocean oxygen content has decreased by 0.5–3%.[17] Oxygen minimum zones, which are permanent features of the open ocean, are expanding.[25] The trend of deoxygenation in the global coastal ocean is still uncertain. Since 1950, the number of hypoxic sites in the global coastal ocean has increased in response to worldwide eutrophication.[26] A quantitative assessment of the severity of

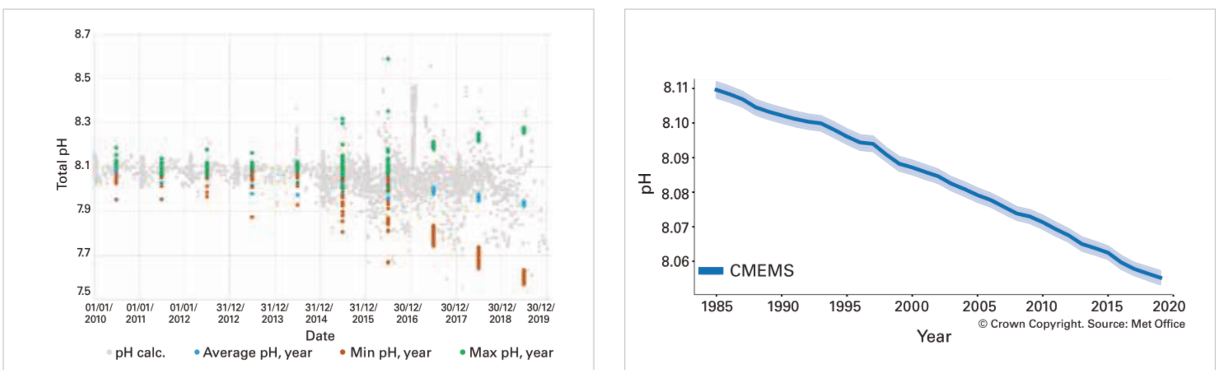


Figure 9. Left: Surface pH values based on ocean acidification data submitted to the 14.3.1 data portal (http://oa.iode.org) for the period from 1 January 2010 to 8 January 2020. The grey circles represent the calculated pH of data submissions (including all data sets with data for at least two carbonate parameters); the blue circles represent the average annual pH (based on data sets with data for at least two carbonate parameters); the red circles represent the annual minimum pH and the green circles represent the annual maximum pH. Note that the number of stations is not constant with time. Right: Global mean surface pH from E.U. Copernicus Marine Service Information (blue). The shaded area indicates the estimated uncertainty in each estimate.

[23] World Meteorological Organization, 2019: *WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2018*, No. 15, https://library.wmo.int/index.php?lvl=notice_display&id=21620.

[24] Friedlingstein, P. et al., 2020: Global Carbon Budget 2020. *Earth System Science Data*, 12(4): 3269–3340, https://doi.org/10.5194/essd-12-3269-2020.

[25] Breitburg, D.et al., 2018: Declining oxygen in the global ocean and coastal waters. *Science (New York, N.Y.)*, 359(6371), https://doi.org/10.1126/science.aam7240.

[26] Diaz, R.J. and R. Rosenberg, 2008: Spreading Dead Zones and Consequences for Marine Ecosystems. *Science*, 321(5891): 926–929, https://doi.org/10.1126/science.1156401.

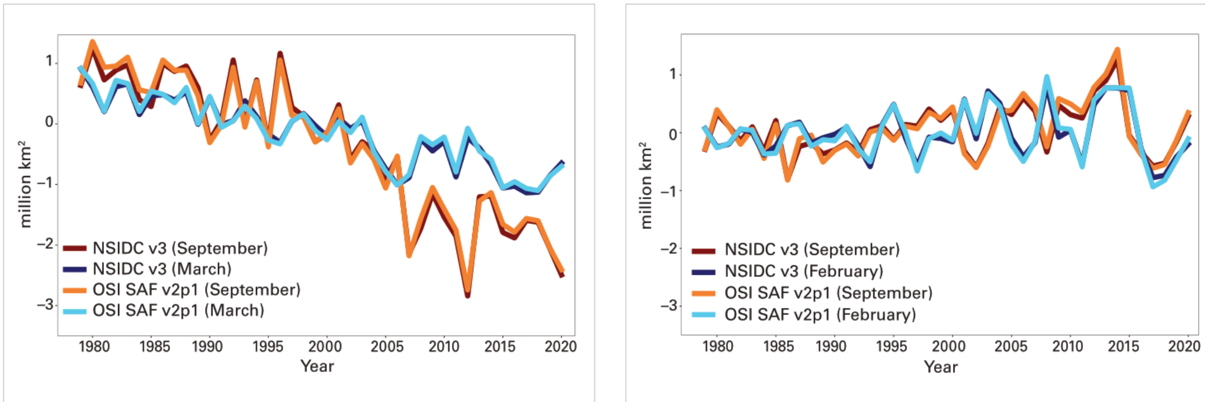


Figure 10. Sea-ice extent difference from the 1981–2010 average in the Arctic (left) and Antarctic (right) for the months with maximum ice cover (Arctic: March; Antarctic: September) and minimum ice cover (Arctic: September; Antarctic: February). *Source:* Data from EUMETSAT OSI SAF v2p1 (Lavergne et al., 2019) and National Snow and Ice Data Centre (NSIDC) v3 (Fetterer et al., 2017) (see reference details in Sea-ice data).

hypoxia on marine life at the global coastal scale requires characterizing the dynamics of hypoxia, for which there is currently insufficient data.

A comprehensive assessment of deoxygenation in the open and coastal ocean would benefit from building a consistent, quality-controlled, open-access global ocean oxygen data set and atlas complying with the FAIR[27] principles. An effort in this direction has been initiated by the Global Ocean Oxygen Network (GO_2NE), the International Ocean Carbon Coordination Project (IOCCP), the National Oceanic and Atmospheric Administration (NOAA) and the German Collaborative Research Centre 754 (SFB 754) project. This effort is part of the Global Ocean Oxygen Decade (GOOD) proposal submitted to the United Nations Decade of Ocean Sciences for Sustainable Development.

CRYOSPHERE

The cryosphere is the domain that comprises the frozen parts of the earth. The cryosphere provides key indicators of the changing climate, but it is one of the most under-sampled domains. The major cryosphere indicators used in this report are sea-ice extent, glacier mass balance and mass balance of the Greenland and Antarctic ice sheets. Specific snow events are covered in the High-impact events in 2020 section.

SEA ICE

In the Arctic, the annual minimum sea-ice extent in September 2020 was the second lowest on record, and record low sea-ice extent was observed in the months of July and October. The sea-ice extents in April, August, November, and December were among the five lowest in the 42-year satellite data record. For more details on the data sets used, see Sea-ice data.

In the Arctic, the maximum sea-ice extent for the year was reached on 5 March 2020. At just above 15 million km^2, this was the 10th or 11th (depending on the data set used) lowest maximum extent on record.[28] Sea-ice retreat in late March was mostly in the Bering Sea. In April, the rate of decline was similar to that of recent years, and the mean sea-ice extent for April was between the second and fourth lowest on record, effectively tied with 2016, 2017, and 2018 (Figure 10).

Record high temperatures north of the Arctic Circle in Siberia (see The Arctic in 2020) triggered an acceleration of sea-ice melt in the East Siberian and Laptev Seas, which continued well into July. The sea-ice extent for July was the lowest on record (7.28 million km^2).[29] The sea-ice retreat in the Laptev Sea was the earliest observed in the satellite era. Towards the end of July, a cyclone entered the Beaufort Sea and spread

[27] FAIR principles: https://www.go-fair.org/fair-principles/

[28] http://nsidc.org/arcticseaicenews/2020/03/

[29] https://cryo.met.no/en/arctic-seaice-summer-2020, https://nsidc.org/arcticseaicenews/2020/08/steep-decline-sputters-out/

the sea ice out, temporarily slowing the decrease of the ice extent. In mid-August, the area affected by the cyclone melted rapidly, which, combined with the sustained melt in the East Siberian and Laptev Seas, made the August extent the 2nd or 3rd lowest on record.

The 2020 Arctic sea-ice extent minimum was observed on 15 September to be 3.74 million km^2, marking only the second time on record that the Arctic sea-ice extent shrank to less than 4 million km^2. Only 2012 had a lower minimum extent at 3.39 million km^2. Vast areas of open ocean were observed in the Chukchi, East Siberian, Laptev, and Beaufort Seas, notwithstanding a tongue of multi-year ice that survived the 2020 melt season in the Beaufort Sea (Figure 13).[30]

Refreeze was slow in late September and October in the Laptev and East Siberian Seas, probably due to the heat accumulated in the upper ocean since the early retreat in late June. The Arctic sea-ice extent was the lowest on record for October and November. December sea-ice growth was faster than average, but the extent remained the second or third lowest on record for the month.

Interannual variability in the annual mean extent of Antarctic sea ice has increased since 1979. For the first 20 years of measurements from 1979 to 1999, there was no significant trend; however, around 2002, the total extent began to increase, reaching a maximum of 12.8 million km^2 in 2014. This was followed by a remarkable decrease over the next three years to a record minimum of 10.7 million km^2 in 2017. The decrease occurred in all sectors but was greatest in the Weddell Sea sector.

In 2020, the Antarctic sea ice extent increased to 11.5 million km^2, only 0.14 million km^2 below the long-term mean. Indeed, extents were close to the long-term mean in all sectors. The Bellingshausen Sea sector had its lowest extent on record in July 2020, but the extent was closer to the mean later in the year.

The Antarctic sea-ice extent in January 2020 showed only a modest increase from the very low values of the previous years, but February 2020 saw a return to less extreme conditions. During the autumn and winter of 2020, the Antarctic sea-ice extent was mostly close to the long-term mean but with positive ice extent anomalies near the maximum in September and October.

The minimum Antarctic sea ice extent in 2020 was around 2.7 million km^2. This occurred between 19 February and 2 March (depending on the data set) and was the seventeenth lowest minimum in the record. It reflected the gradual increase from the record minimum extent of 2.08 million km^2 on 1 March 2017. The maximum extent of the Antarctic sea ice in 2020 was around 19 million km^2 and was observed between 26 and 28 September. This was the thirteenth largest extent in the 42-year record.

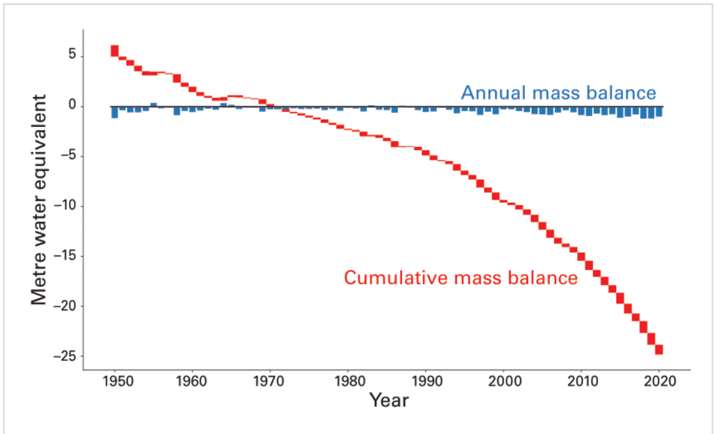


Figure 11. Annual (blue) and cumulative (red) mass balance of reference glaciers with more than 30 years of ongoing glaciological measurements. Global mass balance is based on an average for 19 regions to minimize bias towards well-sampled regions. Annual mass changes are expressed in metre water equivalent (m w.e.), which corresponds to tons per square metre (1 000 kg m^{-2}). *Source:* World Glacier Monitoring Service, 2021, updated

GLACIERS

Glaciers are formed from snow that has compacted to form ice, which can deform and flow downhill to lower, warmer altitudes, where it melts, or if the glacier terminates in the ocean, breaks up, forming icebergs. Glaciers are sensitive to changes in temperature, precipitation and incoming solar radiation, as well as other factors, such as changes in basal lubrication or the loss of buttressing ice shelves.

According to the World Glacier Monitoring Service (Figure 11), in the hydrological year 2018/2019, the roughly 40 glaciers with

[30] https://cryo.met.no/en/arctic-seaice-september-2020

long-term observations experienced an ice loss of 1.18 metre water equivalent (m w.e.), close to the record loss set in 2017/2018. Despite the global pandemic, observations for 2019/2020 were able to be collected for the majority of the important glacier sites worldwide, although some data gaps will be inevitable. Preliminary results for 2020, based on a subset of evaluated glaciers, indicate that glaciers continued to lose mass in the hydrological year 2019/2020. However, mass balance was slightly less negative, with an estimated ice loss of 0.98 m w.e.

The lower rates of glacier mass change are attributed to more moderate climate forcing in some regions, for example in Scandinavia, High Mountain Asia and, to a lesser extent, North America. Lower rates are in some cases explained by high winter precipitation. Most other regions, such as the European Alps or New Zealand, showed strong glacier mass loss, albeit less than in the two preceding years. In contrast, there are indications that glaciers in the Arctic, which account for a large area, were subject to substantially increased melting, but data are still too scarce to establish the overall signal. Although the hydrological year 2019/2020 was characterized by somewhat less negative glacier mass balances in many parts of the Earth, there is a clear trend towards accelerating glacier mass loss in the long term, which is also confirmed by large-scale remote sensing studies. Eight out of the ten most negative mass balance years have been recorded since 2010.

ICE SHEETS

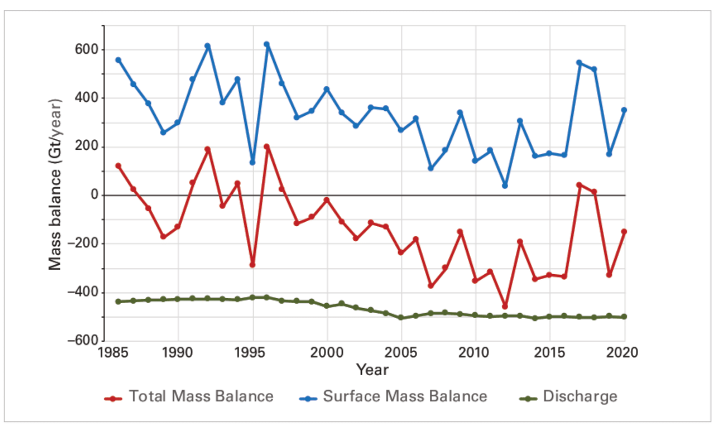
Despite the exceptional warmth in large parts of the Arctic, in particular the very unusual temperatures that were observed in eastern Siberia, temperatures over Greenland in 2020 were close to the long-term mean (Figure 2). The Greenland ice sheet ended the September 2019 to August 2020 season with an overall loss of 152 Gt of ice. This loss was a result of surface melting, the discharge of icebergs and the melting of glacier tongues by warm ocean water (Figure 12) and although significant, was less than the loss of ice in the previous year (329 Gt).

Changes in the mass of the Greenland ice sheet reflect the combined effects of the surface mass balance (SMB) – defined as the difference between snowfall and run-off from the ice sheet, which is always positive at the end of the year – and mass losses at the periphery from the calving of icebergs and the melting of glacier tongues that meet the ocean. The 2019/2020 Greenland SMB was +349 Gt of ice, which is close to the 40-year average of +341 Gt. However, ice loss due to iceberg calving was at the high end of the 40-year satellite record. The Greenland SMB record is now four decades long and, although it varies from one year to another, there has been an overall decline in the average SMB over time (Figure 12). In the 1980s and 1990s, the average SMB gain was about +416 Gt/year. It fell to +270 Gt/year in the 2000s and +260 Gt/year in the 2010s.

The GRACE satellites and the follow-on mission GRACE-FO measure the tiny change of the gravitational force due to changes in the amount of ice. This provides an independent measure of the total mass balance. Based on this data, it can be seen that the Greenland ice sheet lost about 4 200 Gt from April 2002 to August 2019, which contributed to a sea-level rise of slightly more than 1 cm. This is in good agreement with the mass balance from SMB and discharge, which was 4 261 Gt during the same period.

The 2019/2020 melt season on the Greenland ice sheet started on 22 June, 10 days later than the 1981–2020 average. As in previous seasons, there were losses along the Greenlandic west coast and gains in the east. In mid-August, unusually large storms

Figure 12. Components of the total mass balance of the Greenland ice sheet for the period 1986–2020. Blue: surface mass balance (http://polarportal.dk/en/greenland/surface-conditions/), green: discharge, red: total mass balance (the sum of the surface mass balance and discharge). *Source:* Mankoff, K.D. et al., 2020: Greenland Ice Sheet solid ice discharge from 1986 through March 2020. *Earth System Science Data*, 12(2): 1367–1383, https://doi.org/10.5194/essd-12-1367-2020.



The Arctic in 2020

The Arctic has been undergoing drastic changes as the global temperature has increased. Since the mid-1980s, Arctic surface air temperatures have warmed at least twice as fast as the global average, while sea ice, the Greenland ice sheet and glaciers have declined over the same period and permafrost temperatures have increased. This has potentially large implications not only for Arctic ecosystems, but also for the global climate through various feedbacks.[a]

In 2020, the Arctic stood out as the region with the largest temperature deviations from the long-term average. Contrasting conditions of ice, heat and wildfires were seen in the eastern and western Arctic (Figure 13). A strongly positive phase of the Arctic Oscillation during the 2019/2020 winter set the scene early in the year, with higher-than-average temperatures across Europe and Asia and well-below-average temperatures in Alaska, a pattern which persisted throughout much of the year.

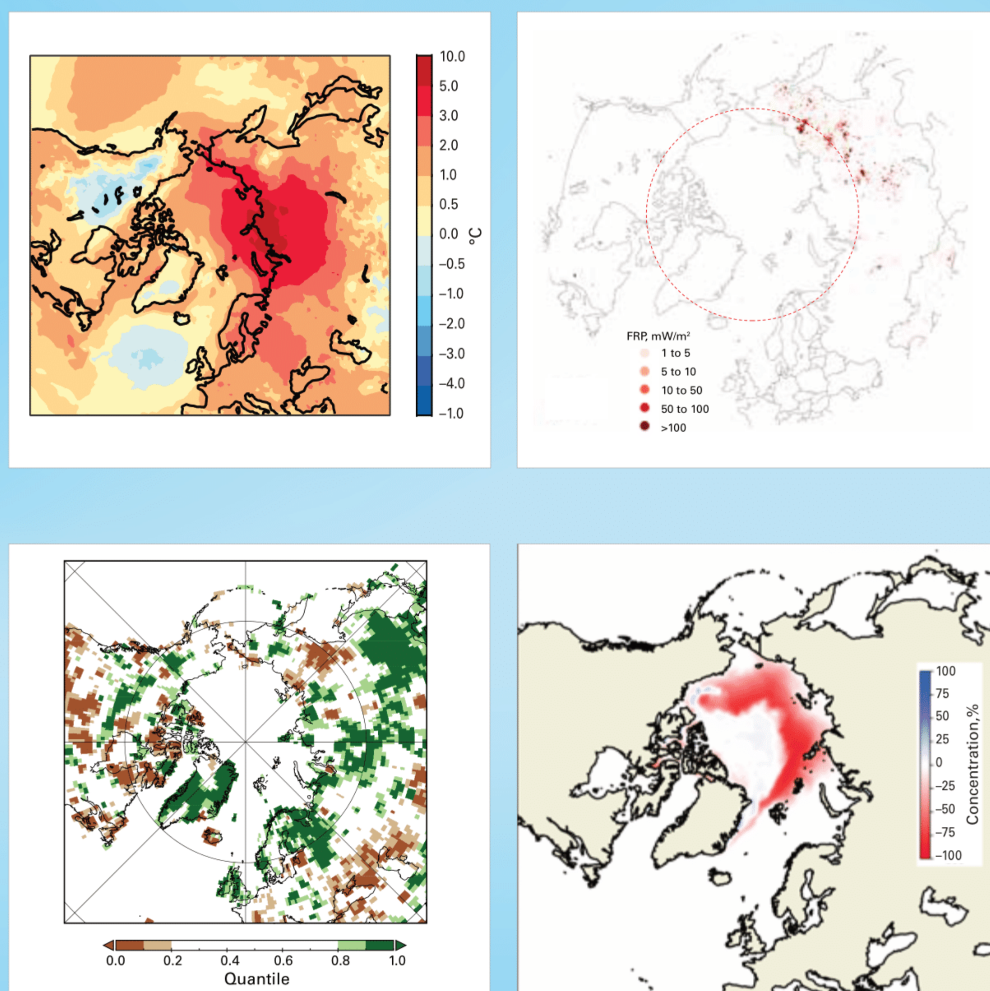


Figure 13. Top left: Temperature anomalies for the Arctic relative to the 1981–2010 long-term average from the ERA5 reanalysis for 2020. *Source:* Copernicus Climate Change Service, ECMWF

Top right: Fire Radiative Power, a measure of heat output from wildfires, in the Arctic Circle between June and August 2020. *Source:* Copernicus Atmosphere Monitoring Service, ECMWF

Bottom left: Total precipitation in 2020, expressed as a percentile of the 1951–2010 reference period, for areas that would have been in the driest 20% (brown) and wettest 20% (green) of years during the reference period, with darker shades of brown and green indicating the driest and wettest 10%, respectively. *Source:* Global Precipitation Climatology Centre (GPCC)

Bottom right: Sea-ice concentration anomaly for September 2020. *Source:* EUMETSAT OSI SAF v2p1 data, with research and development input from the European Space Agency Climate Change Initiative (ESA CCI)

[a] Intergovernmental Panel on Climate Change, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, https://www.ipcc.ch/srocc/.

In a large region of the Siberian Arctic, temperature anomalies for 2020 were more than 3 °C, and in its central coastal parts, more than 5 °C above average (Figure 13). A preliminary record temperature of 38 °C was set for north of the Arctic Circle, on 20 June in Verkhoyansk,[b] during a prolonged heatwave. Heatwaves and heat records were also observed in other parts of the Arctic (see High-impact events in 2020), and extreme heat was not confined to the land. A marine heatwave affected large areas of the Arctic Ocean north of Eurasia (Figure 8). Sea ice in the Laptev Sea, offshore from the area of highest temperature anomalies on land, was unusually low through the summer and autumn. Indeed, the sea-ice extent was particularly low along the Siberian coastline, with the Northern Sea Route ice-free or close to ice-free from July to October. The high spring temperatures also had a significant effect on other parts of the cryosphere. June snow cover was the lowest for the Eurasian Arctic in the 54-year satellite record despite the region having a larger-than-average extent as late as April.[c]

Although the Arctic was predominantly warmer than average for this period, some regions, including parts of Alaska and Greenland, saw close to average or below-average temperatures. As a result, the 2019/2020 surface mass balance for Greenland was close to the 40-year average. Nevertheless, the decline of the Greenland ice sheet continued during the 2019/2020 season, but the loss was below the typical amounts seen during the last decade (see Cryosphere). Sea-ice conditions along the Canadian archipelago were close to average at the September minimum, and the western passage remained closed.[d]

The wildfire season in the Arctic during 2020 was particularly active, but with large regional differences. The region north of the Arctic circle saw the most active wildfire season in an 18-year data record, as estimated in terms of fire radiative power and CO_2 emissions released from fires. The main activity was concentrated in the eastern Siberian Arctic, which was also drier than average. Regional reports[e] for eastern Siberia indicate that the forest fire season started earlier than average, and for some regions ended later, resulting in long-term damage to local ecosystems. Alaska, as well as the Yukon and the Northwest Territories, reported fire activity that was well below average.

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[b] https://public.wmo.int/en/media/news/reported-new-record-temperature-of-38%C2%B0c-north-of-arctic-circle

[c] Mudryk, L.E. et al., 2020: *Arctic Report Card 2020: Terrestrial Snow Cover. United States. National Oceanic and Atmospheric Administration.* Office of Oceanic and Atmospheric Research University of Toronto. Department of Physics Ilmatieteen laitos (Finland) / Finnish Meteorological Institute, https://doi.org/10.25923/P6CA-V923.

[d] Arctic Climate Forum, https://arctic-rcc.org/sites/arctic-rcc.org/files/presentations/acf-fall-2020/2%20-%20Day%202%20-%20ACF-6_Arctic_summary_MJJAS_2020_v2.pdf

[e] Arctic Climate Forum, https://arctic-rcc.org/sites/arctic-rcc.org/files/presentations/acf-fall-2020/3%20-%20Day%201-%20ACF%20October%202020%20Regional%20Overview%20Summary%20with%20extremes%20-281020.pdf

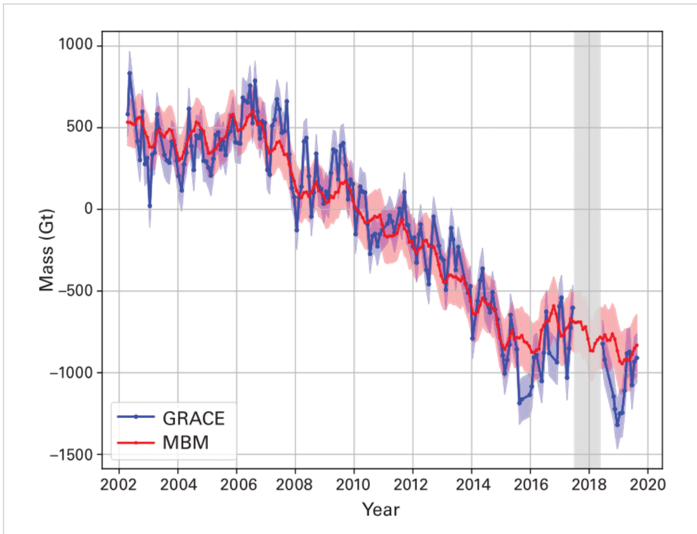

Figure 14. Comparison of Antarctic ice sheet mass changes from GRACE/GRACE-FO satellite gravimetry (blue) and the mass budget method (MBM) (red). This comparison highlights the large interannual variability in mass change, the relatively large uncertainties in these two methods, and their occasional disagreement. *Source:* Velicogna et al., 2020 (see reference details in Antarctic ice sheet data)

brought four times the normal monthly precipitation to western Greenland, most of which fell as snow that temporarily stopped the net loss of ice and was decisive in reducing the amount of melt; this was quite different from the situation in the previous season (2018/2019), in which there were extended high pressure periods and large amounts of sunshine, which significantly increased the summer melt.

There is no routine reporting of the annual mass balance for the Antarctic ice sheet, and reported mass changes typically have a latency of several years. This is because multiple data sets must be combined to reduce uncertainty and bias in mass-change estimates on the continental scale.

Antarctica has exhibited a strong mass loss trend since the late 1990s. This trend accelerated around 2005, and currently, Antarctica loses approximately 175 to 225 Gt per year. Nearly 90% of the acceleration of this trend is due to the increasing flow rates of major glaciers in West Antarctica and the Antarctic Peninsula.[17] This is in contrast to the Greenland ice sheet, where losses from surface melting are of comparable magnitude to those from glacier dynamics. The main driver of faster glacier flow in Antarctica has been enhanced sub-sea melting of fringing ice shelves, with a secondary driver being abrupt ice-shelf collapse due to localized surface melting on the Antarctic Peninsula.[39] This glacier-dynamic response to climate and ocean forcing is strongly controlled by thresholds (ice shelf collapse) and strongly modulated by positive feedbacks in flow. As a result, Antarctica's interannual dynamic losses are largely uncoupled from fluctuations in weather on annual timescales.

Superimposed on this sustained mass loss trend is a large interannual variability in snowfall that fluctuates by several hundred gigatons (Figure 14) around an average of approximately 2 300 Gt to 2 500 Gt per year[31] and has no clear trend over recent decades.[32] These large fluctuations are dominated spatially and temporally by occasional extreme snowfall events.[33] Instrumental observations of snowfall on the continent are extremely scarce, however, and ice-sheet mass changes are instead calculated retrospectively from satellite-observed changes in flow rate (the mass budget method), the gravity field or surface height, combined with modelled surface mass balance, near-surface snow density and isostatic rebound, respectively. Each of these three sets of observations and associated model inputs contains significant uncertainties and potential biases, and the results reported by these techniques do not always agree within their uncertainties.[34] Consensus on Antarctic mass changes therefore emerges only from a detailed inter-comparison of this suite of methods, with careful consideration of their respective strengths and weaknesses.[39,43] No such consensus value is available yet for the 2019/2020 period.

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[31] Mottram, R. et al., 2020: What Is the Surface Mass Balance of Antarctica? An Intercomparison of Regional Climate Model Estimates. *The Cryosphere Discussions*, 1–42, https://doi.org/10.5194/tc-2019-333.

[32] King, M.A. and C.S. Watson, 2020: Antarctic Surface Mass Balance: Natural Variability, Noise, and Detecting New Trends. *Geophysical Research Letters*, 47(12): e2020GL087493, https://doi.org/10.1029/2020GL087493.

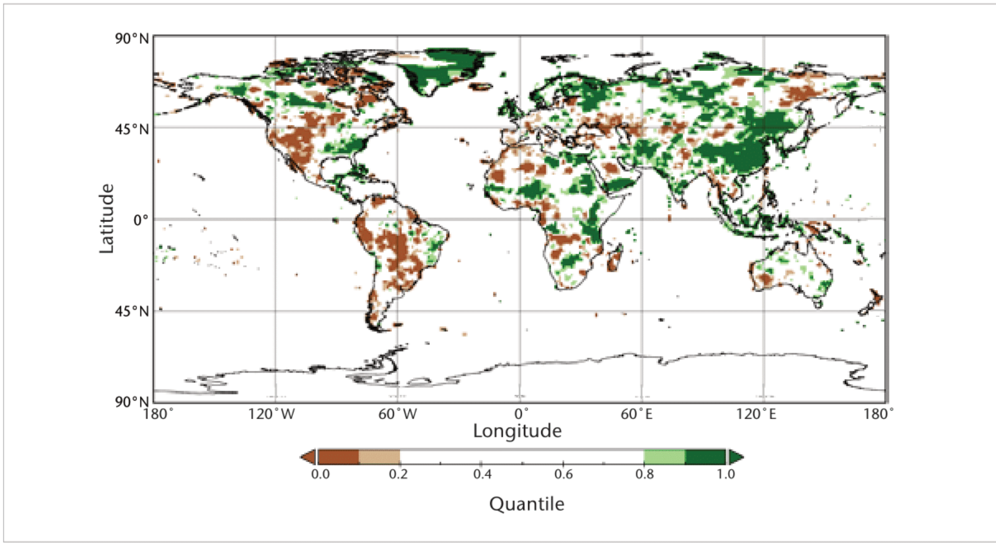
[33] Turner, J. et al., 2019: The Dominant Role of Extreme Precipitation Events in Antarctic Snowfall Variability. *Geophysical Research Letters*, 46(6): 3502–3511, https://doi.org/10.1029/2018GL081517.

[34] Shepherd, A. et al., 2018: Mass Balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, 558(7709): 219–222, https://doi.org/10.1038/s41586-018-0179-y.

PRECIPITATION

Annual precipitation totals in monsoon-influenced regions in North America, Africa, South-West Asia and South-East Asia were unusually high in 2020 (Figure 15, top), as were extreme daily totals (expressed as the 95th percentile of daily totals) (Figure 15, bottom). The African Monsoon extended farther north into the Sahel region than usual. Monsoon seasonal totals in India were 109% of the long-term mean, the third highest seasonal total after 1994 and 2019. East Asia experienced abnormally high annual and extreme daily rainfall totals.

In other regions, the extreme daily totals (95th percentile of daily precipitation amounts) were lower than the long-term mean (Figure 15, bottom), for example, the Maritime Continent (incorporating Indonesia, Papua New Guinea and the Philippines, as well as other islands in the region), Central and North-West Africa, large areas of the Americas and Central and West Europe.



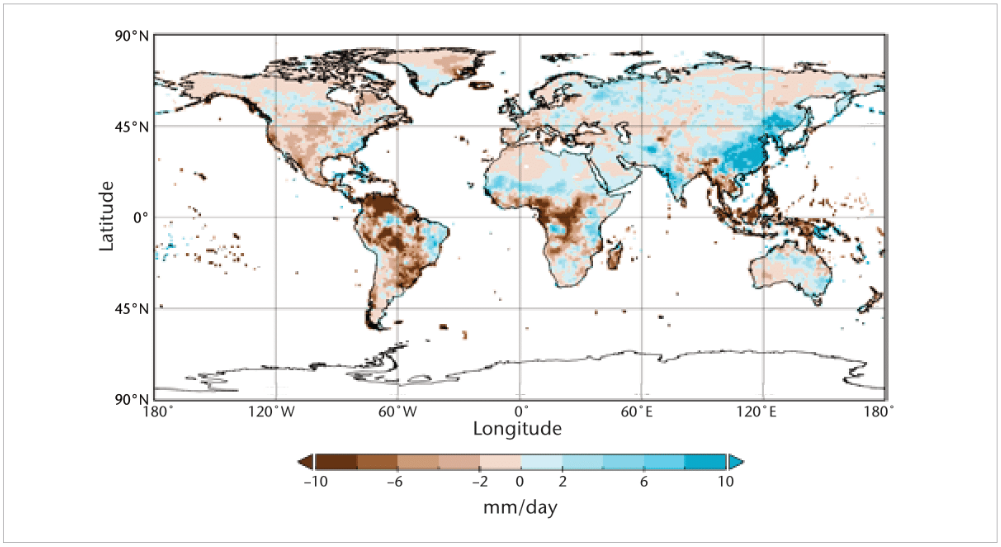


Figure 15. Top: Total precipitation in 2020, expressed as a percentile of the 1951–2010 reference period. The shaded areas are those with precipitation totals in the driest 20% (brown) and wettest 20% (green) of years during the reference period, with darker shades of brown and green indicating the driest and wettest 10%, respectively.
Note: A longer reference period is used here because precipitation is more variable, and a longer period allows a more reliable long-term average to be calculated.
Bottom: Difference between the observed 95th percentile of daily precipitation total in 2020 and the long-term mean based on the 1982–2016 (full year) period. Blue indicates more extreme daily precipitation events than the long-term mean, and brown indicates fewer extreme daily precipitation events than the long-term mean.
Note: The period used here is the full length of the global daily precipitation data set.
Source: GPCC, Deutscher Wetterdienst, Germany

DRIVERS OF SHORT-TERM CLIMATE VARIABILITY

There are many different natural phenomena, often referred to as climate patterns or climate modes, that affect weather at timescales ranging from days to several months. Surface temperatures change relatively slowly over the ocean, so recurring patterns in sea-surface temperature can be used to understand, and in some cases, predict the more rapidly changing patterns of weather over land on seasonal timescales. Similarly, albeit at a faster rate, known pressure changes in the atmosphere can help explain certain regional weather patterns.

In 2020, the El Niño–Southern Oscillation (ENSO) and the Arctic Oscillation (AO) each contributed to weather and climate events in different parts of the world. The Indian Ocean Dipole, which played a key role in the events of 2019, was near-neutral for much of 2020.

EL NIÑO–SOUTHERN OSCILLATION

ENSO is one of the most important drivers of year-to-year variability in weather patterns around the world. It is linked to hazards such as heavy rains, floods, and drought. El Niño, characterized by higher-than-average sea-surface temperatures in the eastern Pacific and a weakening of the trade winds, typically has a warming influence on global temperatures. La Niña, which is characterized by below-average sea-surface temperatures in the central and eastern Pacific and a strengthening of the trade winds, has the opposite effect.

Sea-surface temperatures at the end of 2019 were close to or exceeded El Niño thresholds in the Niño 3.4 region.[4] These temperatures persisted into the early months of 2020, but the event did not strengthen, and sea-surface temperature anomalies in the eastern Pacific fell in March. After a six-month period of neutral conditions – that is, sea-surface temperatures within 0.5 °C of normal – the cool-phase, La Niña, developed in August and strengthened through the northern hemisphere autumn to moderate strength (1.0–1.5 °C below normal). The atmosphere also responded with stronger-than-average trade winds, indicating a coupling with the sea-surface temperatures. La Niña conditions are associated with above-average hurricane activity in the North Atlantic, which experienced a record number of named tropical storms during its 2020 hurricane season, and also with above-average rainfall in Australia, which ended the year with its fourth wettest December on record.

ARCTIC OSCILLATION

AO is a large-scale atmospheric pattern that influences weather throughout the northern hemisphere. The positive phase is characterized by lower-than-average air pressure over the Arctic and higher-than-average pressure over the northern Pacific and Atlantic Oceans. The jet stream is parallel to the lines of latitude and farther north than average, locking up cold Arctic air, and storms can be shifted northward of their usual paths. The mid-latitudes of North America, Europe, Siberia, and East Asia generally see fewer cold air outbreaks than usual during the positive phase of AO. A negative AO has the opposite effect and is associated with a more meandering jet stream and cold air spilling south into the mid-latitudes.

AO was strongly positive during the northern hemisphere 2019/2020 winter and in February was the strongest it had been since January 1993. This contributed to the warmest winter on record for Asia and Europe and the sixth warmest winter on record for the contiguous United States; at the same time, Alaska experienced its coldest winter in more than two decades. By containing cold air in the polar region through the entire winter, the positive AO also contributed to a relatively rare and record-large Arctic ozone hole in March (see Stratospheric ozone and ozone-depleting gases). Additionally, the positive winter phase of AO has been linked to low sea-ice extent the following summer[35] (see Sea ice). AO was strongly positive in November but rapidly declined to large negative values in December and in early 2021.

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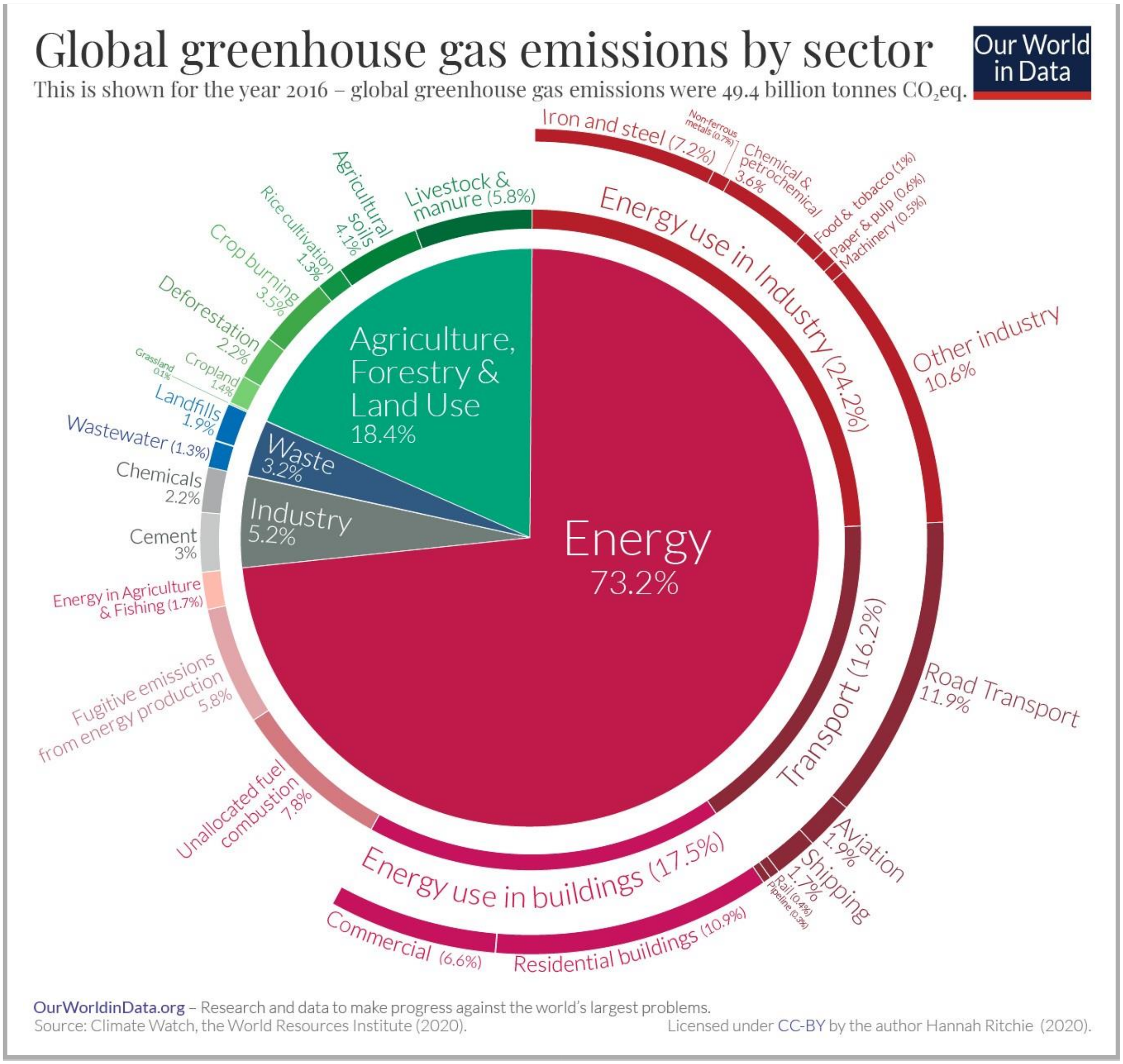
[35] Rigor, I.G. et al., 2002: Response of Sea Ice to the Arctic Oscillation. *Journal of Climate*, 15(18): 2648–2663, https://doi.org/10.1175/1520-0442(2002)015%3c2648:ROSITT%3e2.0.CO;2.

[Climate Change 2022: Impacts, Adaptation & Vulnerability - Full video (https://youtu.be/SDRxfuEvqGg)](https://youtu.be/SDRxfuEvqGg)

Sector by sector: where do global greenhouse gas emissions come from?

Globally, we emit around 50 billion tonnes of greenhouse gases each year. Where do these emissions come from? We take a look, sector-by-sector.

by Hannah Ritchie
September 18, 2020



To prevent severe climate change we need to rapidly reduce global greenhouse gas emissions. The world emits around 50 billion tonnes of greenhouse gases each year *[measured in carbon dioxide equivalents (CO_2eq)]*.[1]

To figure out how we can most effectively reduce emissions and what emissions *can* and *can't* be eliminated with current technologies, we need to first understand where our emissions come from.

In this post I present only one chart, but it is an important one – it shows the breakdown of global greenhouse gas emissions in 2016.[2] This is the latest breakdown of global emissions by sector, published by Climate Watch and the World Resources Institute.[3,4]

The overall picture you see from this diagram is that almost three-quarters of emissions come from energy use; almost one-fifth from agriculture and land use *[this increases to one-quarter when we consider the food system as a whole – including processing, packaging, transport and retail]*; and the remaining 8% from industry and waste.

To know what's included in each sector category, I provide a short description of each. These descriptions are based on explanations provided in the IPCC's Fifth Assessment Report AR5) and a methodology paper published by the *World Resources Institute*.[5,6]

Emissions come from many sectors: we need many solutions to decarbonize the economy

It is clear from this breakdown that a range of sectors and processes contribute to global emissions. This means there is no single or simple solution to tackle climate change. Focusing on electricity, or transport, or food, or deforestation alone is insufficient.

Even within the energy sector – which accounts for almost three-quarters of emissions – there is no simple fix. Even if we could fully decarbonize our electricity supply, we would also need to electrify all of our heating and road transport. And we'd still have emissions from shipping and aviation – which we do not yet have low-carbon technologies for – to deal with.

To reach net-zero emissions we need innovations across many sectors. Single solutions will not get us there.

Let's walk through each of the sectors and sub-sectors in the pie chart, one-by-one.

Energy (electricity, heat and transport): 73.2%

Energy use in industry: 24.2%

Iron and Steel (7.2%): energy-related emissions from the manufacturing of iron and steel.

Chemical & petrochemical (3.6%): energy-related emissions from the manufacturing of fertilizers, pharmaceuticals, refrigerants, oil and gas extraction, etc.

Food and tobacco (1%): energy-related emissions from the manufacturing of tobacco products and food processing (the conversion of raw agricultural products into their final products, such as the conversion of wheat into bread).

Non-ferrous metals: 0.7%: Non-ferrous metals are metals which contain very little iron: this includes aluminium, copper, lead, nickel, tin, titanium and zinc, and alloys such as brass. The manufacturing of these metals requires energy which results in emissions.

Paper & pulp (0.6%): energy-related emissions from the conversion of wood into paper and pulp.

Machinery (0.5%): energy-related emissions from the production of machinery.

Other industry (10.6%): energy-related emissions from manufacturing in other industries including mining and quarrying, construction, textiles, wood products, and transport equipment (such as car manufacturing).

Transport: 16.2%

This includes a small amount of electricity (indirect emissions) as well as all direct emissions from burning fossil fuels to power transport activities. These figures do not include emissions from the manufacturing of motor vehicles or other transport equipment – this is included in the previous point 'Energy use in Industry'.

Road transport (11.9%): emissions from the burning of petrol and diesel from all forms of road transport which includes cars, trucks, lorries, motorcycles and buses. Sixty percent of road transport emissions come from passenger travel (cars, motorcycles and buses); and the remaining forty percent from road freight (lorries and trucks). This means that, if we could electrify the whole road transport sector, and transition to a fully decarbonized electricity mix, we could feasibly reduce global emissions by 11.9%.

Aviation (1.9%): emissions from passenger travel and freight, and domestic and international aviation. 81% of aviation emissions come from passenger travel; and 19% from freight.[7] From passenger aviation, 60% of emissions come from international travel, and 40% from domestic.

Shipping (1.7%): emissions from the burning of petrol or diesel on boats. This includes both passenger and freight maritime trips.

Rail (0.4%): emissions from passenger and freight rail travel.

Pipeline (0.3%): fuels and commodities (e.g. oil, gas, water or steam) often need to be transported (either within or between countries) via pipelines. This requires energy inputs, which results in emissions. Poorly constructed pipelines can also leak, leading to direct emissions of methane to the atmosphere – however, this aspect is captured in the category 'Fugitive emissions from energy production'.

Energy use in buildings: 17.5%

Residential buildings (10.9%): energy-related emissions from the generation of electricity for lighting, appliances, cooking etc. and heating at home.

Commercial buildings (6.6%): energy-related emissions from the generation of electricity for lighting, appliances, etc. and heating in commercial buildings such as offices, restaurants, and shops.

Unallocated fuel combustion (7.8%)

Energy-related emissions from the production of energy from other fuels including electricity and heat from biomass; on-site heat sources; combined heat and power (CHP); nuclear industry; and pumped hydroelectric storage.

Fugitive emissions from energy production: 5.8%

Fugitive emissions from oil and gas (3.9%): fugitive emissions are the often-accidental leakage of methane to the atmosphere during oil and gas extraction and transportation, from damaged or poorly maintained pipes. This also includes flaring – the intentional burning of gas at oil facilities. Oil wells can release gases, including methane, during extraction – producers often don't have an existing network of pipelines to transport it, or it wouldn't make economic sense to provide the infrastructure needed to effectively capture and transport it. But under environmental regulations they need to deal with it somehow: intentionally burning it is often a cheap way to do so.

Fugitive emissions from coal (1.9%): fugitive emissions are the accidental leakage of methane during coal mining.

Energy use in agriculture and fishing (1.7%)

Energy-related emissions from the use of machinery in agriculture and fishing, such as fuel for farm machinery and fishing vessels.

Direct Industrial Processes: 5.2%

Cement (3%): carbon dioxide is produced as a byproduct of a chemical conversion process used in the production of clinker, a component of cement. In this reaction, limestone ($CaCO_3$) is converted to lime (CaO), and produces CO_2 as a byproduct. Cement production also produces emissions from energy inputs – these related emissions are included in 'Energy Use in Industry'.

Chemicals & petrochemicals (2.2%): greenhouse gases can be produced as a byproduct from chemical processes – for example, CO_2 can be emitted during the production of ammonia, which is used for purifying water supplies, cleaning products, and as a refrigerant, and used in the production of many materials, including plastic, fertilizers, pesticides, and textiles. Chemical and petrochemical manufacturing also produces emissions from energy inputs – these related emissions are included in 'Energy Use in Industry'.

Waste: 3.2%

Wastewater (1.3%): organic matter and residues from animals, plants, humans and their waste products can collect in wastewater systems. When this organic matter decomposes it produces methane and nitrous oxide.

Landfills (1.9%): landfills are often low-oxygen environments. In these environments, organic matter is converted to methane when it decomposes.

Agriculture, Forestry and Land Use: 18.4%

Agriculture, Forestry and Land Use directly accounts for 18.4% of greenhouse gas emissions. The food system as a whole – including refrigeration, food processing, packaging, and transport – accounts for around one-quarter of greenhouse gas emissions. We look at this in detail **here**.

Grassland (0.1%): when grassland becomes degraded, these soils can lose carbon, converting to carbon dioxide in the process. Conversely, when grassland is restored (for example, from cropland), carbon can be sequestered. Emissions here therefore refer to the net balance of these carbon losses and gains from grassland biomass and soils.

Cropland (1.4%): depending on the management practices used on croplands, carbon can be lost or sequestered into soils and biomass. This affects the balance of carbon dioxide emissions: CO_2 can be emitted when croplands are degraded; or sequestered when they are restored. The net change in carbon stocks is captured in emissions of carbon dioxide. This does not include grazing lands for livestock.

Deforestation (2.2%): net emissions of carbon dioxide from changes in forestry cover. This means reforestation is counted as 'negative emissions' and deforestation as 'positive emissions'. Net forestry change is therefore the difference between forestry loss and gain. Emissions are based on lost carbon stores from forests and changes in carbon stores in forest soils.

Crop burning (3.5%): the burning of agricultural residues – leftover vegetation from crops such as rice, wheat, sugar cane, and other crops – releases carbon dioxide, nitrous oxide and methane. *Farmers often burn crop residues after harvest to prepare land for the resowing of crops.*

Rice cultivation (1.3%): flooded paddy fields produce methane through a process called 'anaerobic digestion'. Organic matter in the soil is converted to methane due to the low-oxygen environment of waterlogged rice fields. 1.3% seems substantial, but it's important to put this into context: rice accounts for around one-fifth of the world's supply of calories, and is a staple crop for billions of people globally.[8]

Agricultural soils (4.1%): Nitrous oxide – a strong greenhouse gas – is produced when synthetic nitrogen fertilizers are applied to soils. This includes emissions from agricultural soils for all agricultural products – including food for direct human consumption, animal feed, biofuels and other non-food crops (such as tobacco and cotton).

Livestock & manure (5.8%): animals (mainly ruminants, such as cattle and sheep) produce greenhouse gases through a process called 'enteric fermentation' – when microbes in their digestive systems break down food, they produce methane as a by-product. This means beef and lamb tend to have a high carbon footprint, and eating less is an effective way to reduce the emissions of your diet.

Nitrous oxide and methane can be produced from the decomposition of animal manures under low oxygen conditions. This often occurs when large numbers of animals are managed in a confined area (such as dairy farms, beef feedlots, and swine and poultry farms), where manure is typically stored in large piles or disposed of in lagoons and other types of manure management systems 'Livestock' emissions here include direct emissions from livestock only- they do not consider impacts of land use change for pasture or animal feed.

U.S. Energy Information Administration

NATURAL GAS EXPLAINED

NATURAL GAS AND THE ENVIRONMENT

BASICS

Natural gas has many qualities that make it an efficient, relatively clean burning, and economical energy source. However, the production and use of natural gas have some environmental and safety issues to consider.

Natural gas is a relatively clean burning fossil fuel

Burning natural gas for energy results in fewer emissions of nearly all types of air pollutants and carbon dioxide (CO_2) than burning coal or petroleum products to produce an equal amount of energy. About 117 pounds of CO_2 are produced per million British thermal units (MMBtu) equivalent of natural gas compared with more than 200 pounds of CO_2 per MMBtu of coal and more than 160 pounds per MMBtu of distillate fuel oil. The clean burning properties of natural gas have contributed to increased natural gas use for electricity generation and as a transportation fuel for fleet vehicles in the United States.

Natural gas is mainly methane—a strong greenhouse gas

Some natural gas leaks into the atmosphere from oil and natural gas wells, storage tanks, pipelines, and processing plants. The U.S. Environmental Protection Agency estimates that in 2019, methane emissions from natural gas and petroleum systems and from abandoned oil and natural gas wells were the source of about 29% of total U.S. methane emissions and about 3% of total U.S. greenhouse gas emissions.[1] The oil and natural gas industry takes steps to prevent natural gas leaks.

Natural gas exploration, drilling, and production affects the environment

When geologists explore for natural gas deposits on land, they may disturb vegetation and soil with their vehicles. Drilling a natural gas well on land may require clearing and leveling an area around the well site. Well drilling activities produce air pollution and may disturb people, wildlife, and water resources. Laying pipelines that transport natural gas from wells usually requires clearing land to bury the pipe. Natural gas production can also produce large volumes of contaminated water. This water requires proper handling, storage, and treatment so that it does not pollute land and other waters. Natural gas wells and pipelines often have engines to run equipment and compressors, which produce air pollutants and noise.

In areas where natural gas is produced at oil wells but is not economical to transport for sale or contains high concentrations of hydrogen sulfide (a toxic gas), it is burned (flared) at well sites. Natural gas flaring produces CO_2, carbon monoxide, sulfur dioxide, nitrogen oxides, and many other compounds, depending on the chemical composition of the natural gas and on how well the natural gas burns in the flare. However, flaring is safer than releasing natural gas into the air and results in lower overall greenhouse gas emissions because CO_2 is not as strong a greenhouse gas as methane.

U.S. Energy Information Administration

BIOFUELS EXPLAINED

BIOFUELS AND THE ENVIRONMENT

BASICS

Biofuels may have fewer effects on the environment than fossil fuels

Production and use of biofuels is considered by the U.S. government to have fewer or lower negative effects on the environment compared to fossil-fuel derived fuels. There are also potential national economic and security benefits when biofuel use reduces the need to import petroleum fuels. Government programs that promote and/or require biofuels use, such as the U.S. Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS), define the types of biofuels and processes or low-carbon pathways by which biofuels can be produced in order for them to qualify for use under the programs. While biofuels have environmental benefits, their production and use do have effects on the environment.

Pure ethanol and biodiesel are nontoxic and biodegradable, and if spilled, they break down into harmless substances. However, fuel ethanol contains denaturants to make fuel ethanol undrinkable. Similar to petroleum fuels, biofuels are flammable (especially ethanol) and must be transported carefully.

When burned, pure biofuels generally produce fewer emissions of particulates, sulfur dioxide, and air toxics than their fossil-fuel derived counterparts. Biofuel-petroleum blends also generally result in lower emissions relative to fuels that do not contain biofuels. Biodiesel combustion may result in slightly higher amounts of nitrogen oxides relative to petroleum diesel.

Ethanol and ethanol-gasoline mixtures burn cleaner and have higher octane levels than gasoline that does not contain ethanol, but they also have higher evaporative emissions from fuel tanks and dispensing equipment. These evaporative emissions contribute to the formation of harmful, ground-level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before blending with ethanol.

Burning biofuels results in emissions of carbon dioxide (CO_2), a greenhouse gas. However, according to international convention, CO_2 emissions from biofuel combustion are excluded from national greenhouse gas emissions inventories because growing the biomass feedstocks used for biofuel production may offset the CO_2 produced when biofuels are burned.

The effect that biofuel use has on net CO_2 emissions depends on how the biofuels are produced and whether or not emissions associated with cropland cultivation are included in the calculations. Growing plants for fuel is a controversial topic because some people believe the land, fertilizers, and energy used to grow biofuel crops should be used to grow food crops instead. In some parts of the world, large areas of natural vegetation and forests have been cleared or burned to grow soybeans and palm oil trees to make biodiesel. The processes for producing ethanol, renewable diesel, renewable heating oil, and renewable aviation fuel require a heat source, and most producers of these biofuels currently use fossil fuels. Some U.S. ethanol producers burn corn stalks for heat and ethanol producers in Brazil use sugar cane stalks (called bagasse) to produce heat and electricity.

The U.S. government is supporting efforts to produce biofuels with methods that use less energy than conventional fermentation and that use *cellulosic* biomass, which requires less cultivation, fertilizer, and pesticides than corn or sugar cane. *Cellulosic ethanol* feedstock includes native prairie grasses, fast-growing trees, sawdust, and even waste paper. However, there is currently no commercial cellulosic ethanol production in the United States because of technical and economic challenges.

Lipid feedstocks—waste/used cooking oil and animal fats/tallow and grease—have relatively low carbon intensities as feedstocks for biofuels production and they have been used to meet the targets for advanced biofuels under the federal RFS program. The total process (or life-cycle) emissions for lipid feedstocks are low because lipids were previously used for another purpose and the emissions related to transportation of these biofuels feedstocks only account for emissions that occur after the waste oil/grease is collected. Because of their potentially lower carbon intensities, some state governments provide more support for biofuels production from lipid feedstocks than for raw, unused vegetable oil feedstocks. In California, lipids account for the majority of the feedstocks for U.S. non-fuel ethanol biofuels production and also for the majority of credits generated under California's LCFS. The federal RFS currently does not differentiate between lipid and vegetable oil feedstocks as it does with cellulosic and other renewable fuels. At scale, hydrogenated lipid-based biofuels production requires a significant amount of hydrogen, which if produced from fossil fuels, may increase process emissions and thus increase their carbon intensity.

Last updated: April 13, 2022

U.S. Energy Information Administration

BIOMASS EXPLAINED

BIOMASS AND THE ENVIRONMENT

BASICS

Using biomass for energy has positive and negative effects

Biomass and biofuels made from biomass are alternative energy sources to fossil fuels—coal, petroleum, and natural gas. Burning either fossil fuels or biomass releases carbon dioxide (CO_2), a greenhouse gas. However, the plants that are the source of biomass for energy capture almost the same amount of CO_2 through photosynthesis while growing as is released when biomass is burned, which can make biomass a carbon-neutral energy source.[1]

Burning wood

Using wood, wood pellets, and charcoal for heating and cooking can replace fossil fuels and may result in lower CO_2 emissions overall. Wood can be harvested from forests, from woodlots that have to be thinned, or from urban trees that fall down or have to be cut down.

Wood smoke contains harmful pollutants such as carbon monoxide and particulate matter. Modern wood-burning stoves, pellet stoves, and fireplace inserts can reduce the amount of particulates from burning wood. Wood and charcoal are major cooking and heating fuels in poor countries, but if people harvest the wood faster than trees can grow, it causes deforestation. Planting fastgrowing trees for fuel and using fuel-efficient cooking stoves can help slow deforestation and improve the environment.

Burning municipal solid waste (MSW) or wood waste

Burning municipal solid waste (MSW), or *garbage*, in waste-to-energy plants could result in less waste buried in landfills. On the other hand, burning garbage produces air pollution and releases the chemicals and substances in the waste into the air. Some of these chemicals, which are mostly related to the combustion of non-biomass materials in garbage, can be hazardous to people and the environment if they are not properly controlled.

The U.S. Environmental Protection Agency (EPA) applies strict environmental rules to waste-to-energy plants, which require waste-to-energy plants to use air pollution control devices such as scrubbers, fabric filters, and electrostatic precipitators to capture air pollutants.

Scrubbers clean emissions from waste-to-energy facilities by spraying a liquid into the combustion gases to neutralize the acids present in the stream of emissions. Fabric filters and electrostatic precipitators also remove particles from the combustion gases.

The particles—called fly ash—are then mixed with the ash that is removed from the bottom of the waste-to-energy furnace.

A waste-to-energy furnace burns at high temperatures (1,800°F to 2,000°F), which break down the chemicals in MSW into simpler, less harmful compounds.

Disposing ash from waste-to-energy plants

Ash from waste-to-energy plants can contain high concentrations of various metals that were present in the original waste. Textile dyes, printing inks, and ceramics, for example, may contain lead and cadmium.

Separating waste before burning can solve part of the problem. Because batteries are the largest source of lead and cadmium in municipal waste, they should not be included in regular trash. Florescent light bulbs should also not be put in regular trash because they contain small amounts of mercury.

The EPA tests ash from waste-to-energy plants to make sure that it is not hazardous. The test looks for chemicals and metals that could contaminate ground water. Some MSW landfills use ash that is considered safe as a cover layer for their landfills, and some MSW ash is used to make concrete blocks and bricks.

Collecting landfill gas or biogas

Biogas forms as a result of biological processes in sewage treatment plants, waste landfills, and livestock manure management systems. Biogas is composed mainly of methane (a greenhouse gas) and CO_2. Many facilities that produce biogas capture it and burn the methane for heat or to generate electricity. This electricity is considered renewable and, in many states, contributes to meeting state renewable portfolio standards (RPS). This electricity may replace electricity generation from fossil fuels and can result in a net reduction in CO_2 emissions. Burning methane produces CO_2, but because methane is a stronger greenhouse gas than CO_2, the overall greenhouse effect is lower.

Biofuels

Biofuels are generally cleaner burning than petroleum fuels made from crude oil, but production and use of biofuels do have effects on the environment. Biofuels may be considered carbon-neutral because the plants that are used to make biofuels (such as corn and sugarcane for ethanol and soy beans and oil palm trees for biodiesel) absorb CO_2 as they grow and may offset the CO_2 emissions when biofuels are produced and burned.

U.S. Energy Information Administration

ELECTRICITY EXPLAINED

ELECTRICITY AND THE ENVIRONMENT

BASICS

Although electricity is a clean and relatively safe form of energy when it is used, the generation and transmission of electricity affects the environment. Nearly all types of electric power plants have an effect on the environment, but some power plants have larger effects than others.

The United States has laws that govern the effects that electricity generation and transmission have on the environment. The Clean Air Act regulates air pollutant emissions from most power plants. The U.S. Environmental Protection Agency (EPA) administers the Clean Air Act and sets emissions standards for power plants through various programs such as the Acid Rain Program. The Clean Air Act has helped to substantially reduce emissions of some major air pollutants in the United States.

The effect of power plants on the landscape

All power plants have a physical footprint (the location of the power plant). Some power plants are located inside, on, or next to an existing building, so the footprint is fairly small. Most large power plants require land clearing to build the power plant. Some power plants may also require access roads, railroads, and pipelines for fuel delivery, electricity transmission lines, and cooling water supplies. Power plants that burn solid fuels may have areas to store the combustion ash.

Many power plants are large structures that alter the visual landscape. In general, the larger the structure, the more likely it is that the power plant will affect the visual landscape.

Fossil fuel, biomass, and waste burning power plants

In the United States, about 60% of total electricity generation in 2020 was produced from fossil fuels (coal, natural gas, and petroleum), materials that come from plants (biomass), and municipal and industrial wastes. The substances that occur in combustion gases when these fuels are burned include:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)

- Sulfur dioxide (SO_2)
- Nitrogen oxides (NOx)
- Particulate matter (PM)
- Heavy metals such as mercury

Nearly all combustion byproducts have negative effects on the environment and human health:

- CO_2 is a greenhouse gas, which contributes to the greenhouse effect.
- SO_2 causes acid rain, which is harmful to plants and to animals that live in water. SO_2 also worsens respiratory illnesses and heart diseases, particularly in children and the elderly.
- NOx contribute to ground-level ozone, which irritates and damages the lungs.
- PM results in hazy conditions in cites and scenic areas and coupled with ozone, contributes to asthma and chronic bronchitis, especially in children and the elderly. Very small, or *fine PM*, is also believed to cause emphysema and lung cancer.
- Heavy metals such as mercury are hazardous to human and animal health.

Power plants reduce air pollution emissions in various ways

Air pollution emission standards limit the amounts of some of the substances that power plants can release into the air. Some of the ways that power plants meet these standards include:

- Burning low-sulfur-content coal to reduce SO_2 emissions. Some coal-fired power plants *cofire* wood chips with coal to reduce SO_2 emissions. Pretreating and processing coal can also reduce the level of undesirable compounds in combustion gases.
- Different kinds of particulate emission control devices treat combustion gases before they exit the power plant:
  - *Bag-houses* are large filters that trap particulates.
  - Electrostatic precipitators use electrically charged plates that attract and pull particulates out of the combustion gas.
  - Wet scrubbers use a liquid solution to remove PM from combustion gas.
- Wet and dry scrubbers mix lime in the fuel (coal) or spray a lime solution into combustion gases to reduce SO_2 emissions. Fluidized bed combustion also results in lower SO_2 emissions.
- NOx emissions controls include low NOx burners during the combustion phase or selective catalytic and non-catalytic converters during the post combustion phase.

Many U.S. power plants produce CO_2 emissions

The electric power sector is a large source of U.S. CO_2 emissions. Electric power sector power plants that burned fossil fuels or materials made from fossil fuels, and some geothermal power plants, were the source of about 28% of total U.S. energy-related CO_2 emissions in 2020.

Some power plants also produce liquid and solid wastes

Ash is the solid residue that results from burning solid fuels such as coal, biomass, and municipal solid waste. *Bottom ash* includes the largest particles that collect at the bottom of the combustion chamber of power plant boilers. *Fly ash* is the smaller and lighter particulates that collect in air emission control devices. Fly ash is usually mixed with bottom ash. The ash contains all the hazardous materials that pollution control devices capture. Many coal-fired power plants store ash sludge (ash mixed with water) in retention ponds. Several of these ponds have burst and caused extensive damage and pollution downstream. Some coal-fired power plants send ash to landfills or sell ash for use in making concrete blocks or asphalt.

Nuclear power plants produce different kinds of waste

Nuclear power plants do not produce greenhouse gases or PM, SO_2, or NOx, but they do produce two general types of radioactive waste:

- Low-level waste, such as contaminated protective shoe covers, clothing, wiping rags, mops, filters, reactor water treatment residues, equipment, and tools, is stored at nuclear power plants until the radioactivity in the waste decays to a level safe for disposal as ordinary trash, or it is sent to a low-level radioactive waste disposal site.
- High-level waste, which includes the highly radioactive spent (used) nuclear fuel assemblies, must be stored in specially designed storage containers and facilities (see Interim storage and final disposal in the United States).

U.S. Energy Information Administration

GEOTHERMAL EXPLAINED

GEOTHERMAL ENERGY AND THE ENVIRONMENT

BASICS

The environmental effects of geothermal energy depend on how geothermal energy is used or how it is converted to useful energy. Direct use applications and geothermal heat pumps have almost no negative effects on the environment. In fact, they can have a positive effect by reducing the use of energy sources that may have negative effects on the environment.

Geothermal power plants have low emission levels

Geothermal power plants do not burn fuel to generate electricity, but they may release small amounts of sulfur dioxide and carbon dioxide. Geothermal power plants emit 97% less acid rain-causing sulfur compounds and about 99% less carbon dioxide than fossil fuel power plants of similar size. Geothermal power plants use scrubbers to remove the hydrogen sulfide naturally found in geothermal reservoirs. Most geothermal power plants inject the geothermal steam and water that they use back into the earth. This recycling helps to renew the geothermal resource and to reduce emissions from the geothermal power plants.

U.S. Energy Information Administration

HYDROPOWER EXPLAINED

HYDROPOWER AND THE ENVIRONMENT

BASICS

Hydropower generators produce clean electricity, but hydropower does affect the environment

Most dams in the United States were built mainly for flood control, municipal water supply, and irrigation water. Although many of these dams have hydroelectric generators, only a small number of dams were built specifically for hydropower generation.

Hydropower generators do not directly emit air pollutants. However, dams, reservoirs, and the operation of hydroelectric generators can affect the environment.

A dam that creates a reservoir (or a dam that diverts water to a run-of-river hydropower plant) may obstruct fish migration. A dam and reservoir can also change natural water temperatures, water chemistry, river flow characteristics, and silt loads. All of these changes can affect the ecology and the physical characteristics of the river. These changes may have negative effects on native plants and on animals in and around the river. Reservoirs may cover important natural areas, agricultural land, or archeological sites. A reservoir and the operation of the dam may also result in the relocation of people. The physical impacts of a dam and reservoir, the operation of the dam, and the use of the water can change the environment over a much larger area than the area a reservoir covers.

Manufacturing the concrete and steel in hydropower dams requires equipment that may produce emissions. If fossil fuels are the energy sources for making these materials, then the emissions from the equipment could be associated with the electricity that hydropower facilities generate. However, given the long operating lifetime of a hydropower plant (50 years to 100 years) these emissions are offset by the emissions-free hydroelectricity.

Greenhouse gases (GHG) such as carbon dioxide and methane form in natural aquatic systems and in human-made water storage reservoirs as a result of the aerobic and anaerobic decomposition of biomass in the water. The exact amounts of GHG that form in and are emitted from hydropower reservoirs is uncertain and depend on many site specific and regional factors.

U.S. Energy Information Administration

SOLAR EXPLAINED

SOLAR ENERGY AND THE ENVIRONMENT

Solar energy technologies and power plants do not produce air pollution or greenhouse gases when operating. Using solar energy can have a positive, indirect effect on the environment when solar energy replaces or reduces the use of other energy sources that have larger effects on the environment. However, there are environmental issues related to the production and use of solar energy technologies.

Solar energy technologies require use of materials, such as metals and glass, that are energy intensive to make. The environmental issues related to the production of these materials could be associated with solar energy systems when conducting life-cycle or so called *cradle-to-grave* environmental analysis. Studies conducted by a number of organizations and researchers have concluded that PV systems can produce the equivalent amount of energy that was used to manufacture the systems within 1 to 4 years. Most PV systems have operating lives of up to 30 years or more.

There are hazardous chemicals used to make photovoltaic (PV) cells and panels that must be carefully handled to avoid release to the environment. Some types of PV cell technologies use heavy metals, and these types of cells and PV panels may require special handling when they reach the end of their useful life. Some solar thermal systems use potentially hazardous fluids to transfer heat, and leaks of these materials could be harmful to the environment. U.S. environmental laws regulate the use and disposal of hazardous materials. The U.S. Department of Energy is supporting various efforts to address *end-of-life* issues related to solar energy technologies, including the recovery and recycling of the materials used to manufacture PV cells and panels. Several states have enacted laws that encourage recycling of PV panels.

As with any type of power plant, large solar power plants can affect the environment at or near their locations. Clearing land for construction and the placement of the power plant may have long-term effects on the habitats of native plants and animals. However, installing solar energy systems on land with marginal agricultural value or integrating solar energy systems on farms may provide a variety of economic and environmental benefits to farmers.

Some solar power plants may require water for cleaning solar collectors and concentrators or for cooling turbine generators. Using large volumes of ground water or surface water for cleaning collectors in some arid locations may affect the ecosystems that depend on these water resources. In addition, the beam of concentrated sunlight a *solar power tower* creates can kill birds and insects that fly into the beam.

U.S. Energy Information Administration

WIND EXPLAINED

WIND ENERGY AND THE ENVIRONMENT

BASICS

Wind is an emissions-free source of energy

Wind is a renewable energy source. Overall, using wind to produce energy has fewer effects on the environment than many other energy sources. Wind turbines do not release emissions that can pollute the air or water (with rare exceptions), and they do not require water for cooling. Wind turbines may also reduce the amount of electricity generation from fossil fuels, which results in lower total air pollution and carbon dioxide emissions.

An individual wind turbine has a relatively small physical footprint. Groups of wind turbines, sometimes called wind farms, are located on open land, on mountain ridges, or offshore in lakes or the ocean.

Wind turbines have some negative effects on the environment

Modern wind turbines can be very large machines, and they may visually affect the landscape. A small number of wind turbines have also caught fire, and some have leaked lubricating fluids, but these occurrences are rare. Some people do not like the sound that wind turbine blades make as they turn in the wind. Some types of wind turbines and wind projects cause bird and bat deaths. These deaths may contribute to declines in the population of species also affected by other human-related impacts. The wind energy industry and the U.S. government are researching ways to reduce the effect of wind turbines on birds and bats.

Most wind power projects on land require service roads that add to the physical effects on the environment. Producing the metals and other materials used to make wind turbine components has impacts on the environment, and fossil fuels may have been used to produce the materials. Although most of the materials used to make wind turbines can be reused or recycled, turbine blades, as most are currently constructed, cannot be recycled. Researchers at the National Renewable Energy Laboratory (NREL) established an approach to manufacturing wind turbine blades, employing a thermoplastic resin system. These thermoplastic resins enable a manufacturing process that allows wind turbine blades to be recycled at their end of life and also reduces the energy required to manufacture blades.

Last updated: December 17, 2021

Key Topic 2: Measuring and Monitoring a Changing Climate

6. Describe the history of international collaboration on climate change and analyze the successes and shortcomings.

7. Describe the various sources of scientific data which are used as evidence of climate change and explain how we know this data to be reliable.

8. Evaluate climate data and draw conclusions based on that data.

9. Explain the use of modelling in forecasting climate and the sources of uncertainty in climate projections.

Study Resources

Resource Title	Source	Located on
A Short History of International Climate Change Negotiations – from Rio to Glasgow	*Mark Maslin, University College London, 2021*	Pages 50-56
Climate Models	*US National Oceanic and Atmospheric Administration (NOAA), 2022*	Pages 57-59
Climate Change Projections	*Government of Canada, Canadian Centre for Climate Services, 2021*	Pages 60-61

Please Note: Hyperlinks found in text are not considered required reading; however, included video links are required to watch.

Study Resources begin on the next page →

A Short History of International Climate Change Negotiations – from Rio to Glasgow

25 January 2021

Despite decades of intense and continuous international negotiations on climate change, progress has been slow. Professor Mark Maslin reflects on the history of negotiations and why there is now hope that states will substantially cut down greenhouse gas emissions.

The last 30 years have been a period of intense and continuous international negotiation to deal with climate change. During the same 30 years, humanity has doubled the amount of anthropogenic carbon dioxide in the atmosphere.

In 1989 Margaret Thatcher, the Prime Minster of the UK, gave an address to the UN outlining the science of climate change, the threat it posed to all nations, and the actions needed to avert the crisis. She summed up by saying: “We should work through this great organisation and its agencies to secure world-wide agreements on ways to cope with the effects of climate change, the thinning of the ozone layer, and the loss of precious species” (Margaret Thatcher Foundation, 2020). This sentiment was echoed in similar speeches by George Bush Senior, President of the United States, including one in 1992 when he outlined his ‘Clear Skies’ and ‘Global Climate Change’ initiatives at the National Oceanic and Atmospheric Administration.

This was because by the end of the 1980s the threat of climate change had finally been recognized. This was due to the global temperature record ‘hockey stick’ upturn at the end of the 1980s (Maslin, 2021). This led to the rediscovery of the underpinning science of climate change that had been essentially carried out and settled by the mid-1960s (Weart, 2008). This was combined with our increased knowledge of how past climate was controlled by changes in atmospheric CO2 and significant improvements in supercomputer modelling of our climate system (Maslin, 2021). There was also the emergence of global environmental awareness in the late 1980s driven by a series of catastrophic local pollution events and the discovery of the ozone hole over Antarctica (Corfee-Morlot et al., 2007). By the beginning of the 1990s climate change had become a global issue - even if it was still a highly disputed one (Oreskes and Conway, 2012).

The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 and produced its very first science report in 1990. Two years later, with support from leaders from all around the world, the UN held the Rio Earth Summit - officially called the United Nations Conference on Environment and Development (UNCED) - to help member states cooperate on sustainability and protecting the world’s environment. The Summit was a huge success and led to the *Rio Declaration on Environment and Development*, the local sustainability initiative called Agenda 21 and Forest Principles (Gupta, 2014). It also set up the *United Nations Convention to Combat Desertification*, the *Convention on Biological Diversity* and the *Framework Convention on Climate Change (UNFCCC)* that underlies the negotiations to limit global greenhouse gas emissions. The Rio Earth Summit also laid the foundations for the Millennium Development Goals and the subsequent Sustainable Development Goals.

The United Nations Framework Convention on Climate Change (UNFCCC) officially came into force on 21 March 1994. As of March 2020, the UNFCCC has 196 parties. Enshrined within the UNFCCC are a number of principles including agreement by consensus of all parties and differential responsibilities (Gupta, 2014). The latter is because the UNFCCC acknowledges that different countries have emitted different amounts of greenhouse gases (GHGs) and therefore need to make greater or lesser efforts to reduce their emissions. For example, per capita emissions of CO2 in the USA are ten times greater than in India. The UNFCCC pays heed to the principle of contraction and convergence - the idea that every country must reduce its emissions and that all countries must converge on net zero emissions. The net zero emissions target emerged from the important IPCC 1.5˚C global warming report published in 2018 which clearly showed that to achieve 1.5˚C there had to be zero carbon emissions by about 2050 and then negative carbon emissions for the rest of the century (IPCC, 2018).

Kyoto 1997

Since the UNFCCC was set up, the nations of the world, ‘the parties’, have been meeting annually at the ‘Conference of the Parties’ (COP) to move negotiations forward. Only five years after the UNFCCC was created, at COP3 in December 1997, the first international agreement was drawn up, the Kyoto Protocol (Gupta, 2014). This stated the general principles for a worldwide treaty on cutting GHG emissions and, more specifically, that all developed nations would aim to cut their emissions by 5.2% relative to their 1990 levels by 2008-12. The Kyoto Protocol was ratified and signed in Bonn on 23 July 2001, making it a legal treaty. The USA, under the leadership of President Bush, withdrew from the climate negotiations in March 2001 and so did not sign the Kyoto Protocol at the Bonn meeting. With the USA producing about one-quarter of the world’s carbon dioxide pollution at this time, this was a big blow for the treaty. Moreover, the targets set by the Kyoto Protocol were reduced during the Bonn meeting to make sure that Japan, Canada, and Australia would join. Australia finally made the Kyoto Protocol legally binding in December 2007.

In order to balance out the historic legacy of emissions by developed countries, the treaty did not include developing countries, but it was assumed that developing countries would join the post-2012 agreement. The Kyoto Protocol came into force in February 2005, after Russia ratified the treaty, thereby meeting the requirement that at least 55 countries representing more than 55 per cent of the global emissions were participating (Gupta, 2014).

Copenhagen 2009

There were huge expectations of COP15 (Copenhagen) in 2009 despite coming a year after the global financial crash. New quantitative commitments were expected to ensure a post-2012 agreement in order to move seamlessly on from the Kyoto Protocol. Barack Obama had just become President of the USA, raising hopes of a more positive approach. The EU had prepared an unconditional 20% reduction of emissions by 2020 on a 1990 baseline and a conditional target rising to 30% if other developed countries adopted binding targets. Most other developed countries had something to offer. Norway was willing to reduce emissions by 40% and Japan by 25% from a 1990 baseline. Even the USA offered a 17% reduction on a 2005 baseline, which was an equivalent drop of 4% on a 1990 baseline. But the Copenhagen conference went horribly wrong. First the Danish government had completely underestimated the interest in the conference and provided a venue that was too small. So in the second week, when all the high-powered country ministers and their support arrived, there was not enough room, meaning that many NGOs were denied access to the negotiations. Second, it was clear that the negotiators were not ready for the arrival of the ministers and that there was no agreement. This led to the leaking of 'The Danish Text', subtitled 'The Copenhagen Agreement', and the proposed measures to keep average global temperature rise to 2°C above pre-industrial levels (Gupta, 2014). It started an argument between developed and developing nations as it was brand new text that had just appeared in the middle of the conference. Developing countries accused the developed countries of working behind closed doors and making an agreement that suited them without seeking consent from the developing nations (Byrne and Maslin, 2015). Lumumba Stanislaus Di-Aping, chairman of the G77, said, 'it's an incredibly imbalanced text intended to subvert, absolutely and completely, two years of negotiations. It does not recognize the proposals and the voice of developing countries' (Guardian, 2009).

The final blow to getting an agreement on binding targets came from the USA. Barack Obama, arriving only two days before the end of the conference, convened a meeting of the USA with the BASIC (Brazil, South Africa, India, and China) countries which excluded other UN nations, and created the Copenhagen Accord (Maslin, 2021). This recognized the scientific case for keeping temperature rises below 2°C, but did not contain a baseline for this target, nor commitments for reduced emissions that would be necessary to achieve it. Earlier proposals that would have aimed to limit temperature rises to 1.5°C and cut CO2 emissions by 80 per cent by 2050 were dropped. The agreement made was non-binding and countries had until January 2010 to provide their own voluntary targets. It was also made clear that any country that signed up to the Copenhagen Accord was also stepping out of the Kyoto Protocol. Hence the USA was able to move away from the binding targets of Kyoto Protocol, which should have been enforced until 2012, and a weak voluntary commitment approach was adopted. The Bolivian delegation summed up the way the Copenhagen Accord was reached - 'anti-democratic, anti-transparent and unacceptable' (Guardian, 2009). It was also not clear what legal status the Copenhagen Accord had as it was only 'noted' by the parties, not agreed, as only 122, subsequently rising to 139 countries, agreed to it (Bryne and Maslin, 2015).

Trust in the UNFCCC negotiations took another blow when in January 2014 it was revealed that the US Government negotiators had information during the conference obtained by eavesdropping on meetings of other conference delegations. Documents leaked by Edward Snowden showed how the US National Security Agency (NSA) had monitored communications between countries before and during the conference. The leaked documents show that the NSA provided US delegates with advance details of the Danish plan to 'rescue' the talks should they founder, and also about China's efforts before the conference to coordinate its position with that of India (Guardian, 2014).

Paris 2015
The failure of COP15 in Copenhagen and its voluntary commitments cast a long shadow over the successive COP meetings, compounded by the revelation by Wikileaks that US aid funding to Bolivia and Ecuador was reduced because of their opposition to the Copenhagen Accord Guardian (2010). It took over five years for the negotiations to recover from the mess created by Barack Obama and the USA negotiators. At COP16 in Cancun and COP17 in Durban the UNFCCC negotiations were slowly put back on track with the aim of getting legally binding targets. Significant progress was made in the REDD+ (Reduced Emissions from Deforestation and Forest Degradation), including safeguards for local people. It was, however, at COP18 in Doha in December 2012 that a second commitment period starting in January 2013 was agreed, to last eight years. This ensured that all Kyoto mechanisms and accounting rules remained intact for this period, and that parties could review their commitments with a view to increasing them. All this laid the foundations for the possibility of a future global climate agreement, which was agreed at COP21 in Paris in 2015.

The climate negotiations in Paris 2015 were a huge success primarily because the French hosts understood the grand game of international negotiation and used every trick in the book to get countries to work together to achieve an agreement signed by all (Lewis, 2015). The agreement states that the parties will hold temperatures to "well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Paris was a high-stakes game of geopolitical poker. Surprisingly, the least powerful countries did much better than expected. The climate talks were subject to a series of shifting alliances going beyond the usual income-rich northern countries and income-poor global south countries. Central to this was, firstly, the US-Chinese diplomacy as both agreed to limit emissions. Secondly, a new grouping of countries called the Climate Vulnerable Forum forced the 1.5°C target higher up the political agenda, so much so that it is mentioned in the key aims of the agreement (Lewis, 2015). Political support from the Paris Agreement allowed the IPCC to write the seminal 1.5˚C global warming report which was published in 2018. This report documented the significant increase in the impact between a 1.5˚C and 2.0˚C world (IPCC, 2018). It also documented how a 1.5˚C world could be achieved - which in essence shows that the world must have net zero carbon emissions by 2050 and then carbon must be taken out of the atmosphere for the rest of the century. The quicker the world gets to net zero the less carbon needs to be extracted from the atmosphere between 2050 and 2100 (Goodall, 2020). The Paris Agreement was just the start of the process because taking into account all the country pledges and assuming that they will be fulfilled then the world would still warm by about 3˚C (Maslin, 2019).

The role of global environmental social movements
There have been three main waves of environmental social movements. The first was in the late 1980s and early 1990s and provided global support for the Rio Summit. The second wave was in 2008 and 2009, focusing on the hope of a major climate deal at the Copenhagen climate conferences. In the UK it was very successful and lead to the Climate Change Act in 2008 (Bryne, 2019). As we know, Copenhagen ended in abject failure due to the lack of international leadership, sabotage by the US, lobbying by powerful climate change deniers and the global

worries about dealing with the 2008 global financial crash (Maslin, 2021). For almost 10 years the global environmental movement was held back due to the focus on the global economy. This all changed in 2018.

The third wave of the global environmental social movement started in 2018 (Figueres and Rivett-Carnac, 2020). In May 2018 Extinction Rebellion was set up in the UK and launched in October 2018 with over 100 academics calling for action on climate change. The aim of Extinction Rebellion is to use non-violent civil disobedience to compel governments around the world to avoid tipping points in the climate system and biodiversity loss to avoid both social and ecological collapse (Lewis and Maslin, 2018). In November 2018 and April 2019 they brought central London to a standstill, and Extinction Rebellion has now spread to at least 60 other cities around the world.

In August 2018, Greta Thunberg - at the age of 15 - started to spend her school days outside the Swedish Parliament holding a sign saying Skolstrejk för klimatet (School strike for climate) calling for stronger action on climate change. Soon other students all around the world started similar school strikes once a month on a Friday and they called the movement ‘Fridays for Future’ (Thunberg, 2019). It has been estimated that by the end of 2019 there were over 4500 strikes across over 150 countries, involving 4 million school children and this has rising further in 2020 (Fridays for Future, 2020).

In 2018 and 2019 three extremely influential IPCC reports were published. First, in 2018, was the Special Report on Global Warming of 1.5°C which documented what the world needed to do if global temperature rise was to be kept at only 1.5˚C (IPCC, 2018). It also showed the positive and negative interactions of climate change mitigation and the Sustainable Development Goals. The second was the special report on the land and how climate change would impact desertification, land management, food security, and the terrestrial ecosystems (IPCC, 2019a). The third was the IPCC Special Report on the Ocean and Cryosphere showing the impacts of climate change on the speed of melting of ice sheets, mountain glaciers and sea ice, and their implications of sea level rise and marine ecosystems (IPCC, 2019b).

This new social movement and the very latest science inspired many corporations to take a leading role (Hawken, 2018). Microsoft has set the agenda for the technology sector with the ambitious target to become carbon negative by 2030. By 2050 they want to remove all the carbon pollution from the atmosphere that they and their supply chain have emitted since the founding of the company in 1975. Sky has set the agenda for the media sector; as they are already carbon neutral they have pledged that they and their supply chain will go carbon negative by 2030. BP has also declared that it will be carbon neutral by 2050 by eliminating or offsetting over 415 million tons of carbon emissions. These companies form part of a group of over 850 global companies that have pledged to adopt Science Based Targets, meaning, in effect, that they will all have achieved net zero carbon emissions by 2050 (CDP, 2020).

Given all this pressure in 2019, governments all around the world started to declare that we are, in fact, in a climate emergency and action has to be taken. At the time of the publication of this article, over 1,400 local governments and over 35 countries have made climate emergency declarations. Despite the fact that in 2020 the whole world was focused on dealing with the Covid-19 pandemic, climate change remained a major issue (Jones and Maslin, 2020).

Glasgow 2021

This new wave of public global environmental concern meant there were great expectations for COP26 in Glasgow at the end of 2020, co-hosted by the UK and Italy. But due to the Covid-19 pandemic, the resultant lockdowns, and the major impact on both Italy and Britain, this pivotal meeting was postponed until November 2021. This meeting is critical because it is the third meeting of the parties to the 2015 Paris Agreement (CMA3) and is the first global stock-take outlined in the Paris Agreement. COP26 will review the progress made since 2015 and encourage greater commitments and pledges from countries to cut their greenhouse gas emissions. Importantly this will be the first COP meeting where 'net zero' carbon emissions targets will be the primary global ambition, and the discussion will be about how fast this can be achieved and which countries will lead (Hawken, 2018; Figueres and Rivett-Carnac, 2020; Mann, 2021).

Despite 2020 and 2021 being dominated by the Covid-19 pandemic, the geopolitical landscape around climate change has seismically shifted. First, in June 2019, the UK parliament amended the Climate Change Act (2008) to require the government to reduce the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050. Second, the European Commission is proposing that the EU reduces its GHG emissions by at least 55% by 2030 from 1990 levels, instead of the 40% cut agreed six years ago. This target would be written into EU law and made binding on all 27-member states. This is a major step towards the EU pledge of matching the UK ambition of reaching carbon neutrality by 2050. Third, in September 2020 China's President Xi Jinping announced via video-link to the UN General Assembly in New York that the country would aim to reach peak emissions before 2030, followed by a long-term target to become carbon neutral by 2060. China is the world's largest carbon emitter accountable for around 28% of global GHG emissions and up to now has not committed to a long-term emissions goal. Under the Paris Agreement, China had pledged to cut the carbon intensity of its economy by 60-65% against a 2005 baseline. This announcement came after long and detailed discussions between China and the EU concerning climate change.

COP26 marks the re-engagement with the USA, second largest emitter of around 15% of global GHG emissions. In 2017 the Paris Agreement had a major setback. President Trump declared he was taking the USA out of the Agreement, as he believed it was unfair and biased towards developing countries. In accordance with Article 28 of the Paris Agreement, a country cannot give notice of withdrawal from the Agreement before three years of its start date in the relevant country. So, the earliest possible effective withdrawal date by the United States was November 4, 2020—one day after the 2020 U.S. presidential election. President Biden has already re-joined the Paris Agreement and is a clear advocate of collective international action to deal with climate change. He has appointed John Kerry as United States Special Presidential Envoy for Climate, which has been made a cabinet position.

The new President faces additional challenges because over the four years of the Trump presidency nearly 100 environmental rules and regulations have been rescinded or are in the process of being removed. These included rolling back the Obama administration's fuel efficiency and emissions standards for vehicles, reductions in their coal emissions standards for coal-fired power plants, and weakening the efficient lighting regulation, meaning less efficient light bulbs can still be purchased after 2020. President Biden is already undoing many of these changes through executive orders.

For example President Trump also gave the executive orders to approve two controversial oil pipelines, Keystone XL and Dakota Access. In 2018, plans were announced to allow drilling in nearly all US waters, creating a huge expansion of offshore oil and gas leases. In 2019, the Trump administration completed plans for opening the entire coastal plain of the Arctic National Wildlife Refuge to drilling. All of these are in the process of being rescinded.

For the first time in over a decade there is now hope that the nations of the world can cut greenhouse gas emissions significantly and start the journey to a cleaner, greener, safer, healthier and more sustainable world.

Conclusion

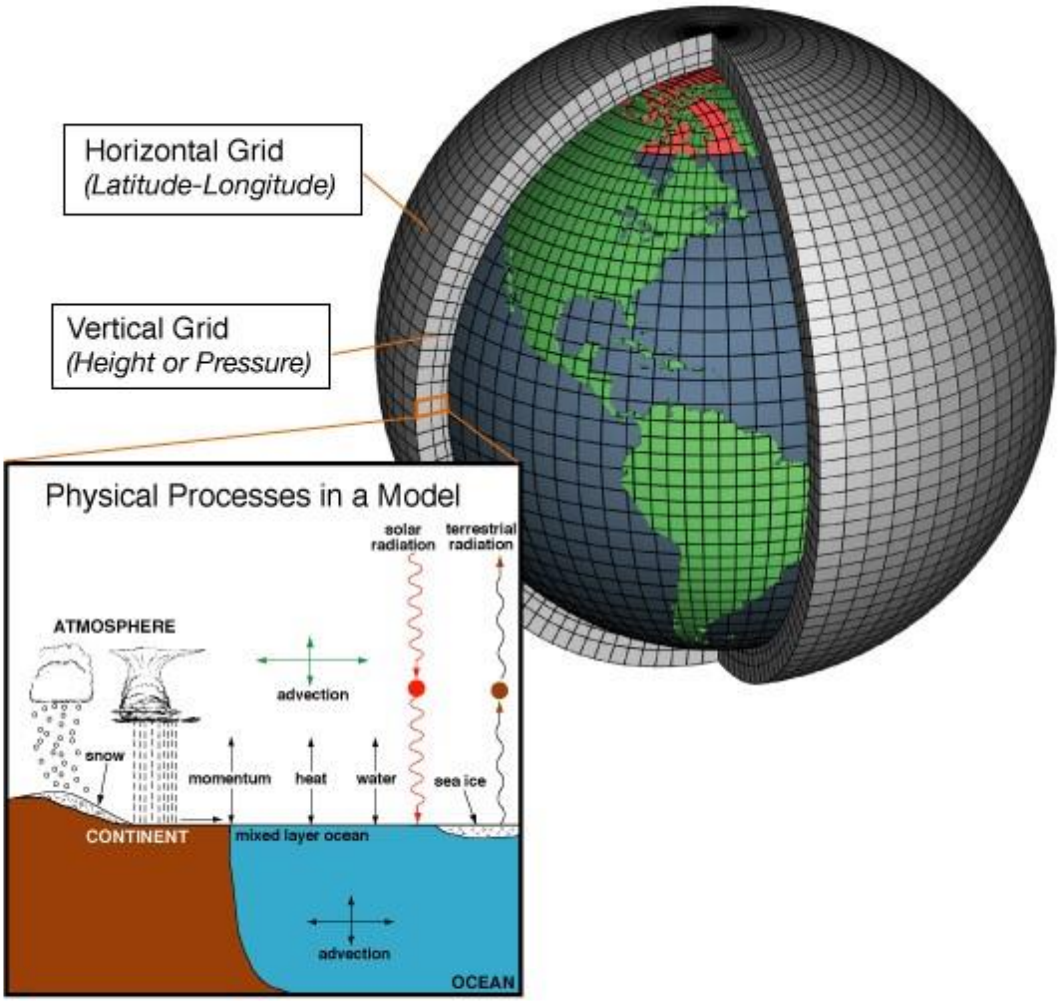
In the last 30 years the amount of human-emitted carbon dioxide has doubled. This represents a collective failure of the world’s leaders to focus on this issue. As a consequence, the ambition of the climate change negotiations has increased. The Kyoto Protocol aimed for developed countries to cut emissions by 5.2% relative to their 1990 levels, while the Glasgow COP26 will aim to get all countries to agree to be net carbon zero as early as possible in this century. No one is underestimating how difficult but important it is to get a deal in Glasgow.

Climate Models

How We Use Models

Models help us to work through complicated problems and understand complex systems. They also allow us to test theories and solutions. From models as simple as toy cars and kitchens to complex representations such as flight simulators and virtual globes, we use models throughout our lives to explore and understand how things work.

Climate Models, and How They Work



This image shows the concept used in climate models. Each of the thousands of 3-dimensional grid cells can be represented by mathematical equations that describe the materials in it and the way energy moves through it. The advanced equations are based on the fundamental laws of physics, fluid motion, and chemistry. To "run" a model, scientists specify the climate forcing (for instance, setting variables to represent the amount of greenhouse gases in the atmosphere) and have powerful computers solve the equations in each cell. Results from each grid cell are passed to neighboring cells, and the equations are solved again. Repeating the process through many time steps represents the passage of time. Image *source: NOAA (http://celebrating200years.noaa.gov/breakthroughs/climate_model/modeling_schematic.html).*

Climate models are based on well-documented physical processes to simulate the transfer of energy and materials through the climate system. Climate models, also known as general circulation models or GCMs, use mathematical equations to characterize how energy and matter interact in different parts of the ocean, atmosphere, land. Building and running a climate model is complex process of identifying and quantifying Earth system processes, representing them with mathematical equations, setting variables to represent initial conditions and subsequent changes in climate forcing, and repeatedly solving the equations using powerful supercomputers. Check out The Very, Very Simple Climate Model » (https://scied.ucar.edu/simple-climate-model)

Climate Model Resolution

Climate models separate Earth's surface into a three-dimensional grid of cells. The results of processes modeled in each cell are passed to neighboring cells to model the exchange of matter and energy over time. Grid cell size defines the resolution of the model: the smaller the size of the grid cells, the higher the level of detail in the model. More detailed models have more grid cells, so they need more computing power.

Climate models also include the element of time, called a time step. Time steps can be in minutes, hours, days, or years. Like grid cell size, the smaller the time step, the more detailed the results will be. However, this higher temporal resolution requires additional computing power.

How are Climate Models Tested?

Once a climate model is set up, it can be tested via a process known as “hind-casting.” This process runs the model from the present time backwards into the past. The model results are then compared with observed climate and weather conditions to see how well they match. This testing allows scientists to check the accuracy of the models and, if needed, revise its equations. Science teams around the world test and compare their model outputs to observations and results from other models.

Using Scenarios to Predict Future Climate

Once a climate model can perform well in hind-casting tests, its results for simulating future climate are also assumed to be valid. To project climate into the future, the climate forcing is set to change according to a possible future scenario. Scenarios are possible stories about how quickly human population will grow, how land will be used, how economies will evolve, and the atmospheric conditions (and therefore, climate forcing) that would result for each storyline.

In 2000, the Intergovernmental Panel on Climate Change (IPCC) issued its Special Report on Emissions Scenarios (SRES) (http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0), describing four scenario families to describe a range of possible future conditions. Referred to by letter-number combinations such as A1, A2, B1, and B2, each scenario was based on a complex relationship between the socioeconomic forces driving greenhouse gas and aerosol emissions and the levels to which those emissions would climb during the 21st century. The SRES scenarios have been in use for more than a decade, so many climate model results describe their inputs using the letter-number combinations.

In 2013, climate scientists agreed upon a new set of scenarios that focused on the level of greenhouse gases in the atmosphere in 2100. Collectively, these scenarios are known as Representative Concentration Pathways or RCPs. Each RCP indicates the amount of climate forcing, expressed in Watts per square meter, that would result from greenhouse gases in the atmosphere in 2100. The rate and trajectory of the forcing is the pathway. Like their predecessors, these values are used in setting up climate models.

Learn more about RCPs » (http://www.skepticalscience.com/rcp.php?t=1)

Results of Current Climate Models

Around the world, different teams of scientists have built and run models to project future climate conditions under various scenarios for the next century. So the groups can make a fair comparison of their results, they run the same experiment. Because each climate model is slightly different, the results show a range of projections. Though yearly values projected for temperature and precipitation differ among the models, the trend and magnitude of change is fairly consistent.

Global climate model results from groups around the world project that global temperature will continue to increase. They also show that human decisions and behavior we choose today will determine how dramatically climate will change in the future.

How are Climate Models Different from Weather Prediction Models?

Unlike weather forecasts, which describe a detailed picture of the expected daily sequence of conditions starting from the present, climate models are probabilistic, indicating areas with higher chances to be warmer or cooler and wetter or drier than usual. Climate models are based on global patterns in the ocean and atmosphere, and records of the types of weather that occurred under similar patterns in the past.

Climate Change Projections

How computer models help us understand climate

The most powerful computers on Earth are used to run climate models. Scientists use these models to understand how Earth's climate works and to make predictions about how it might change in the future.

Climate models have successfully helped reconstruct climates of the distant and recent past, answering important questions, such as "what caused the last ice age?". The proven ability of climate models to describe Earth's past and present climates gives us confidence that they can simulate the planet's future climate, too.

There are many research centres and thousands of climate scientists creating and fine-tuning computerized climate models worldwide. For example, the Met Office Hadley Centre for Climate Science and Services in England is one of the world's leading climate research institutions. It has over 200 staff dedicated to climate research and uses clusters of supercomputers to create some of the most effective climate models in the world. Here in Canada, the federal Canadian Centre for Climate Modelling and Analysis (CCCma) has been creating excellent climate models since the early 1980s.

Climate scientists at institutions like the Hadley Centre and the CCCma combine scientific research and advanced computing to predict what the climate will look like in the decades to come.

General Circulation Models

The first computer models describing global warming were created in the 1960s. They calculated changes in the temperature of the planet by modelling the balance between the energy coming in from the sun and the energy escaping Earth's atmosphere back into space. The scientific community has been improving on these first models for over 50 years now.

Modern climate models are called "General Circulation Models" or "Earth Systems Models." They address much more than the sun-Earth energy balance. Working from the foundations of physics and chemistry, they take thousands of factors into account to model the entire climate system, including solar radiation, greenhouse gas emissions, volcanic eruptions, cloud formation, ocean currents, chemical reactions in the atmosphere, land use changes, and much more.[1]

New climate models are constantly improving our understanding of the climate system and our improving understanding of the climate system is improving the models. The overall conclusions of the models have not changed—human greenhouse gas emissions are driving global warming.[2]

How do we know climate models work?

Models allow scientists to test their understanding of how the climate works and how it might change in the future. But do the models do a good job of simulating the real world?

Climate models are extensively tested by “hindcasting”, which means modelling the climate of the past.

Climate models are considered successful only if they can recreate to a high degree the averages, extremes, and seasonal patterns that match up with observed climate.

There is one major difference between predicting climate and predicting weather. A weather forecast attempts to create very precise hour-by-hour predictions on a very small scale. Climate models, on the other hand, effectively combine many simulations of possible weather to produce the accumulated story of what average and extreme conditions might happen. In other words, the goal of a climate model is to project changes in climates over years, decades and longer, whereas weather predictions are interested in what is expected to happen in the coming days.

Climate models do create simulations of day-to-day weather over many years, but in no way are they meant to be used to state what the weather is expected to be in the future, on any particular day or sequence of days. Instead, these daily simulations are interpreted statistically, resulting in statements about the probability of particular weather conditions being observed in the future. They do not produce weather forecasts; they produce climate projections. And importantly, scientists keep track of how well models perform as the years pass. Since 1990, for example, the observed rate of global warming is well within the original range projected by climate models.

Why do we use so many climate models?

Canada is one of dozens of countries that has independently produced its own climate models. International organizations help coordinate all of these modelling experiments and gather them into an “ensemble”, or collection of many different models.

Why do this? Although each model is carefully designed to be consistent and plausible, working with an ensemble of many models lets us look at a range of future projections instead of just one. Working with ensembles lets us do a better job of taking natural climate variability into account, helps eliminate the effects of modelling uncertainty, and means that our conclusions are not biased by the weaknesses or strengths of any one model on its own.

Comparing the results of many different models makes one thing very clear: all climate models clearly indicate that temperatures will continue to rise as greenhouse gas emissions accumulate in the atmosphere.

Key Topic 3: Risks and Impacts to Natural Resources and Society from a Changing Climate

10. Explain the consequences of climate changes on aquatic, forest, wildlife and soil ecosystems.

11. Describe the social and economic impacts of climate change.

Study Resources

Resource Title	Source	Located on
Climate Impacts on Ecosystems	*US Environmental Protection Agency, 2017*	Pages 63-66
Impacts to Canadian agriculture from climate changes	*Agriculture and Agri-Food Canada, 2020*	Pages 67-70
Impacts on ecosystems and fisheries	*Fisheries and Oceans Canada, 2019*	Pages 71-74
5 Ways Climate Change Impacts Forests	*North Carolina State University, Forestry and Environmental Resources Research, 2021*	Pages 75-78
How Climate Change Impacts the Economy	*Renee Cho, Columbia Climate School, 2019*	Pages 79-84
This is how climate change could impact the global economy	*Natalie Marchant, Article in World Economic Forum, 2021*	Pages 85-86
Earth Observation to Mitigate Impacts of Climate Change and Support Sustainable Business Decisions	*L3HARRIS GEOSPATIAL, 2022*	Pages 87-94
Social Dimensions of Climate Change	*The World Bank, 2022*	Pages 95-96
The Disproportionate Impact of Climate Change on Indigenous Communities	*Paige Laduzinsky, KCET, 2019*	Pages 97-101
Southeast Asia to bear the brunt of worsening global climate, IPCC warns	*Robin Hicks, Eco-Business, 2021*	Pages 102-105
Climate change triggers mounting food insecurity, poverty, and displacement in Africa	*World Meteorological Organization (WMO), 2021*	Pages 106-109

Please Note: Hyperlinks found in text are not considered required reading; however, included video links are required to watch.

Study Resources begin on the next page →

Climate Impacts on Ecosystems

Key Points
• Climate change can alter where species live, how they interact, and the timing of biological events, which could fundamentally transform current ecosystems and food webs. • Climate change can overwhelm the capacity of ecosystems to mitigate extreme events and disturbance, such as wildfires, floods, and drought. • Mountain and arctic ecosystems and species are particularly sensitive to climate change. • Projected warming could greatly increase the rate of species extinctions, especially in sensitive regions.

Overview
Climate is an important environmental influence on ecosystems. Changing climate affects ecosystems in a variety of ways. For instance, warming may force species to migrate to higher latitudes or higher elevations where temperatures are more conducive to their survival. Similarly, as sea level rises, saltwater intrusion into a freshwater system may force some key species to relocate or die, thus removing predators or prey that are critical in the existing food chain.

Climate change not only affects ecosystems and species directly, it also interacts with other human stressors such as development. Although some stressors cause only minor impacts when acting alone, their cumulative impact may lead to dramatic ecological changes.[1] For instance, climate change may exacerbate the stress that land development places on fragile coastal areas. Additionally, recently logged forested areas may become vulnerable to erosion if climate change leads to increases in heavy rain storms.

Changes in the Timing of Seasonal Life Cycle Events
For many species, the climate where they live or spend part of the year influences key stages of their annual life cycle, such as migration, blooming, and reproduction. As winters have become shorter and milder, the timing of these events has changed in some parts of the country:

Range Shifts
As temperatures increase, the habitat ranges of many North American species are moving north and to higher elevations. In recent decades, in both land and aquatic environments, plants and animals have moved to higher elevations at a median rate of 36 feet (0.011 kilometers) per decade, and to higher latitudes at a median rate of 10.5 miles (16.9 kilometers) per decade.

While this means a range expansion for some species, for others it means movement into less hospitable habitat, increased competition, or range reduction, with some species having nowhere to go because they are already at the top of a mountain or at the northern limit of land suitable for their habitat. [4][5] These factors lead to local extinctions of both plants and animals in some areas. As a result, the ranges of vegetative biomes are projected to change across 5-20% of the land in the United States by 2100. [4]

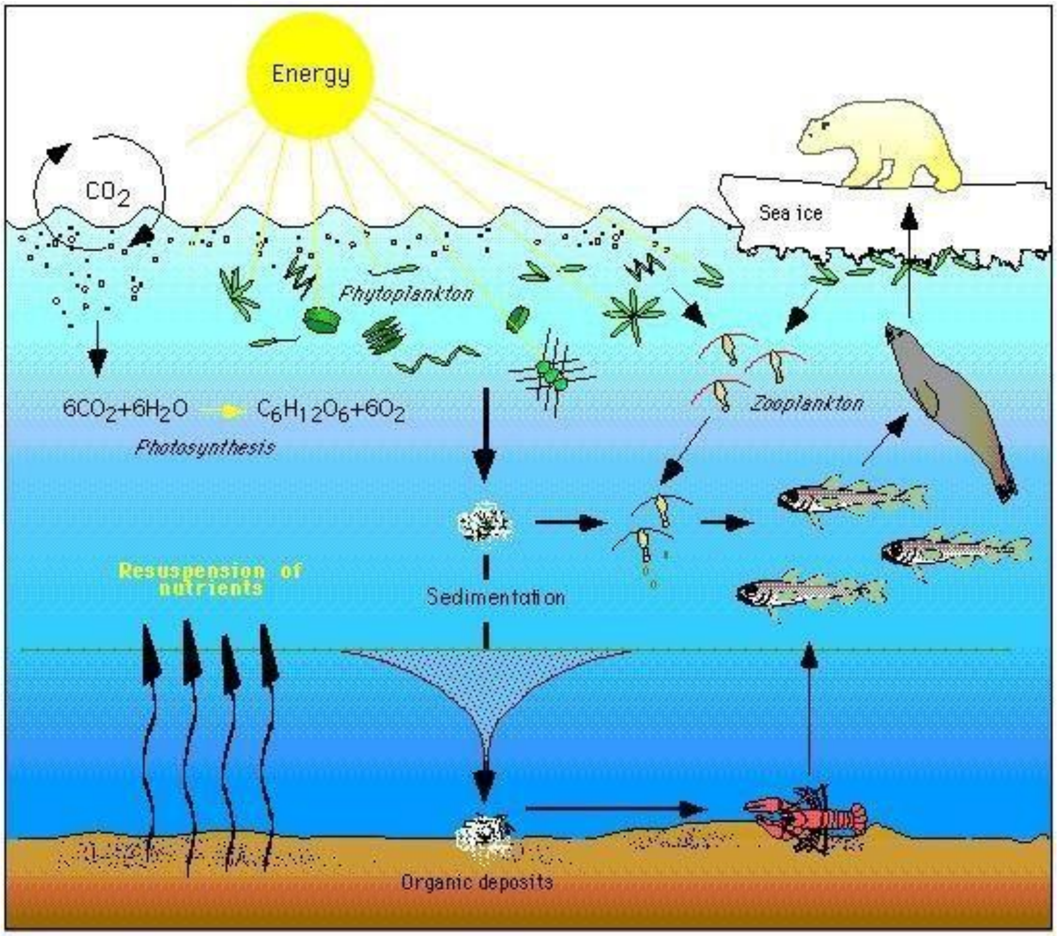
For example, boreal forests are invading tundra, reducing habitat for the many unique species that depend on the tundra ecosystem, such as caribou, arctic foxes, and snowy owls. Other observed changes in the United States include a shift in the temperate broadleaf/conifer forest boundary in the Green Mountains of Vermont; a shift in the shrubland/conifer forest boundary in New Mexico; and an upward elevation shift of the temperate mixed/conifer forest boundary in Southern California.

As rivers and streams warm, warmwater fish are expanding into areas previously inhabited by coldwater species.[5] As waters warm, coldwater fish, including many highly-valued trout and salmon species, are losing their habitat, with projections of 47% habitat loss by 2080.[4] In certain regions in the western United States, losses of western trout populations may exceed 60 percent, while in other regions, losses of bull trout may reach about 90 percent.[5] Range shifts disturb the current state of the ecosystem and can limit opportunities for fishing and hunting.

See the Agriculture and Food Supply Impacts page for information about how habitats of marine species have shifted northward as waters have warmed.

Food Web Disruptions

The impact of climate change on a particular species can ripple through a food web and affect a wide range of other organisms. For example, the figure below shows the complex nature of the food web for polar bears. Not only is the decline of sea ice impairing polar bear populations by reducing the extent of their primary habitat, it is also negatively impacting them via food web effects. Declines in the duration and extent of sea ice in the Arctic leads to declines in the abundance of ice algae, which thrive in nutrient-rich pockets in the ice. These algae are eaten by zooplankton, which are in turn eaten by Arctic cod, an important food source for many marine mammals, including seals. Seals are eaten by polar bears. Hence, declines in ice algae can contribute to declines in polar bear populations. [2][6][7]



Buffer and Threshold Effects

Ecosystems can serve as natural buffers from extreme events such as wildfires, flooding, and drought. Climate change and human modification may restrict ecosystems' ability to temper the impacts of extreme conditions, and thus may increase vulnerability to damage. Examples include reefs and barrier islands that protect coastal ecosystems from storm surges, wetland ecosystems that absorb floodwaters, and cyclical wildfires that clear excess forest debris and reduce the risk of dangerously large fires. [4]

In some cases, ecosystem change occurs rapidly and irreversibly because a threshold, or "tipping point," is passed. One area of concern for thresholds is the Prairie Pothole Region in the north-central part of the United States. This ecosystem is a vast area of small, shallow lakes, known as "prairie potholes" or "playa lakes." These wetlands provide essential breeding habitat for most North American waterfowl species. The pothole region has experienced temporary droughts in the past. However, a permanently warmer, drier future may lead to a threshold change—a dramatic drop in the prairie potholes that host waterfowl populations, which subsequently provide highly valued hunting and wildlife viewing opportunities. [8]

Similarly, when coral reefs become stressed from increased ocean temperatures, they expel microorganisms that live within their tissues and are essential to their health. This is known as coral bleaching. As ocean temperatures warm and the acidity of the ocean increases, bleaching and coral die-offs are likely to become more frequent. Chronically stressed coral reefs are less likely to recover. [5][9]

Pathogens, Parasites, and Disease

Climate change and shifts in ecological conditions could support the spread of pathogens, parasites, and diseases, with potentially serious effects on human health, agriculture, and fisheries. For example, the oyster parasite, *Perkinsus marinus*, is capable of causing large oyster die-offs. This parasite has extended its range northward from Chesapeake Bay to Maine, a 310-mile expansion tied to above-average winter temperatures.[10] For more information about climate change impacts on agriculture, visit the Agriculture and Food Supply Impacts page. To learn more about climate change impacts on human health, visit the Health Impacts page.

Extinction Risks

Climate change, along with habitat destruction and pollution, is one of the important stressors that can contribute to species extinction. The IPCC estimates that 20-30% of the plant and animal species evaluated so far in climate change studies are at risk of extinction if temperatures reach the levels projected to occur by the end of this century.[1] Global rates of species extinctions are likely to approach or exceed the upper limit of observed natural rates of extinction in the fossil record.[1] Examples of species that are particularly climate sensitive and could be at risk of significant losses include animals that are adapted to mountain environments, such as the pika; animals that are dependent on sea ice habitats, such as ringed seals and polar bears; and coldwater fish, such as salmon in the Pacific Northwest.[4][5]

Impacts to Canadian agriculture from climate changes

How will climate change impact Canada and Canadian agriculture? Increased temperatures, longer growing seasons, shifting precipitation patterns and an increase in frequency and intensity of extreme events from climate change will bring both challenges and opportunities to Canada's agricultural sector.

The impacts of climate change will not be uniform across Canada, nor will they be uniform across seasons. In terms of production, there are likely to be opportunities, in some regions, to grow warmer-weather crops and take advantage of a longer growing season with less cold weather events that can damage crops. There will also be challenges to production arising from water stress (flooding or drought), heat stress, wind damage, increased pest and disease pressures, and the impact from these multiple stressors on soil health, which can reduce the productivity, profitability and competitiveness of Canadian farmers.

Opportunities

A warming climate may provide opportunities for agriculture in certain regions with an expansion of the growing season in response to milder and shorter winters. This could increase productivity and allow the use of new and potentially more profitable crops. For a high-latitude country like Canada, future warming is expected to be more pronounced than the global average. Northern regions and the southern and central Prairies will see more warming than other regions. Most regions will likely be warmer with longer frost-free seasons. Atmospheric carbon dioxide (CO^2) concentrations are expected to increase in the future which promotes the growth of small grains and oilseeds by increasing photosynthesis and crop water use efficiency. Corn will mostly benefit from increased water use efficiency and less from increases in photosynthesis.

Challenges

Increased temperatures, longer growing seasons, shifting precipitation patterns and an increase in the frequency and intensity of extreme events from climate change will bring challenges to Canada's agricultural sector. In most of Canada, springs will be wetter, summers will be hotter and drier, and winters will be wetter and milder. Changes in temperature and precipitation patterns will increase reliance on irrigation and water-resource management, notably across the Prairies and the interior of British Columbia where moisture deficits are greatest, but also in regions where there has not traditionally been a need to irrigate. In many parts of the country, wetter than normal springs will present challenges such as the need to delay seeding. Flooding and other extreme events, including wildfires, may result in loss or relocation of livestock and damage to crops; and increased frequency and intensity of storms could result in power outages, affecting livestock heating and cooling systems as well as automated feeding and milking systems.

A rise in the incidence of days over 30 °C will bring challenges to both crop and livestock producers. Some crops, such as canola and wheat, are particularly vulnerable to heat stress during the flowering period, and high temperatures can result in lower weight gains in livestock, reduced reproductive capacity, reduced milk and egg production, and in extreme cases, livestock mortality. Longer, warmer summers and milder winters will result in greater overwinter survival of pests and diseases, as well as a northward expansion of pests and diseases not currently found in Canada. Additional pest pressures can impact both crop and livestock production and could potentially affect the marketability/acceptability of Canadian exports. Plant protein may decrease in the future under higher atmosphere CO^2 resulting in lower grain quality.

While growing seasons will be longer, variability in growing seasons will bring challenges. The last spring frost and first fall frost dates have remained highly variable across the country, making it difficult for farmers to manage seeding and harvesting accordingly, although this may be less of a challenge as warming continues. Tree fruit crops are particularly vulnerable to late frosts occurring during flowering, which may affect yields. Climate change may also affect the prevalence of pollinators as plant flowering periods may change and the range of pollinators may be altered.

Impact by region

While all of Canada will be affected, the impacts will not be uniform across the different agricultural landscapes, with distinct issues for five regions: 1) Pacific Region [British Columbia]; 2) Prairies Region [Alberta, Saskatchewan, Manitoba]; 3) Central Canada [Ontario, Quebec]; 4) Atlantic Canada [New Brunswick, Nova Scotia Prince Edward Island, Newfoundland, Labrador] and 5) Northern Canada [Northwest Territories, Nunavut, Yukon]. Below are the top impacts per region:

1. Pacific Region
    - Access to adequate water is the greatest concern for producers in a number of regions in British Columbia. British Columbia relies on the annual snowpack and glacial meltwater for stream water recharge. As glaciers recede and less precipitation falls as snow, water levels will be reduced, which may lead to reduced soil moisture and water scarcity through the growing season.
    - Temperature increases will would add more frost-free and growing degree days that could improve yields, and enable new cropping options in some regions.
    - More frequent and intense storms, floods, and drought are expected annually, adding uncertainty to food production.
    - Warmer winter temperatures could increase pest and disease pressure by improving over-wintering survival of new and existing species.
    - Tree fruit crops may be especially vulnerable to variable autumn and spring frosts.
    - Sea level rise and salt intrusion may impact coastal agriculture.

2. Prairie Region
    - Increased frost-free periods may provide opportunities for the expansion of warm weather crops such as corn and soybeans as well as a potential northwards expansion of agricultural production where soils permit.
    - Reduced precipitation later in the growing season, coupled with increased heat will cause stress to plants and may have a negative impact on yields.
    - More frequent spring flooding, summer droughts and extreme weather events are expected.
    - Reduced streamflow, less snowmelt to recharge rivers and earlier peak flows could lead to reduced access to water for irrigation during the summer and greater competition for groundwater reserves.
    - A warmer climate may bring new pests and diseases.
    - Increased temperatures could affect livestock health, resulting in reduced milk, egg and meat production and even fatalities; increased cooling costs for producers.
    - Higher CO^2 levels may result in greater productivity from crops such as wheat, barley, canola, soybeans and potatoes.

3. Central Canada
    - Warmer spring weather will extend the growing season, however wetter springs may delay planting/seeding operations due to waterlogged fields and increase soil erosion and nutrient runoff.
    - Increased evapotranspiration due to higher summer temperatures could increase water stress in plants but may be offset by increases in water use efficiency as a result of higher atmospheric CO^2.
    - For northern areas of central Canada, there is an increase in frost-free days, a longer growing season, opportunity for warmer-weather crops (including corn, soybeans), as well as a potential northwards expansion in agricultural production where soils permit.
    - More variability in spring and fall temperatures can stress fruit trees causing blossom loss due to late frosts.
    - Increased temperatures could affect livestock health, resulting in reduced milk, egg and meat production and even fatalities; increased cooling costs for producers.

4. Atlantic Canada
    - Extended periods of hot temperatures resulting in reduced soil moisture and extended drought periods are a concern (increased pressures on yields and forage shortfalls, etc.)
    - Extended periods of drought and dry conditions could put pressure on water table elevations and the need for irrigation.
    - Increase in frost-free days, longer growing season, opportunity for warmer-weather crops (including corn soybeans).

- Rising sea level, erosion and storm surges could negatively impact the Atlantic region, particularly Prince Edward Island and eastern New Brunswick.
- Flooding or waterlogged soil due to increased precipitation could negatively impact agriculture. Wetter springs may delay planting/seeding operations due to waterlogged fields.
- In some parts of Atlantic Canada, the milder winter temperatures could have implications for overwintering of pests and diseases.
- Intrusion of salt water in agricultural lands is a concern and could compromise soil and surface water quality.

5. Northern Canada
   - Impacts on viability of ice roads, affecting access and food security for imported foods as well as for locally harvested food.
   - Increased frost-free season could facilitate a limited expansion of northern agriculture assuming appropriate soils and adapted cultivars.
   - Longer growing seasons may increase the potential for greenhouse production due to reduced winter heating costs.

Government of Canada Gouvernement du Canada

Impacts on ecosystems and fisheries

Canada's marine ecosystems are undergoing significant changes. These changes are related to a combination of climate change, natural variability, and other human pressures, such as fishing. Climate change is impacting our oceans and coastal communities, and we are seeing its results on all three of our coasts.

Climate change affects the long-term trends in ocean temperature and changes seasonal cycles of warming and cooling. This can affect the amount of food and oxygen available to marine plants and animals. For example, phytoplankton are small plants that form the base of the ocean food web and grow primarily in the upper ocean where sunlight is available. They are highly dependent on a supply of nutrients from waters far below the ocean surface. This vertical nutrient supply can be impacted by increasing ocean temperature because it makes it more difficult to pump nutrients to the ocean surface. Changing temperature can also impact the timing of phytoplankton blooms (large masses which can change the colour of seawater, e.g. red tides), which can subsequently impact overall productivity of the marine ecosystem.

Biological impacts

The biological impacts of changing ocean conditions can vary. Some species may actually fare better in future conditions, while others will not be able to adapt to the new conditions fast enough. If they can't adapt or migrate to new habitats that are suitable, then some species may even go extinct.

Ocean acidification can make it difficult for many species to survive and thrive, and can have a variety of impacts on marine animal and plant life. There may be both direct and indirect effects on species of ecological and/or economic importance and we still have much to learn about these biological and ecological impacts.

Some marine organisms of economic importance like oysters, mussels and lobsters use calcium carbonate to form their shells or exoskeletons. As the ocean becomes more acidic, it takes more energy to build calcium carbonate shells or skeletons. In some cases, shells and animal exoskeletons may break down or corrode, and for some organisms, it may be impossible to build their shells or exoskeletons altogether. For some species, only parts of their life cycle (e.g. very early stages) may be particularly sensitive.

Other ecologically important organisms, such as some species of microscopic animals called zooplankton, also use calcium carbonate to build their shells. For example, pteropods (small swimming snails) are suffering damaging effects of ocean acidification in the open ocean. As the amount of available carbonate and the pH of oceans continue to decrease, the shells of pteropods begin to dissolve. As zooplankton are a main food source for many species (e.g.

juvenile salmon and whales), these animals may struggle to find food and may change their diets. When organisms at the base of the food chain are at risk, the entire food web may also be at risk. The sensory capacity of fish may also be affected, making it more difficult for them to find food or to prevent being eaten themselves by predators.

Some organisms are sensitive to very small changes in pH while others aren't so there may be 'winners' and 'losers' in a future ocean environment. For example, some species of marine plants, such as seaweeds and sea grasses, may benefit from increased levels of CO_2 in seawater because they need CO_2 for photosynthesis, just like plants on land. In other cases, a very small pH change can have harmful effects on marine life, impacting reproduction, growth and survival. Alternatively, it is possible that some species may have the capacity to adapt over time by changing their diets, or moving to more favorable/less acidic environments, while some populations may suffer, decline or disappear. Harmful algal blooms occur when dense aggregations of microscopic simple plants (phytoplankton) grow out of control and produce toxic or harmful effects on fish, shell fish, marine mammals and birds. In the future, the frequency and toxicity of these harmful blooms are expected to rise in due to warmer acidified seawater conditions, which may also then impact human food security.

Other stressors, such as increased ocean temperatures and low oxygen conditions, may further compound these impacts. This means that aquatic organisms will encounter many changes in their environment at the same time. Higher temperatures and lowered oxygen levels add pressure to habitats that are already affected by other human impacts. How successful they are may depend on how much food is available. Changes lower down in the food web will impact larger species as well, since they depend on the smaller, more directly affected species as a food source.

Increased carbon dioxide in the atmosphere will also lead to higher water temperatures because of the greenhouse effect. Ocean acidification also occurs alongside hypoxia (low oxygen levels in the water) because of increasing water temperatures and higher amounts of nutrients coming from land sources, like agriculture. Species intolerant of hypoxia would need to avoid low oxygen waters to survive. For example, cod are expected to avoid waters at oxygen levels below 28%. Coastal areas close to large cities and agricultural centers are subject to pollution and excessive nutrients in the water; these nutrients can increase plant life communities to a level that kills animals from a lack of oxygen (eutrophication).

Shifting distributions of marine species

Changes in maximum ocean temperatures are leading to shifts in the distribution of many species.

Animals can respond in a range of ways to warmer waters. If an organism is not at the maximum temperature that it can tolerate, then higher temperatures may be beneficial because they may experience increased growth rates and allow the species to reproduce at a smaller size. Survival may increase if animals grow faster through critical life history stages. However, if the water is too warm for an organism to tolerate, animals that are able will move to and/or survive better in cooler waters, which were more similar to their original habitat before the temperature shift occurred.

If climate change alters the environment where a species lives, it may change its location to nd more suitable conditions elsewhere. Certain species may change their location to follow food sources or to remain at the optimal water temperature for their survival. These re-locations can impact local species as the new arrivals compete for food and can also bring diseases or parasites.

Climate change can also increase the range for some species to include areas where new habitat becomes suitable while the old habitat is still in use. In this case, some individuals move into the new areas, while other individuals remain in their original region. Ranges may also get smaller in situations where parts of the old area no longer support the species and there is no new suitable area to live in.

Invasive Species

In some cases, climate change can allow unwanted species to establish themselves in new areas. In other cases, such as when sea ice melts, some species need to move to survive.

Plants or animals that enter a new environment where they hadn't been before and become established are called invasive species. Organisms can be introduced in new areas through human activities, such as the movement of ships. It can also happen because habitats change and become more suitable for new species. For example, warming waters or changing ocean chemistry can provide a new location range for these species to then live in. These new species can become problematic. They dominate their new environment and out-compete local organisms. Invasive species can take advantage of "disturbances" in an ecosystem to become established.

Let's look at three examples:

- the Arctic was a harsher region for species from other parts of the world to live because of the cold temperatures
  - as the Arctic waters warm, certain species migrate there and are able to grow and reproduce
- eel grass beds help maintain coastal beach structure and provide nursery areas for lots of young fish and shellfish but because of green crabs, originally from Europe, they are being uprooted
  - while some populations of green crabs are unable to survive in colder northern waters, an increase in temperature might allow them to become even more invasive
- marine tunicates, or sea squirts, are simple animals that have been found in areas where they weren't found before
  - many types of sea squirts have invaded and spread around Prince Edward Island

  - they grow in clumps or like mats on solid surfaces, such as docks and boats, and are very hard to remove
  - they are problematic for the local mussel aquaculture industry causing productivity losses
  - as an attempt to prevent further spread of this species, movement of shellfish has to be controlled

Impact on Arctic mammals

Marine mammals experience a range of impacts due to climate change. Ocean acidification, shifts in habitat, or invasive species affect some species that large mammals rely on for food. These threats combine to make life more di cult for many large mammals.

In the Arctic, air temperatures are increasing about three times faster than the global average. As a result, dramatic reductions in Arctic sea ice cover are already evident and well documented. This makes animals that live in the Arctic particularly vulnerable to climate change. Many Arctic and subArctic species use ice as a critical habitat during key stages in their life cycle. Some species such as ringed seals use fast-ice, the solid ice connected to shore. Others, such as harp seals and walrus, use the drifting ice or what's called pack ice. Bowhead whales and narwhals rely on sea ice for their habitat and to support the food they eat. Seals rely on the marine environment for foraging. They must haul out on land or ice to rest, for breeding and moulting, or as a platform to access feeding areas. As the temperature warms and storms become more severe, sea ice is less widespread, lasts for shorter periods, and is not as thick as it was before.

Our ongoing research

We are monitoring and studying the effects that changing ocean conditions are having on Canada's ecosystems and commercial fisheries.

We do research and/or modelling to:

- identify which marine species or stocks are the most vulnerable to changing climate and ocean conditions
- address knowledge gaps associated with climate change impacts and the vulnerability of fisheries and coastal ecosystems
- identify changes in habitats and species distributions

5 Ways Climate Change Impacts Forests

From droughts and wildfires to pests and pathogens, climate change is wreaking havoc on the world's forests.

August 31, 2021 | Andrew Moore

Forests occupy nearly a third of Earth's land surface, providing humans and countless other species with a wide range of benefits and services — from ecological functions such as water and air purification to goods such as lumber and paper.

But according to a recent report released by the United Nations, climate change is expected to worsen over the next century as greenhouse gas emissions continue to increase, a trend that experts say will have consequences for the health of forests worldwide.

At NC State's College of Natural Resources, Robert Scheller is examining the impacts of climate change and human activities on long-term landscape health and developing models to forecast landscape change to inform policy and management decisions.

Scheller's most recent book, "Managing Landscapes for Change," explores how future landscapes will be shaped by pervasive change and where, when, and how society should manage landscapes for change.

We recently spoke with Scheller, a professor in the Department of Forestry and Environmental Resources and the college's interim associate dean of research, about the potential impacts that climate change could have on forests in North Carolina and beyond. Here's what we found out:

Tree Migration

In response to climate change, some tree species will shift their ranges and migrate into landscapes in which they don't typically grow.

"Climate change can create new habitats for tree species and make existing habitats unsuitable. And like any other living thing, trees go where they can survive," Scheller said. "This process is already underway."

Some tree species are migrating uphill and northward as temperatures increase, while other species are migrating downhill and westward as changing precipitation patterns create drier conditions.

Palmetto trees, for example, could become more common throughout North Carolina in the next 50 or 60 years as they migrate from nearby states like Georgia and Florida, according to Scheller.

"Species redistribution isn't necessarily a bad thing. But it's possible that some trees could go extinct, especially those with small ranges," he said. "So if there are species we're concerned about, we need to collect their seeds and plant them in areas where we think they'll survive climate change."

Forest Fires

Since 2000, an annual average of 72,600 wildfires have occurred across the U.S., scorching an average of 7 millions acres of land, including forests, each year. That's more than double the average annual acreage burned in the 1990s. Unfortunately, though, the worst is yet to come.

Climate change is creating warmer temperatures, deeper droughts and drier vegetation, according to Scheller. These conditions will persist in the coming decades and lead to an increase in the extent, intensity and frequency of wildfires, especially in the western U.S.

According to the National Interagency Fire Center, a total of 43,438 wildfires have burned more than 4.5 million acres across the U.S. this year so far, with a majority of the blazes occurring in western states like California, Oregon and Montana. However, as the planet warms, North Carolina and other southeastern states could begin to experience larger wildfires.

"We've created the perfect conditions for wildfires, and I don't see that changing anytime soon," Scheller said. "In the South, states like North Carolina and Florida have a lot of roads that prevent fire from spreading. But under the right conditions, a

large fire could certainly cross roads and cause a lot of damage."

Scheller is currently examining the potential impact of climate change on wildfires in the Southeast, especially in the Appalachian Mountains where fighting the blazes is often difficult because of the region's rugged terrain.

Severe Droughts

With average temperatures rising due to climate change, historically dry areas across the U.S. are likely to experience less precipitation and increased risk of longer, more intense droughts. In fact, recent droughts have been the most prevalent and severe in decades or centuries.

The latest map from the United States Drought Monitor, a collaboration between several federal agencies and the University of Nebraska, shows that at least 50% of the West is currently experiencing "severe" or "exceptional" drought conditions.

Research shows that trees respond to the stress of drought by closing their stomata, the pores that let in carbon dioxide. This forces trees to rely on stored sugars and starches, and if they run out of those energy sources before the drought is over, they can die from 'carbon starvation'.

In addition, when trees lose too much water too quickly during a drought, air bubbles can form and prevent the transportation of water from the roots to the leaves, a process that can also result in death.

"Some landscapes are getting so dry that they can't support forests at all. It's pushing forests out of their physiological limits. This is especially true in the southwestern United States," Scheller said. “But that doesn’t mean every tree is going to die. Some forests will be replaced by shrublands.”

Scheller added that the southeastern U.S., in contrast, may experience more frequent, shorter periods of precipitation due to climate change, resulting in increased forest productivity and growth.

Pests and Pathogens

When trees are exposed to a drought or wildfire, they can become less resilient to pests and pathogens, according to Scheller. And with climate change creating warmer, drier conditions in some regions across the country, forests could face increased outbreaks.

“Trees have less energy to defend themselves when they’re stressed out by drought and other challenging conditions,” Scheller said. “They become more vulnerable to insects, fungi, bacteria, viruses and so on.”

Pests and pathogens typically occur at low population or infection levels in forests, but they occasionally wreak havoc on trees. In 2018, for example, pests and pathogens damaged more than 6 million acres of forests nationwide, according to the most recent report from the U.S. Forest Service.

Climate change will likely expand the range and prevalence of forest pests and pathogens, according to Scheller. The warmer temperatures and drier conditions associated with drought, in particular, could increase the reproductive rate of certain insect species.

Scheller said this phenomenon is already evident in the western U.S. where pests populations are causing massive tree die-offs, with the bark beetle alone destroying 45 million acres of forest in recent years.

“Wildfires get all the press, but insects are killing far more trees in the western U.S. than wildfires,” Scheller concluded.

Carbon Competition

In recent years, polluting companies worldwide have announced plans to utilize forest carbon offset projects to achieve net-zero greenhouse gas emissions by 2050 as investors demand sustainable practices and governments look to promote renewable energy technologies.

These projects allow polluting companies to pay private landowners to capture, store and prevent carbon dioxide from reaching the atmosphere, according to Scheller.

Landowners who participate in these projects can earn “carbon credits” for preserving trees and then sell the credits to polluting companies so that they can continue to emit carbon dioxide, with the exchange balancing out emissions to prevent an overall increase of emissions.

But in addition to utilizing existing forests, some companies are purchasing and reforesting land in an effort to earn even more carbon credits, a strategy that could create “economic uncertainty” for the forest products industry, according to Scheller.

“A lot of companies are looking into reforestation, which is great for places like the Amazon and Africa. But it will create a lot of competition for land, and that could totally upend the forest products industry,” he said.

Scheller added that the price of paper, lumber and other forest products will likely increase in the coming decades as a result of carbon offset projects, with some landowners preferring to receive a yearly payment rather than wait several decades to log and sell their trees.

In addition, fewer trees may be available for logging due to wildfires, insects, and drought, creating further upward pressure on the price of forest products, according to Scheller.

How Climate Change Impacts the Economy

BY RENEE CHO |JUNE 20, 2019

The Fourth National Climate Assessment, published in 2018, warned that if we do not curb greenhouse gas emissions and start to adapt, climate change could seriously disrupt the U.S. economy. Warmer temperatures, sea level rise and extreme weather will damage property and critical infrastructure, impact human health and productivity, and negatively affect sectors such as agriculture, forestry, fisheries and tourism. The demand for energy will increase as power generation becomes less reliable, and water supplies will be stressed. Damage to other countries around the globe will also affect U.S. business through disruption in trade and supply chains.

A recent report examined how climate change could affect 22 different sectors of the economy under two different scenarios: if global temperatures rose 2.8˚ C from pre-industrial levels by 2100, and if they increased by 4.5˚ C. The study projected that if the higher-temperature scenario prevails, climate change impacts on these 22 sectors could cost the U.S. $520 billion each year. If we can keep to 2.8˚ C, it would cost $224 billion less. In any case, the U.S. stands to suffer large economic losses due to climate change, second only to India, according to another study.

We are already seeing the economic impacts of the changing climate. According to Morgan Stanley, climate disasters have cost North America $415 billion in the last three years, much of that due to wildfires and hurricanes.

In 2017, Texas's estimated losses from Hurricane Harvey were $125 billion; Hurricane Sandy caused about $71 billion of damages in 2012. And while it's not yet possible to directly link climate change to hurricanes, warmer temperatures and higher sea levels are known to enhance their intensity and destructiveness.

"Science advances also give us more detailed spatial information to say which assets and operations are in harm's way with climate change—for example say, just how many buildings will be inundated due to sea level rise," said climatologist Radley Horton, associate research professor at Lamont-Doherty Earth Observatory. But the indirect economic impacts may be felt long before an actual disaster.

"For example, it's not just whether a building is underwater or not," he said. "What's important are the harder-to-define things like when does societal risk perception shift? It may be that buildings lose their value before the water actually arrives, once people realize that eventually the water's going to arrive. We need deeper thinking about the interconnection between physical and social systems."

Here are some of the many ways that climate change will likely affect our economy, both directly and indirectly.

Agriculture

The sector most vulnerable to climate risk is agriculture.

Environmental economist Geoffrey Heal, a professor in the Columbia Business School, explained that although agriculture makes up a fairly small part of the total U.S. economy, "locally these effects could be big. There are about a dozen states in the Midwest that are very dependent on agriculture and they could take quite a big hit."

They already have. Extreme rainfall events have increased 37 percent in the Midwest since the 1950s, and this year, the region has experienced above normal amounts of rain and snowmelt that have caused historic flooding.

Many fields have washed away and livestock have drowned; Nebraska alone lost $440 million worth of cattle, and as of March, Iowa had suffered $1.6 billion in losses.

The National Oceanic and Atmospheric Administration (NOAA) expects the coming months to bring even more flooding, which could impact our food supply. To date, farmers have only planted 67 percent of their corn crop compared to last June, when they had planted 96 percent. This lost yield could cause prices for animal feed and ethanol to rise, and potentially disrupt marketplaces at home and abroad. As a result of climate change impacts, the Midwest is projected to lose up to 25 percent of its current corn and soybean yield by 2050.

In addition to flooding, increased heat and drought will likely reduce crop yields. According to a 2011 National Academy of Sciences report, for every degree Celsius the global thermostat rises, there will be a 5 to 15 percent decrease in overall crop production. Many commodity crops such as corn, soybean, wheat, rice, cotton, and oats do not grow well above certain temperature thresholds. In addition, crops will be affected by less availability of water and groundwater, increased pests and weeds, and fire risk. And as farmers struggle to stay afloat by finding ways to adapt to changing conditions, prices will likely increase and be passed along to consumers.

Infrastructure

Much of our society's critical infrastructure is at risk from flooding. "Sea level rise could potentially cause a loss of value of assets in the trillions of dollars—probably anywhere from two to five trillion dollars—by the end of the century," said Heal. "That's loss from damage to housing, damage to airports on the coasts, damage to docks, the railway line that runs up and down the East Coast all of which is within a few feet of sea level, damage to I-95 which runs also along the coast. And that's just the East Coast. If you take a global perspective, this is repeated around the world." Much of this infrastructure will likely need to be repaired or replaced.

Military bases are also vulnerable. According to a 2016 report published by the Center for Climate and Security policy institute, sea level rise could flood parts of military bases along the East and Gulf coasts for up to three months a year as soon as 2050. Inland military installations near rivers are also vulnerable, because they can overflow with heavy precipitation, which is expected to become more common as the atmosphere warms. Extreme weather will necessitate more maintenance and repair for runways and roads, infrastructure and equipment.

In addition, our communication systems will be affected. A 2018 study found that over 4,000 miles of fiber optic cable as well as data centers, traffic exchanges and termination points — the lifeblood of the global information network — are at risk from sea level rise. According to

NOAA's sea level rise projections, this infrastructure could be underwater by 2033 because most of it is buried along highways and coastlines. When it was built 25 years ago, climate change was not a concern, so while the cables are water resistant, they are not waterproof. New York, Miami and Seattle and large service providers including CenturyLink, Intelliquent and AT&T are most at risk. Threats to the internet infrastructure could have huge implications for businesses in the U.S.

Human health and productivity

If temperatures rise 4.5˚ C by 2090, 9,300 more people will die in American cities due to the rising heat. The annual losses associated with extreme temperature-related deaths alone are projected to be $140 billion.

Increasing warmth and precipitation will also add to the risk of waterborne and foodborne diseases and allergies, and spur the proliferation of insects that spread diseases like Zika, West Nile, dengue and Lyme disease into new territories. Extreme weather and climate-related natural disasters can also exacerbate mental health issues. The most vulnerable populations, such as the elderly, children, low-income communities and communities of color, will be most affected by these health impacts.

Temperature extremes are also projected to cause the loss of two billion labor hours each year by 2090, resulting in $160 billion of lost wages. Because of heat exposure, productivity in the Southeast and Southern Great Plains regions is expected to decline by 3 percent, and some counties of Texas and Florida could lose more than 6 percent of labor hours each year by 2100. According to a 2014 Rhodium Group study, the largest climate change-related economic losses in the U.S. will be from lost labor productivity.

Tourism

Two billion dollars could be lost in winter recreation due to less snow and ice. For example, rapid warming in the Adirondack Mountains could decimate the winter activity sector, which makes up 30 percent of the local economy.

In addition, as water temperatures increase, water quality could suffer due to more frequent and more intense algae blooms, which can be toxic, thus curtailing recreational water activities and freshwater fishing. More frequent and severe wildfires will worsen air quality and discourage tourism. Sea level rise could submerge small islands and coastal areas, while deforestation and its destructive impacts on biodiversity could make some tourist destinations less attractive.

Businesses and the financial market

Climate change and its impacts across the globe will threaten the bottom line of businesses in a variety of ways. The frequency and intensity of extreme weather, both in the U.S. and in other countries, can damage factories, supply chain operations and other infrastructure, and disrupt transport. Drought will make water more expensive, which will likely affect the cost of raw materials and production. Climate volatility may force companies to deal with uncertainty in the price of resources for production, energy transport and insurance. And some products could become obsolete or lose their market, such as equipment related to coal mining or skiing in an area that no longer has snow.

Whether in the U.S. or abroad, new regulations such as carbon pricing and subsidies that favor a competitor may affect a business's bottom line. A company's reputation could also suffer if it's seen as doing something that hurts the environment. And investors and stakeholders are increasingly worried about the potential for "stranded assets"—those that become prematurely obsolete or fall out of favor, and must be recorded as a loss, such as fossil fuels that many believe should stay in the ground or real estate in a newly designated flood plain.

In 2018, the Carbon Disclosure Project asked more than 7,000 companies to assess their financial risks from climate change. The CDP found that, unless they took preemptive measures, 215 of the world's 500 biggest companies could lose an estimated one trillion dollars due to climate change, beginning within five years. For example, Alphabet (Google's parent company) will likely have to deal with rising cooling costs for its data centers. Hitachi Ltd.'s suppliers in Southeast Asia could be disrupted by increased rainfall and flooding. Some companies have already been impacted by climate change-related losses. Western Digital Technologies, maker of hard disks, suffered enormous losses in 2011 after flooding in Thailand disrupted its production.

PG&E became liable for fire damages and had to file for bankruptcy after its power lines sparked California's deadliest wildfire last fall. And GE cost its investors $193 billion between 2015 and 2018 because it overestimated demand for natural gas and underestimated the transition to renewable energy.

"The movement away from fossil fuels will have a big impact which could affect banks and investment firms that have relationships with the fossil fuel industry," said Heal. "For example, the stock market value of the U.S. coal industry in 2011 was something like $37 billion. Today it's about $2 billion. So anybody that lent a lot of money to the coal industry 10 years back would be in trouble. One of the things worrying those in the financial field is that this could happen to the oil and gas industry. So people who have invested in them or lent money to them are potentially at risk."

Climate change and opportunity

The good news is that climate change also presents business opportunities. The Carbon Disclosure Project reported that 225 of the world's 500 biggest companies believe climate change could generate over $2.1 trillion in new business prospects.

There will be more opportunity in clean energy, resilient and green buildings, and energy efficiency. Hybrid and electric vehicle production and the electric public transit sector are expected to grow. Construction of green infrastructure and more resilient coastal infrastructure could create many new jobs. Carbon capture and sequestration and uses of captured CO2 present opportunities, especially in light of the new 45Q federal tax credits. In addition, there are forward-thinking new businesses—witness the dramatic rise of Beyond Meat, the company selling plant-based burgers at Carl's Jr. and A&W.

As the Arctic sea ice melts, new shipping lines will open up for trade, substantially cutting transport time. The warming Arctic could also offer more prospects for oil and gas drilling. Weather satellites and radar technology will be in demand to monitor extreme weather. Air conditioning and cooling products will be needed around the world. Biotech companies are developing new crops that are resistant to climate change impacts. Pharmaceutical companies expect increased demand for drugs to combat diseases such as malaria and dengue and other infectious diseases. And the market for military equipment and private security services may expand because the scarcity of resources could trigger civil unrest and conflict.

What individuals, businesses and governments can do to protect themselves

How much climate change will hurt the economy depends on what measures we take to adapt to and prepare for it.

Individuals need to consider the implications of climate change when choosing where to spend and invest their money. And be aware that while a particular risk may not seem to be factored into prices yet, things could turn on a dime when the realization of risk sinks in, resulting in a massive redistribution of wealth. So it's best not to buy or move to an area near wild lands, which have a higher risk of wildfires. Don't move into a flood zone or buy real estate in an area that's vulnerable to sea level rise. And in any case, purchase flood and fire insurance, and diversify your investments.

Individuals should also think about different opportunities in terms of new places that people are moving to. And, if possible, people who work outdoors in construction, agriculture or tourism should consider alternative jobs within the sector or new industries to work in.

Businesses and financial entities

Businesses need to scrutinize their operations carefully. "There's a groundswell towards the view that any companies that fail to study their exposure to extreme weather and fail to disclose the types of vulnerabilities, including indirect ones, are going to have a hard time in the future," said Horton. "Are companies looking at what's coming down the road and making strategies to deal with it? I think investors are going to demand that and the companies that don't do that are going to have trouble getting underwriting, getting infrastructure funded by the Moody's of the world, and getting insurance." He added that he's seen a change in the last three or four years in what his students are demanding and believes that young people in the future will not work for companies that are not thinking about climate change.

Banks and funds need to analyze where their investments are and see if they are vulnerable to climate change. Have they invested in someone who has coastal property, or given a loan to a fossil fuel company or in agriculture operations that might be affected by climate change? Sixty-three percent of financial risk managers surveyed now believe climate change is a major concern. As a result, "The total value of funds that have integrated environmental, social and governance factors into their investment process has more than quadrupled since 2014, rising to $485 billion as of April," reported the Wall Street Journal.

Governments

Governments should proactively think about the risks their communities face before disaster strikes. They should be investing in resiliency measures such as hardening infrastructure, improving water resources, building redundancy into important systems, moving people out of harm's way and improving health care services. "You want to do it before the disaster but you also need to be cognizant that the only time people will listen seems to be right after a disaster," said Horton. "Those are also the times when money's available to rebuild."

Government leaders are currently debating whether the country can afford the Green New Deal (an ambitious plan to address climate change) or something like it. The question should be, 'can we afford not to afford it?' Nobel Prize-winning economist Joseph Stiglitz, a professor at Columbia University, wrote in an op ed, "We will pay for climate breakdown one way or another, so it makes sense to spend the money now to reduce emissions rather than wait until later to pay a lot more for the consequences… It's a cliché, but it's true: An ounce of prevention is worth a pound of cure."

This is how climate change could impact the global economy

Jun 28, 2021

Impact of climate change can be capped by reaching net zero

Image: REUTERS/Jason Cairnduff

- **The largest impact of climate change is that it could wipe off up to 18% of GDP off the worldwide economy by 2050 if global temperatures rise by 3.2°C, the Swiss Re Institute warns.**
- **Forecast based on temperature increases staying on the current trajectory and the Paris Agreement and net-zero emissions targets not being met.**
- **Figure could rise to 18% of GDP by mid-century if temperatures increase by 3.2°C in the most severe scenario.**
- **Climate change is a systemic risk that must be addressed now, warns Swiss Re.**

The global economy could lose 10% of its total economic value by 2050 due to climate change, according to new research.

The report The economics of climate change: no action not an option, published by the Swiss Re Institute, said the forecast about the impact of climate change was based on temperature increases staying on the current trajectory and Paris Agreement and net-zero emission targets not being met.

However, it also warns that this figure could rise significantly to 18% of gross domestic product (GDP) by mid-century if no action is taken and temperatures rise by 3.2°C.

Impact of Climate Change

The Swiss Re Institute's Climate Economics Index stress tests how global warming will affect 48 countries – representing 90% of the world economy – and ranks their climate resilience.

	Temperature rise scenario, by mid-century			
	Well-below 2°C increase	2.0°C increase	2.6°C increase	3.2°C increase
	Paris target	*The likely range of global temperature gains*		*Severe case*
Simulating for economic loss impacts from rising temperatures in % GDP, relative to a world without climate change (0°C)				
World	−4.2%	−11.0%	−13.9%	−18.1%
OECD	−3.1%	−7.6%	−8.1%	−10.6%
North America	−3.1%	−6.9%	−7.4%	−9.5%
South America	−4.1%	−10.8%	−13.0%	−17.0%
Europe	−2.8%	−7.7%	−8.0%	−10.5%
Middle East & Africa	−4.7%	−14.0%	−21.5%	−27.6%
Asia	−5.5%	−14.9%	−20.4%	−26.5%
Advanced Asia	−3.3%	−9.5%	−11.7%	−15.4%
ASEAN	−4.2%	−17.0%	−29.0%	−37.4%
Oceania	−4.3%	−11.2%	−12.3%	−16.3%

Global temperature rises will negatively impact GDP in all regions by mid-century. Image: Swiss Re Institute: The economics of climate change.

It lays out the expected impact on global GDP by 2050 under four different scenarios compared to a world without climate change. These are:

- 4% if Paris Agreement targets are met (a well-below 2°C increase)
- 11% if further mitigating actions are taken (2°C increase)
- 14% if some mitigating actions are taken (2.6°C increase)
- 18% if no mitigating actions are taken (3.2°C increase).

The impact of climate change has been forecasted to be the hardest hit for Asian economies, with a 5.5% hit to GDP in the best-case scenario, and 26.5% hit in a severe scenario.

However, there were significant regional variations in the data. Advanced Asian economies are predicted to see GDP losses of 3.3% in case of a below-2°C rise and 15.4% in a severe scenario, while ASEAN countries are forecast to see drops of 4.2% and 37.4% respectively.

China is at risk of losing nearly 24% of its GDP in a severe scenario compared to forecast losses of 10% for the US, Canada and the UK and 11% for Europe.

The Middle East & Africa, meanwhile, would see a drop of 4.7% if temperature rises stay below 2°C and 27.6°C in the severe case scenario, the report added.

Earth Observation to Mitigate Impacts of Climate Change and Support Sustainable Business Decisions

Environmental, Social and Corporate Governance (ESG) criteria are a set of standards for a company's operations that can serve as a corporate "scorecard" to measure a businesses' sustainability and societal impacts. Remotely sensed Earth observation is key to monitor environmental criteria (the "E" in ESG) including identifying sources of air or water pollution, and measuring progress towards sustainability goals including approaches on climate action and the preservation of natural habitat and biodiversity.

COP26 made it clear – Things need to change

The 2021 United Nations Climate Change Conference (also known as COP26) that was recently held in Glasgow, Scotland, made it clear that our planet is under increasing pressure, and things need to change. The over-riding theme of the conference was that the planet has entered a critical time of global crises and transformational change and solving our climate crisis is arguably the most pressing problem of our time. Therefore, it is imperative to not only manage and mitigate the risks that climate change poses, it is of equal importance to identify potential opportunities to increase sustainable practices and develop a posture of resilience.

At COP26, major initiatives and plans were discussed to reduce emissions, end deforestation and protect our oceans. On the business side of the equation, organizations are waking up to the realization that sustainable practices with innovative solutions are needed to ensure the long-term creation of wealth and prosperity. The emerging business bottom line: Sustainable prosperity requires meeting the needs of the present, without compromising the future.

What is ESG and why businesses should care about sustainability?

To optimize sustainability in business operations, integrated strategies can be linked to economic performance, social responsibility and environmental management. Adoption of these strategic practices leads to operating under ESG criteria. Since ESG criteria are used to evaluate socially responsible investments, compliance is of critical importance to avoid ESG related risks and a maintain a continued stream of investment capital.

But it isn't just financial institutions and socially responsible investors that are looking to finance companies that place environmental sustainability on at least equal footing with profits. Investors and consumers across the board are becoming increasingly concerned about the downstream consequences of their investing and buying decisions. Customers want to feel good about what they purchase and want to see the companies they buy from make a positive difference in the world. As consumer and investor pressure increases, ESG criteria will continue to grow in importance for driving investment and purchase decisions, which in turn will elevate the importance of the accurate monitoring and measuring of ESG related practices.

The value of Earth observation for businesses

The availability of Earth observation data and the applications that leverage it have grown exponentially in recent years. As the quality and revisit rates of satellite data has risen, there have also been advances in big data and machine learning that have enabled the extraction of insights and answers that were not possible before. This has prompted businesses to add geospatial data and analytics to their decision-making processes, an addition that has proven to be invaluable, particularly when it comes to physical, location-specific assets.

Periodic satellite-based monitoring of industrial locations can reveal insights that allow for estimates on commodity types of goods and investments concerning sustainability. This information helps answer business intelligence questions such as industrial land usage (size of an asset, construction, demolition); employment data (counting cars at plants and stores); raw material stockpiles (containers, crude oil tanks etc.); product inventory (manufactured cars, etc.); and much more.

In terms of sustainability, the real-world information revealed by Earth observation data provides investors with quantitative, measurable ESG indices. For example, it can be determined how businesses and industries are managing their carbon emissions, how they are impacting (or polluting) the environment, and what their greenhouse gas (GHG) emission levels are?

Satellite data reveals insights based on observed data and not on proxies by estimates or reporting. And, if you can measure it, you can manage it – Earth observation can deliver hard numbers that can be measured and compared over time. This powerful source of incontrovertible evidence goes beyond what a company may report on its own accord. Earth observation will influence what is disclosed so sustainability reports avoid “greenwashing”.

Example 1: Earth observation helps businesses curb GHG emissions

To tackle the pollution problem, Earth observation technology can support businesses to improve ESG performance. This is accomplished with monitoring to help reduce emissions, to better understand carbon sources, to pinpoint super-emitters so repairs can be made, and to ensure carbon reduction commitments are meet. Carbon dioxide (C02) is the most common climate-warming gas, accounting for nearly 80% of all greenhouse gas emissions. C02 is followed by Methane gas as the next most common climate-warming gas, and while it accounts for lower emissions, it is exponentially more potent in warming up the Earth's atmosphere.

Greenhouse gases such as methane (CH_4) and CO_2 absorb electromagnetic radiation in many parts of the infrared spectrum, which can be measured with hyperspectral sensors. Satellite data can reveal and verify evidence of greenhouse gas hotspots such as increased levels of nitrogen dioxide (a major pollutant associated with industrial activity).

Along with satellite data, wind speed and direction can connect a pollution cloud to a site or specific facility. This type of monitoring can determine in near-real time the source of atmospheric or water pollution. The following are examples of how remote sensing can monitor GHG emissions to help meet climate change mitigation targets:

- AVIRIS-C and AVIRIS-NG are hyperspectral airborne sensors (JPL /NASA) that detect and measure methane and carbon dioxide emission plumes (Figure 2).
- The upcoming hyperspectral satellite constellation Carbon Mapper (Planet/NASA) will help accelerate the mitigation of methane super-emitters, independently verify power plant CO2 emissions globally, and deliver 25+ other hyperspectral indicators for carbon and ecosystem management (at about 30m pixel resolution) (Figure 3).
- GHGSat is building its own satellite constellation to monitor greenhouse gases in high resolution, providing emission data and intelligence to businesses, governments, regulators and investors worldwide.
    - Orbital Sidekick is establishing a space-based infrastructure of hyperspectral sensors that will be able to monitor environmental pollution.

As announced at COP26 by the European Space Agency (ESA) and the European Union's Earth-monitoring program Copernicus, a new space mission is currently being developed by ESA and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Once operational (expected 2026), the satellites of this mission, called European CO2 Monitoring and Verification Support Capacity (CO2MVS) on anthropogenic emissions, will be able to measure concentrations of the two most common greenhouse gases (carbon dioxide and methane). Currently the satellite Sentinel-5P of the European Union Copernicus mission can provide valuable information on greenhouse gas emissions, though at much poorer resolutions (Figure 4).

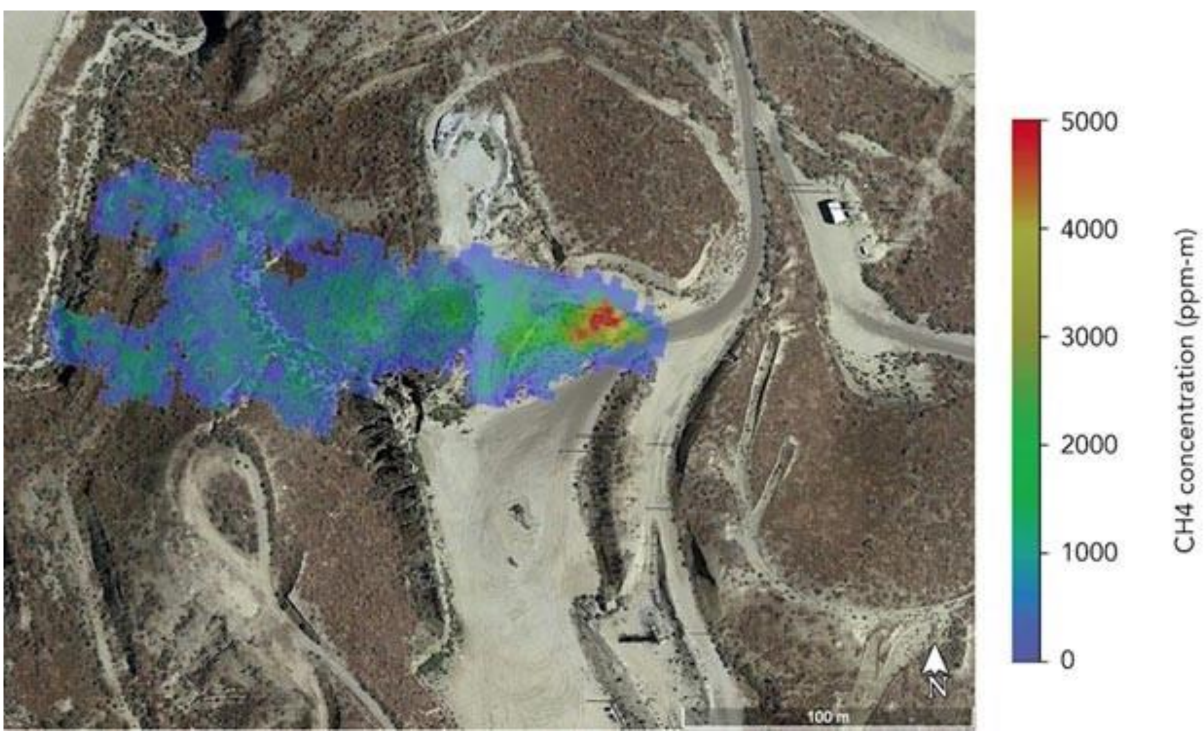


Fig. 2: A methane plume detected by NASA's AVIRIS-NG in the summer of 2020 indicates a leaking gas line in an oil field in California. Source: NASA/JPL-Caltech

(https://climate.nasa.gov/news/3074/nasa-built-instrument-will-help-spot-greenhouse-gashttps://climate.nasa.gov/news/3074/nasa-built-instrument-will-help-spot-greenhouse-gas-super-emitters/super-emitters/)

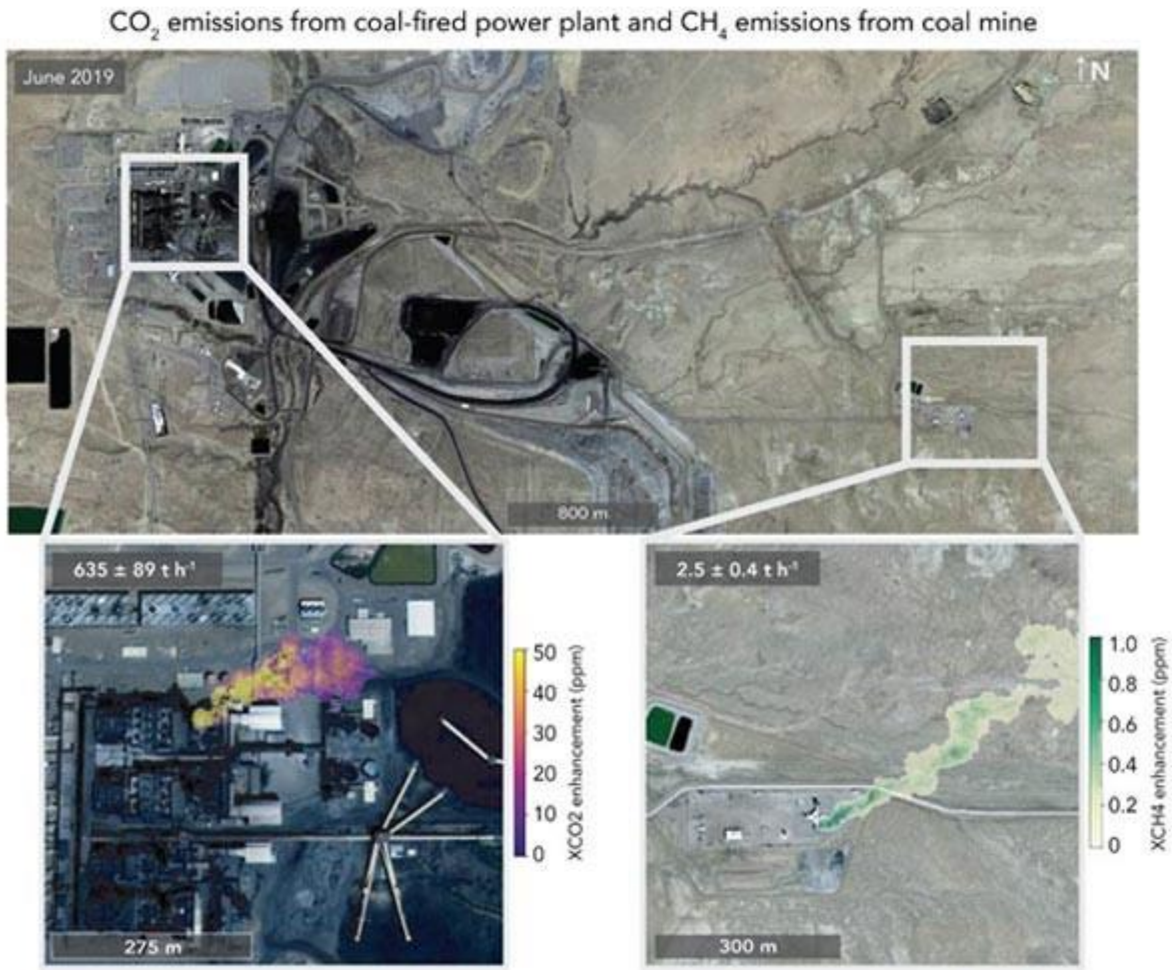
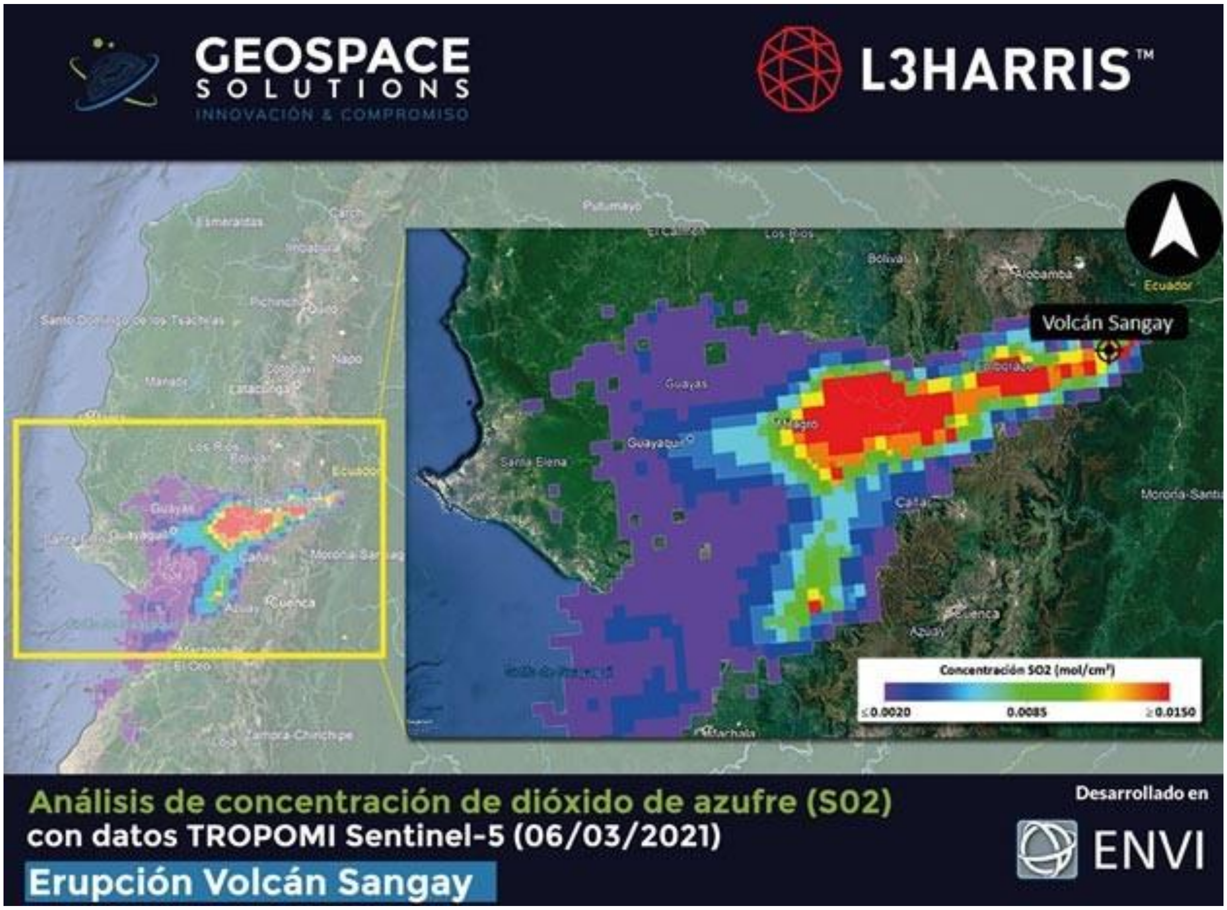


Fig. 3. San Juan coal mine and nearby power plant in New Mexico: methane gas is venting to the atmosphere during coal extraction (right-most inset box). Extracted coal is sent to the power plant, where CO2 is released as a byproduct of electricity generation (left box).

Example 2: How Earth observation can help business identify climate change impacts



Earth observation has become a key instrument for organizations to study how climate and environmental changes are likely to affect industries and markets worldwide. Companies are finding it difficult to identify exposure and quantify risks of their physical assets due to changing climate conditions such as natural disasters and other extreme climatic events. If affected, climate disasters directly impact the fiscal performance of a company. Therefore, accurate measures are needed to help manage and price their climate related risk exposure based on various scenarios. This in turn enables financial institutions that are investing in these companies to quantify the climate risk factors in their portfolio. Earth observation can help to estimate the expected impact of climatic change and a potential disaster's impact on physical assets of a company (infrastructure) as well as their markets (agriculture).

Example 3: Earth observation to monitor deforestation and support certification programs

Another example where earth observation can help support more sustainable business practices is in controlling standards for sustainability certification programs. There are more and more certification programs in place for practices such as fair-trade and organic food. Particularly for those that are certifying forestry and agricultural products including timber, palm oil, coffee, cocoa or tea, Earth observation can help in supporting and verifying that environmentally appropriate, socially beneficial, and economically viable sustainability standards are met.

Deforestation, largely driven by economic pressure, is one of the largest sources of greenhouse gas emissions. Synthetic Aperture Radar (SAR) satellite sensors can monitor land cover even under cloudy conditions and without the sun's light, making it an important technology for monitoring boreal and tropical regions.

In Brazil for example, most illegal cutting occurs in the rainy season as the cloud cover makes it nearly impossible for optical imagery to consistently monitor areas. SAR based Earth observation can be used to map, monitor, measure, and analyze remote and large forested areas, not only to identify and track deforestation, but also to ensure responsible land use and to control sustainability standards for certification programs.

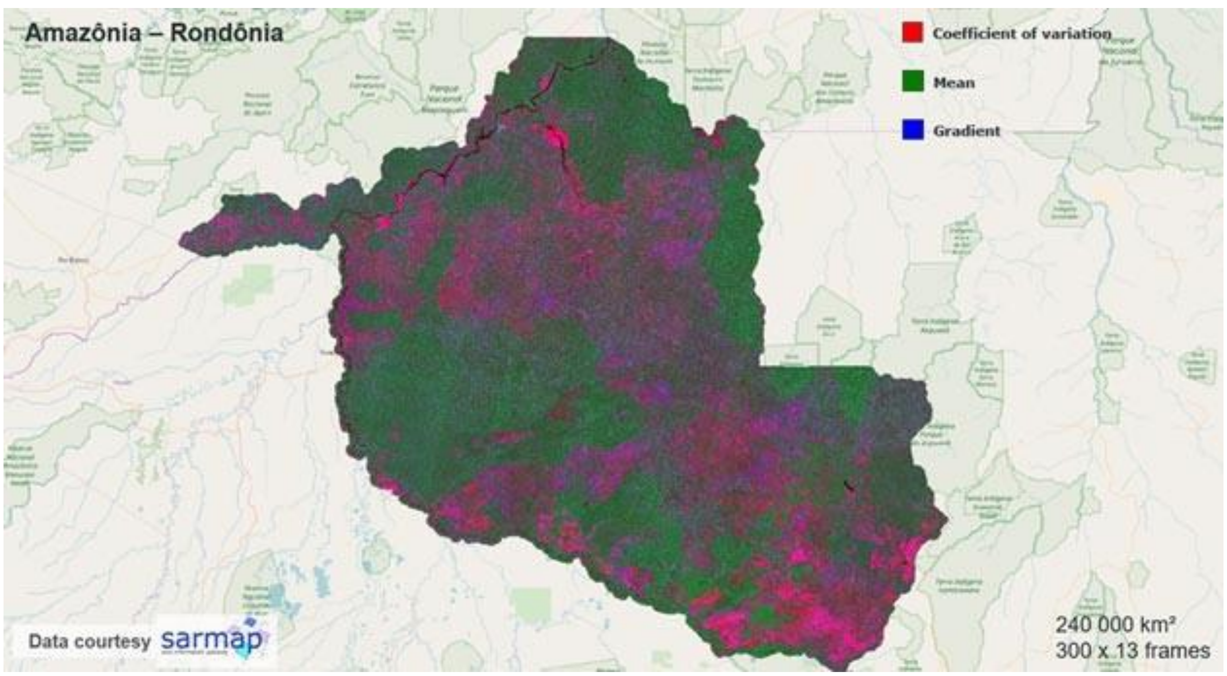


Fig. 5: Temporal descriptors derived from statistical Sentinel-1 SAR time series processing with ENVI SARscape® in Amazonia, Brazil: Deforestation is obvious when there are sudden changes in the SAR backscatter over time (which is particularly sensitive to forest biomass), here highlighted in purple. Source: sarmap s.a. (https://www.sarmap.ch)

To sum it up: Earth observation is a powerful tool to support sustainable business decisions

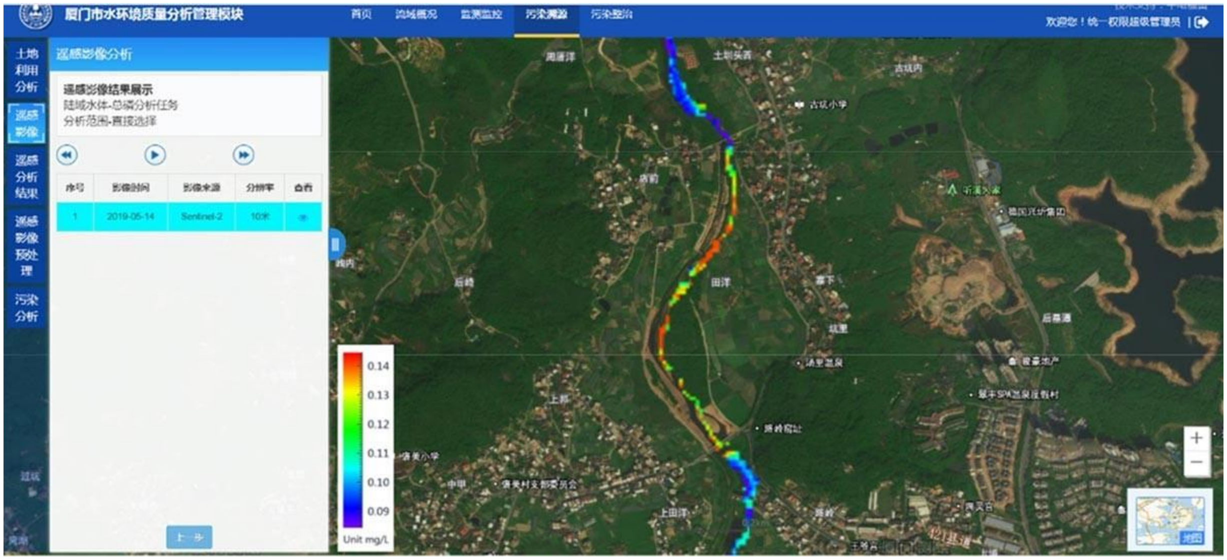


Fig. 6: Example of a detected water pollution (phosphorus) incident in June 2019 from satellite imagery, displayed in the ENVI based operational Platform for Intelligent Environment Protection of the Xiamen Municipal Bureau of Ecological Environment, China. Source: L3Harris

These examples show that sustainability not only has a positive impact on solving our most pressing global problems and strengthening resilience, but sustainability is also good for business. Adopting sustainable practices through innovative solutions, including design, planning and technology, creates long-term value and wealth. The business case for sustainability is made through the mitigation of climate change related risks and compliance with ESG criteria (particularly the "E"), that increasingly are driving investment decisions, impacted by economic, social and environmental global pressures.

Earth observation is a key instrument to help organizations in their analysis and management of sustainability related risks, to adopt more sustainable practices, promote development goals, measure and verify reported commitments, and demonstrate positive impacts for investors, customers and the public. Combining Earth observation data with other sources such as reports, analytics, and social media can help facilitate more transparent and timely decision making. This includes approaches for climate action and the preservation of natural habitats and biodiversity, and to track and report on targets and hold individuals, businesses and governments accountable.

Looking toward the future

Earth observation can provide detailed metrics particularly on environmental related risk exposures to measure ESG criteria status and progress. Earth observation also plays a unique role in supporting the assessment of national and international sustainability programs such as the European Commission's Green Deal policy initiative to shape a zero-carbon economy, the Next Generation EU recovery fund that focuses on a digital transition and tackling climate change impacts, and the Sustainable Development Goals (SDGs) set by the United Nations. This is the world's shared plan to end extreme poverty, reduce inequality, and protect the planet by 2030 – creating an inclusive, sustainable and resilient future for everyone.

What does the future hold for the Earth observation industry itself? Sustainability has the potential to act as long-term driver for investments in Earth observation data and technology, across all type of industries. This investment provides the industry the opportunity to do good in the world, help build an enduring and sustainable future and leave the world a better place tomorrow than it is today!

Social Dimensions of Climate Change

As the climate continues to change, millions of poor people face greater challenges in terms of extreme events, health effects, food security, livelihood security, migration, water security, cultural identity, and other related risks.

Climate change is deeply intertwined with global patterns of inequality. The most vulnerable people bear the brunt of climate change impacts yet contribute the least to the crisis. As the impacts of climate change mount, millions of vulnerable people face disproportionate challenges in terms of extreme events, health effects, food security, livelihood security, water security, and cultural identity.

Certain social groups are particularly vulnerable to crises, for example, female-headed households, children, persons with disabilities, Indigenous Peoples and ethnic minorities, landless tenants, migrant workers, displaced persons, sexual and gender minorities, older people, and other socially marginalized groups. The root causes of their vulnerability lie in a combination of their geographical locations; their financial, socio-economic, cultural, and gender status; and their access to services, decision-making, and justice.

Poor and marginalized groups are calling for more ambitious action on climate change. Climate change is more than an environmental crisis – it is a social crisis and compels us to address issues of inequality on many levels: between wealthy and poor countries; between rich and poor within countries; between men and women, and between generations. The Intergovernmental Panel on Climate Change (IPCC) has highlighted the need for climate solutions that conform to principles of climate justice (i.e., recognition and procedural and distributive justice) for more effective development outcomes.

The most vulnerable are often also disproportionately impacted by measures to address climate change. In the absence of well-designed and inclusive policies, climate change mitigation measures can place a higher financial burden on poor households; for example, policies that expand public transport or carbon pricing may lead to higher public transport fares which can impact poorer households more. Similarly, if not carefully addressed, limiting forestry activities to certain times of the year could impact indigenous communities that depend on forests year-round for their livelihoods. In addition to addressing the distributional impacts of decarbonizing economies there is also a need to understand and address the social inclusion, cultural and political economy aspects – including agreeing on the types of transitions needed (economic, social, etc.) and identifying opportunities to address social inequality in these processes.

While much progress has been made on the science and the types of policies needed to support a transition to low carbon, climate resilient development, a challenge facing many countries is engaging citizens who may not understand climate change, and garnering the support of those who are concerned that they will be unfairly impacted by

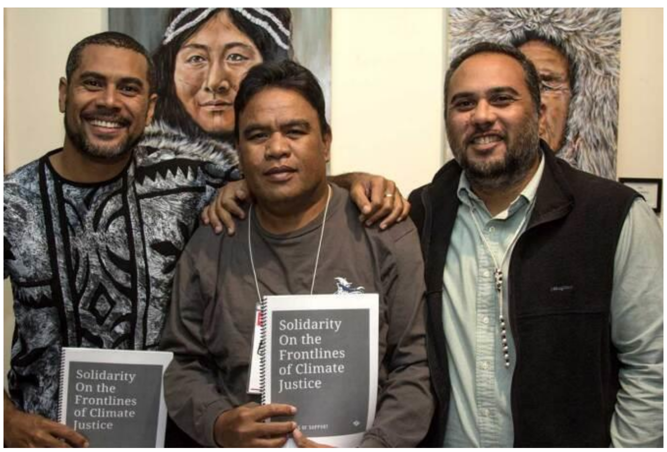
climate policies. It is critical that people are brought along in the choices to be made – this requires transparency, access to information and citizen engagement on climate risk and green growth in order to create coalitions of support or public demand to reduce climate impacts and to overcome behavioral and political inertia to decarbonization, as well as to generate new ideas for and ownership of solutions.

Moreover, communities bring unique perspectives, skills, and a wealth of knowledge to the challenge of strengthening resilience and addressing climate change. They should be engaged as partners in resilience-building rather than being regarded merely as beneficiaries. Research and experience have shown that community leaders can set priorities, influence ownership, and design and implement investment programs that are responsive to their community's own needs. The IPCC's latest report recognizes the value of diverse forms of knowledge such as scientific, Indigenous and local knowledge in building climate resilience. Innovations in the architecture of climate finance can connect communities and marginalized groups to the higher-level policy, technical and financial assistance that they need for locally relevant and effective development impacts.

The Disproportionate Impact of Climate Change on Indigenous Communities

The case studies, images, and content for this article are drawn from the exhibition "Climate Stories," curated by the author and on view at the Global Museum at San Francisco State University through May 22, 2020.

Now more than ever, the topic of climate change has been receiving national attention and is at the forefront of many conversations. In addition to altering environments, it also has a social impact. Extreme weather events have been happening more than ever in recorded history, disrupting both ecosystems and livelihoods for people across the globe. However, marginalized communities, including Indigenous groups, are often the people most affected by devastating storms, flooding, or fires. Recent environmental changes brought on by climate change uniquely impact Indigenous people, especially because of their relationships with the land, ocean, and natural resources. The United Nations Department of Economic and Social Affairs articulately states, "Climate change poses threats and dangers to the survival of Indigenous communities worldwide, even though Indigenous peoples contribute the least to greenhouse gas emissions."



Members of the First Peoples' Convening on Climate Forced Displacement, which took place in October 2018. | Rob Stapleton, Creative Commons

"We all breathe this one air, we all drink the same water. We all live on this one planet. We need to protect the Earth. If we don't, the big winds will come and destroy the forest. Then you will feel the fear that we feel."

stated by Raoni Metuktire, Indigenous activist and chief of the Kayapó community in Brazil

In the words of Survival International, an organization championing tribal peoples around the world, "Indigenous people are on the front line of climate change." When community worldviews are deeply tied to the environment, what happens when that environment starts to change rapidly? Or when ancestral homelands that communities have lived in for thousands of years start to disappear? A few of the direct consequences of changing environmental conditions include loss of natural resources, restricted access to traditional gathering areas for food and medicine, and forced displacement or relocation. Despite these challenges, many Indigenous communities are adapting traditional lifeways and advocating for change.

Traditional Ecological Knowledge (TEK) is an essential part of the climate conversation. In California, tribes across the state are actively involved in climate change-related planning and adaptation. The Karuk tribe in northern California recently completed a Climate Adaptation Plan that leans on Traditional Ecological Knowledge to protect their culture, according to Bill Tripp, deputy director of the Karuk Natural Resources Department. The tribe is currently implementing indigenous burning practices to reduce the buildup of forest fuels and help prevent high-severity wildfires. Many other tribal communities, including the North Fork Mono and Amah Mutsun Tribal Band, are also engaged in prescribed burning. The Coast Miwok are currently working with the National Park Service at Point Reyes to help protect cultural sites that are disappearing due to erosion and flooding. The organization Climate Science Alliance is supporting the La Jolla Band of Luiseño Indians to create a climate adaption plan. These projects and partnerships are just a few of the many climate change initiatives currently led by California tribal communities.

These climate-related impacts extend beyond California. Climate change affects Indigenous communities across the globe who live in or are connected to a broad diversity of natural environments. The Carteret Islands in Papua New Guinea are the first place in the world to require population relocations specifically due to climate change. However, Papua New Guinea was also the first country to submit a formal climate action plan under the Paris Agreement, just one of many examples of community action and response. In Australia, which is currently facing drought, increased wildfires, rising sea levels, and coral bleaching in the Great Barrier Reef, many Aboriginal and Torres Strait Islander people are advocating for policy change within the Australian government for climate change planning, which includes actions like reducing carbon emissions and building emergency sea walls.

Aerial view of the Carteret Islands. | Courtesy of NASA

Many Pacific Islander communities are also building new infrastructure and creating relocation plans. Native Hawaiian people — whose lifeways have long been linked with the ocean — are some of the global leaders in climate change policy, planning, and adaptation. In 2018, the Hawai'i legislature passed two bills pledging to make the state carbon neutral by 2045.

Fishing continues to be an important part of life in Hawai'i, as a source of food and trade. For thousands of years, Native Hawaiians built fish ponds in coastal estuaries to produce millions of pounds of fish as a staple food source. Rising temperatures are now drying up these ancestral ponds. Community members today are moving nets, installing aeration systems, and using flexible harvest strategies in these ponds to adapt to warming ocean temperatures.

Many Native Alaskan tribes, which include Yupik, Inuit, Iñupiat, and Aleut communities, have lived in ancestral villages along the coast for thousands of years, relying on fishing and subsistence hunting of marine mammals such as seals and walrus for survival. Due to rapid sea ice melt, approximately 87% of Native Alaskan villages are experiencing erosion, and many are being forced to move. Hunters have also turned to new methods, including flying drones over ancestral hunting grounds, to track sea ice and walrus populations.

Traditional Native Alaskan seal hunting, circa 1911. | Public Domain

When changing environmental conditions result in habitat loss, this can offset the balance between humans and important wildlife species. In Papua New Guinea, the crocodile and the cassowary bird — two culturally significant species — are losing habitat due to rising river levels. One of the creation stories from the Iatmul community in Papua New Guinea describes a world engulfed by water. An ancestral crocodile came and scooped part of the submerged land onto its back, lifting it to the surface. Ironically, thousands of years later, this prophetic creation story seems all too real. The cassowary, a critically endangered bird species, is seen as kin, and the use of their bones and feathers in material culture signifies relationships with ancestors.

A canoe prow carved into the shape of a crocodile from the Iatmul Community in Papua New Guinea, collection of the Global Museum, San Francisco State University. | Courtesy of the Global Museum.

Plants can also serve as indicators of climate change. Even subtle differences in weather patterns can lead to a decrease in biodiversity. Indigenous communities are having to adapt agricultural practices, which often serve as the main food source for a region, and are losing the ability to gather medicinal plants that they rely on for healing. As temperatures continue to increase, some species that live in delicate microclimates, such as cloud forests and rainforest biomes, may no longer be able to survive.

For example, Indigenous communities in the Amazon Basin, which is home to over 80,000 plant species, have long relied on plants for medicinal purposes, many of which are also used in modern pharmaceuticals. Deforestation and land exploitation have made it more difficult to gather these species. Indigenous peoples in the Amazon Basin regions of Brazil, Peru, and Ecuador are actively fighting to protect their ancestral territories from oil development and deforestation, frequently resulting in deadly consequences. Community members today often use cultural items such as headdresses and face paint for protests and political action in addition to traditional use.

Headdress worn by Chief Raoni Metuktire, collection of the Global Museum, San Francisco State University. | Courtesy of the Global Museum.

As these case studies show, environmental changes can have major impacts on Indigenous people. Climate change impacts communities not only from an environmental standpoint but also at a cultural level. There are multiple Indigenous environmental groups, grassroots organizations, and guardians who are working together to combat these issues. As powerfully stated by Raoni Metuktire, Indigenous activist and chief of the Kayapó community in Brazil: “We all breathe this one air, we all drink the same water. We all live on this one planet. We need to protect the Earth. If we don’t, the big winds will come and destroy the forest. Then you will feel the fear that we feel.”

Southeast Asia to bear the brunt of worsening global climate, IPCC warns

Aug 17, 2021

The IPCC's sixth assessment report is the latest in a series of reports that assess the science of climate change, its impacts and risks.

Image: REUTERS/Lisa Marie David

Climate Change

- **Global warming is expected to reach the dangerous 1.5C level as early as the 2030s.**
- **This planetary change is expected to worsen already extreme situations of flooding and droughts around the world.**
- **The recent IPCC report predicts particularly stark consequences for Southeast Asia, one of the planet's most vulnerable regions to climate change.**

The first major assessment from climate experts in nearly a decade predicts no end to rising temperatures before 2050 unless greenhouse gas emissions are slashed. Vulnerable Southeast Asia needs to mount stronger climate defences.

Climate change is likely to worsen extreme weather events like flooding and droughts. Image: EbvImages

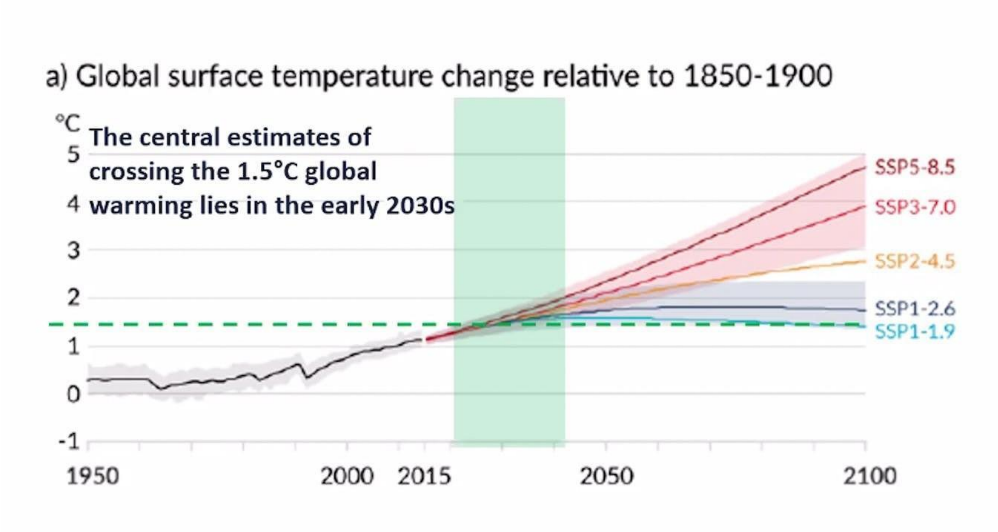
The world is expected to get warmer much faster than previously expected without drastic moves to cut greenhouse gas pollution. Rising temperatures will lead to dangerous weather extremes and rising sea levels in the coming years, according to a new report from the Intergovernmental Panel on Climate Change (IPCC), authored by the world's leading climate scientists.

A global warming increase of 1.5°C above pre-industrial levels, a marker that world leaders pledged not to exceed this century when the Paris Agreement was signed in 2015, could be reached by 2030 — possibly earlier — as greenhouse gas emissions continue to rise despite widely-promised climate action by the world's biggest carbon polluters.

The climate-critical 1.5 °C warming increase is expected to land a decade earlier than a prediction the IPCC made three years ago under all emissions scenarios.

The IPCC's sixth assessment report (IPCC6AR) is the latest in a series of reports that assess the science of climate change, its impacts and risks.

The 3,949-page report is a "code red for humanity," said Antonio Guterres, secretary-general of the United Nations, in remarks appended to the release. "This report must sound a death knell for coal and fossil fuels before they destroy our planet."



Five global warming scenarios from IPCC that depend on greenhouse gas concentrations in the atmosphere Image: IPCC

Professor Benjamin Horton, a principal investigator at the Earth Observatory of Singapore at Nanyang Technological University and one of the report's review editors, said that the findings are "unambiguous" on the dangers of global heating beyond 1.5°C, which he said will have "progressively serious, centuries' long and, in some cases, irreversible consequences."

The report predicts particularly stark consequences for Southeast Asia, one of the planet's most vulnerable regions to climate change. The archipelagic regional bloc will be hit by rising sea levels, heat waves, drought, and more intense and frequent bouts of rain. Known as "rain bombs", heavy rain events will intensify by seven per cent for each degree of global warming.

Although Southeast Asia is projected to warm slightly less than the global average, sea levels are rising faster than elsewhere, and shorelines are retreating in coastal areas where 450 million people live. Rising waters are projected to cost Asia's major cities billions in damage this decade, according to a recent study, and the impact is amplified by tectonic shifts and the effects of groundwater withdrawal, Horton told Eco-Business.

Nineteen of the 25 cities most exposed to a one-metre sea-level rise are in Asia, seven in the Philippines alone. But sea levels could rise by much more — up to 15 metres by some estimates — if the polar ice sheets melt, a catastrophic climatic phenomenon known as a tipping point, which will set off a domino effect of other climate events.

"The threat of climate change is increasing, and it is increasing rapidly," said Horton. "With many low-lying coastal cities exposed to sea-level rise and tropical cyclone risk, dramatic increases in heat and humidity expected across the region, and extreme precipitation forecast in some areas, but drought anticipated in others, Southeast Asian societies and economies will be increasingly vulnerable without adaptation and mitigation."

Southeast Asia's weak climate defence

IPCC's report found that human activity was "unequivocally" to blame for increasingly harsh climate events such as heatwaves, floods and droughts, and achieving net-zero greenhouse gas emissions by 2050, as outlined in the Paris Agreement, was necessary to limit warming to 1.5°C.

Though Southeast Asian nations are projected to suffer among the harshest effects of climate change, most of the region's countries' do not have carbon reduction strategies in place that will effectively mitigate the severity of the climate risks outlined by IPCC's report.

Southeast Asia's largest economy, Indonesia, plans to achieve net-zero by 2060, and though the country' energy minister recently said it could easily hit this target, the country is still 60 per cent powered by coal, the single biggest driver of manmade emissions. Malaysia has said it will cut emissions intensity by 45 per cent by 2030, but also plans to ramp up its use of coal power.

Singapore, which has warmed 80 per cent faster than the rest of the region over the past 70 years, has said it will achieve net-zero emissions some time in the next half of the century, "as soon as it is viable". Thailand, Vietnam and the Philippines plan to set net-zero emissions targets ahead of COP26, a landmark climate change conference in November spearheaded by the United Nations.

To meet more ambitious climate targets, Southeast Asia's developing nations are partly banking on climate finance to help them tackle a problem caused mainly by industrialised countries. In 2009, rich countries promised US$100 billion a year in funding by 2020 to help climate-vulnerable poorer nations tackle climate change, but a recent study shows that the pledged finance has not materialised.

"After years of limited action, many countries, pushed by a concerned public and corporations, seem willing to curb their carbon emissions. We are hopelessly unprepared to deal with increasingly severe extreme weather events, even though these have been predicted by the IPCC for decades," Horton said.

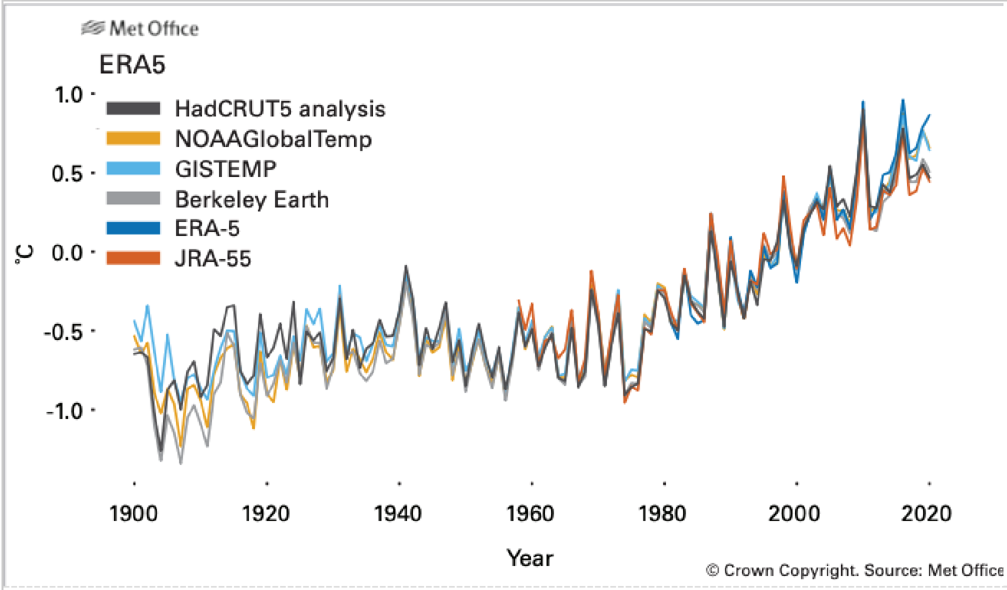
Dr Stephen Cornelius, chief adviser on climate change and World Wide Fund for Nature's (WWF) lead on the IPCC, commented that "every fraction of a degree of warming matters to limit the dangers of climate change."

"It is clear that keeping global warming to 1.5°C is hugely challenging and can only be done if urgent action is taken globally to reduce greenhouse gas emissions and protect and restore nature," he said.

Climate change triggers mounting food insecurity, poverty, and displacement in Africa

Melting of iconic African glaciers symbolizes changes to Earth system

Geneva, 19 October 2021 (WMO) - Changing precipitation patterns, rising temperatures and more extreme weather contributed to mounting food insecurity, poverty and displacement in Africa in 2020, compounding the socio-economic and health crisis triggered by the COVID-19 pandemic, according to a new multi-agency report coordinated by the World Meteorological Organization (WMO).



Area average land air temperature anomalies in °C relative to the 1981–2010 longterm average for Africa (WMO Regional Association I) based on six temperature data sets. Source: Met Office, United Kingdom

The State of the Climate in Africa 2020 report provides a snapshot of climate change trends and impacts, including sea level rise and the melting of the continent's iconic glaciers. It highlights Africa's disproportionate vulnerability and shows how the potential benefits of investments in climate adaptation, weather and climate services and early warning systems far outweigh the costs.

"During 2020, the climate indicators in Africa were characterized by continued warming temperatures, accelerating sea-level rise, extreme weather and climate events, such as floods, landslides and droughts, and associated devastating impacts. The rapid shrinking of the last remaining glaciers in eastern Africa, which are expected to melt entirely in the near future, signals the threat of imminent and irreversible change to the Earth system, " said WMO Secretary-General Prof. Petteri Taalas in a foreword.

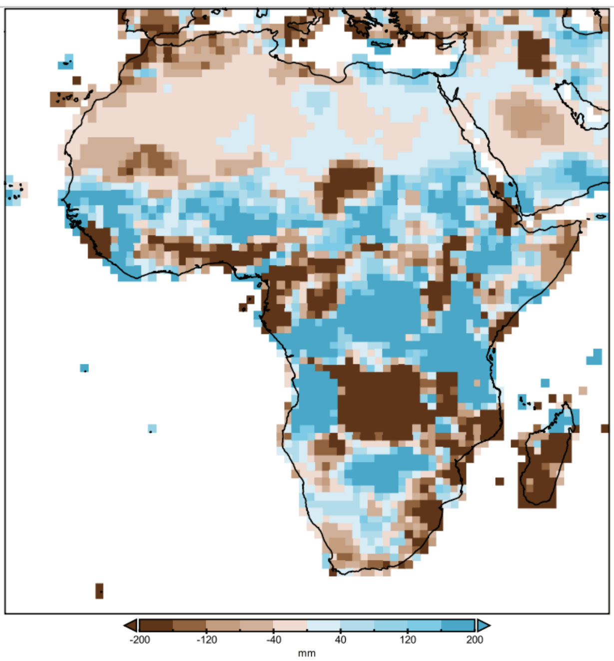
"Along with COVID-19 recovery, enhancing climate resilience is an urgent and continuing need. Investments are particularly needed in capacity development and technology transfer, as well as in enhancing countries' early warning systems, including weather, water and climate observing systems, " said Prof Taalas.

The report is a collaborative product of WMO, the African Union Commission, the Economic Commission for Africa (ECA) through the Africa Climate Policy Centre (ACPC), international and regional scientific organizations and United Nations agencies. It is accompanied by a story map which highlights the key messages.

It is being released on 19 October during the Extraordinary World Meteorological Congress and ahead of the UN Climate Change negotiations, COP26. It adds to the scientific evidence about the urgency to cut global greenhouse gas emissions, step up the level of climate ambition and increase financing for adaptation.

«Africa is witnessing increased weather and climate variability, which leads to disasters and disruption of economic, ecological and social systems. By 2030, it is estimated that up to 118 million extremely poor people (i.e. living on less than US$ 1.90/day) will be exposed to drought, floods and extreme heat in Africa, if adequate response measures are not put in place. This will place additional burdens on poverty alleviation efforts and significantly hamper growth in prosperity, » said H.E. Josefa Leonel Correia Sacko Commissioner for Rural Economy and Agriculture African Union Commission.

« In sub-Saharan Africa, climate change could further lower gross domestic product (GDP) by up to 3% by 2050. This presents a serious challenge for climate adaptation and resilience actions because not only are physical conditions getting worse, but also the number of people being affected is increasing, » she said in the foreword.



Absolute precipitation anomalies for 2020 in relation to the 1981–2010 reference period. Blue areas indicate above average precipitation while brown areas indicate below-average precipitation. Source: Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst, Germany

Key messages

Temperatures: The 30-year warming trend for 1991–2020 was higher than for the 1961–1990 period in all African subregions and significantly higher than the trend for 1931–1960. Africa has warmed faster than the global average temperature over land and ocean combined. 2020 ranked between the third and eighth warmest year on record for Africa, depending on the dataset used.

Sea level rise: The rates of sea-level rise along the tropical and South Atlantic coasts and Indian Ocean coast are higher than the global mean rate, at approximately 3.6 mm/yr and 4.1 mm/yr, respectively. Sea levels along the Mediterranean coasts are rising at a rate that is approximately 2.9 mm/yr lower than the global mean.

Glaciers: Presently, only three mountains in Africa are covered by glaciers – the Mount Kenya massif (Kenya), the Rwenzori Mountains (Uganda) and Mount Kilimanjaro (United Republic of Tanzania). Although these glaciers are too small to act as significant water reservoirs, they are of eminent touristic and scientific importance. Their current retreat rates are higher than the global average. If this continues, it will lead to total deglaciation by the 2040s. Mount Kenya is expected to be deglaciated a decade sooner, which will make it one of the first entire mountain ranges to lose glaciers due to human-induced climate change.

Precipitation: Higher-than-normal precipitation – accompanied by flooding - predominated in the Sahel, the Rift Valley, the central Nile catchment and north-eastern Africa, the Kalahari basin and the lower course of the Congo River.

Dry conditions prevailed in the northern coast of the Gulf of Guinea and in north-western Africa and along the south-eastern part of the continent. The drought in Madagascar triggered a humanitarian crisis.

High impact events: There was extensive flooding across many parts of East Africa. Countries reporting loss of life or significant displacement of populations included the Sudan, South Sudan, Ethiopia, Somalia, Kenya, Uganda, Chad, Nigeria (which also experienced drought in the southern part), Niger, Benin, Togo, Senegal, Côte d'Ivoire, Cameroon and Burkina Faso. Many lakes and rivers reached record high levels, including Lake Victoria (in May) and the Niger River at Niamey and the Blue Nile at Khartoum (in September).

Food insecurity: The compounded effects of protracted conflicts, political instability, climate variability, pest outbreaks and economic crises, exacerbated by the impacts of the coronavirus disease (COVID-19) pandemic, were the key drivers of a significant increase in food insecurity. A desert locust invasion of historic proportions, which began in 2019, continued to have a major impact in East and the Horn of Africa in 2020.

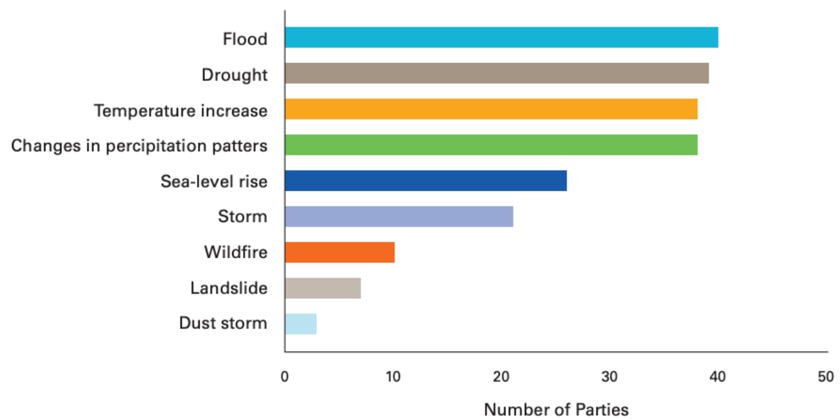
Food insecurity increases by 5–20 percentage points with each flood or drought in sub-Saharan Africa. Associated deterioration in health and in children's school attendance can worsen longer-term income and gender inequalities. In 2020, there was an almost 40% increase in population affected by food insecurity compared with the previous year.

Displacement: An estimated 12% of all new population displacements worldwide occurred in the East and Horn of Africa region, with over 1.2 million new disaster-related displacements and almost 500 000 new conflict-related displacements. Floods and storms contributed the most to internal disaster-related displacement, followed by droughts.

Investments: In sub-Saharan Africa, adaptation costs are estimated at US$ 30–50 billion (2–3% of regional gross domestic product (GDP)) each year over the next decade, to avoid even higher costs of additional disaster relief. Climate-resilient development in Africa requires investments in hydrometeorological infrastructure and early warning systems to prepare for escalating high-impact hazardous events.

Early warnings: Household surveys by the International Monetary Fund (IMF) in Ethiopia, Malawi, Mali, the Niger and the United Republic of Tanzania found, among other factors, that broadening access to early warning systems and to information on food prices and weather (even with simple text or voice messages to inform farmers on when to plant, irrigate or fertilize, enabling climate-smart agriculture) has the potential to reduce the chance of food insecurity by 30 percentage points.

Adaptation: Rapid implementation of African adaptation strategies will spur economic development and generate more jobs in support of economic recovery from the COVID-19 pandemic. Pursuing the common priorities identified by the African Union Green Recovery Action Plan would facilitate the achievement of the continent's sustainable and green recovery from the pandemic while also enabling effective climate action.



Hazards of greatest concern for the African Region. Source: WMO analysis of the nationally determined contributions (NDCs) of 53 countries in Africa

Key Topic 4: Policies and Programs for Adapting to a Changing Climate

12. Explain how various levels of government, non-governmental organizations, and individuals are involved in mitigating and adapting to climate change at the local, national, and international levels.
13. Describe innovative technologies and programs designed to combat climate change.
14. Explain the importance of primary resource sectors (forestry, agriculture, fisheries) to the economy of New Brunswick.
15. Describe the unique challenges faced by regions largely dependent on primary resources, and how climate change influences these challenges
16. Explain how to best apply climate change risk assessment and adaptation measures in regions with primary resource dependent economies.

Study Resources

Resource Title	Source	Located on
VIDEO: UN Sustainable Development Goals – Overview – CLICK LINK	*United Nations, 2018*	Page 112; 2 Minutes
Federal Adaptation Policy Framework for Climate Change	*Government of Canada, 2016*	Pages 113-118
Memorandum of Cooperation between the Government of Canada and the Government of the State of California of the United States of America concerning Climate Action and Nature Protection	*Government of Canada, 2022*	Pages 119-123
How Can Technology Help Combat Climate Change	*World Economic Forum, 2022*	Pages 124-127
Carbon Sequestration	*University of California – Davis, 2021*	Pages 128-132
A Profile of the Natural Resource Sector in New Brunswick	*NBJobs.ca, 2021*	Pages 133-141
Atlantic Provinces, Regional Perspectives Report	*Government of Canada, 2022*	Pages 142-150
Perspectives on Canada's East Coast region; in Canada's Marine Coasts in a Changing Climate	*Savard, J.-P., van Proosdij, D. and O'Carroll, S.; (ed.) D.S. Lemmen, F.J. Warren, T.S. James and C.S.L. Mercer Clarke; Government of Canada, Ottawa, ON; 2016*	Pages 151-189

Climate Change: Impacts on Forests	*Government of Canada, Natural Resources Canada (NRCan), 2020*	Pages 190-192
Canada's Partnership with Indigenous Peoples on Climate	*Environment and Climate Change Canada, 2022*	Pages 193-195
Renewable Energy Brings About Improvement In People's Livelihoods and Helps Fight Climate Change	*International Model Forest Network (IMFN), 2019*	Pages 196-198

Please Note: Hyperlinks found in text are not considered required reading; however, included video links are required to watch.

Study Resources begin on the next page

[UN Sustainable Development Goals - Overview (https://youtu.be/M-iJM02m_Hg)](https://youtu.be/M-iJM02m_Hg)

Federal Adaptation Policy Framework for Climate Change

The Federal Adaptation Policy Framework guides domestic action by the Government of Canada to address adaptation to the impacts of climate variability and change. It sets out a vision of adaptation in Canada, objectives, roles of the federal government, and provides criteria for setting priorities for action. While adapting to climate change requires a long-term vision, this framework is aimed at targeting medium-term strategies.

Climate change impacts are already being observed across a wide range of federal services, programs, policies, and regulations and all must adapt. Implementation of this framework is intended to result in adaptation considerations being proactively and explicitly included in federal processes, in order that adaptation planning, and programming occurs as part of ongoing federal activities. The framework will support decision making in federal organizations' planning of adaptation elements in their programming and in central agencies reviewing of programs with adaptation elements. It calls for consideration of climate change impacts, without prescribing how or when to adapt.

This domestic framework will also serve as input to the development of Canada's international policy on climate change adaptation.

Context

The Earth's climate is already changing, and it will continue to change in the medium-term, regardless of the effectiveness of global measures to reduce greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) agrees that the rate of change will exceed that to which humans or ecosystems can easily adjust without explicit planning and action by decision-makers.

The impacts of a changing climate are evident in every region and sector across Canada. Higher temperatures, declining sea and lake ice, diminishing glaciers, melting permafrost, more heat waves, more violent storms, and increased coastal erosion are some of the changes being observed. The North is particularly vulnerable to the impacts of climate change, as they are experiencing changes that are more extreme and occurring at a faster rate than the rest of Canada. The impacts of many recent severe weather events demonstrate that Canadian communities, critical infrastructure and human health are vulnerable to climate change. Some of the most widespread impacts in Canada are related to waterways and water resources, which affect agriculture, fisheries, energy production, transportation systems, municipalities, and recreation. Climate change impacts are not only physical; they can have long-lasting economic, social, environmental, and human health effects. While there will be negative impacts as a result of climate change, Canada will also experience benefits such as longer agricultural and ice-free shipping seasons and expanded tourism and recreation opportunities.

Canadians need to adapt to the changing climate by taking action to reduce negative consequences and to take advantage of new opportunities that the changes may bring. Climate-sensitive decisions can no longer be based solely on historical climate data.

According to the IPCC, adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects that moderates harm or exploits beneficial opportunities. Adaptation requires making decisions in the face of the uncertainty inherent in the prediction of future climate change and variability, in the cumulative impact of climate impacts, and of future socio-economic challenges and opportunities. Adaptation involves reducing vulnerability and strengthening resilience to climate change and variability. Adaptation is best guided by incorporating new scientific information (e.g., future climate models and scenarios) into existing risk management processes.

Vision statement

Recognizing the need to adapt to climate change, the wide variation in climate impacts across Canada, and the many groups that are involved in adaptation, the Government of Canada adopts the following vision:

> Canada is resilient to a changing climate by successfully adapting to the challenges and opportunities, and ensuring the health, safety, and security of Canadians and Canada's environmental, social, and economic wealth in a long term and sustainable manner.

Objectives

The following are the objectives of the Federal Adaptation Policy Framework:

1. Canadians understand the relevance of climate change and associated impacts on their quality of life.
2. Canadians have the necessary tools to adapt to climate change effectively.
3. The federal government, as an institution, is resilient to a changing climate.

The federal role

Given the broad health, environmental, social, and economic impacts of climate change, the federal government must take action to ensure that it effectively integrates climate change considerations into its own programs, policies, and operations and facilitates action by others. These roles are accomplished by:

1. Generating and sharing knowledge

The Government of Canada plays a crucial ongoing role in the generation and provision of scientific information to support evidence-based decision making related to climate change impacts and adaptation. In some cases, the federal government hosts knowledge and expertise not found elsewhere in Canada. This includes a range of activities, such as periodic national assessments of climate change, development of innovative new technologies and practices, ongoing environmental monitoring, research in specific areas (e.g., climate change projections, climate change effects on forests, and transportation infrastructure), and support for and engagement with stakeholders in the development of tools for adaptation. This role capitalizes on federal strengths in science and technology that are not replicated outside the Government. It is also essential to the understanding of critical issues and the ability of stakeholders to develop and apply effective responses.

The Government of Canada is well positioned to mobilize economies of scale to generate and deliver fundamental knowledge and information that can be applied across the country. Sharing information, both within the federal government, the international community, and with other external stakeholders (e.g., academia) will increase awareness of climate change impacts, assist with capacity building, and reduce adaptation costs in all regions and sectors. By participating in the generation of new information and tools, the federal government will ensure that this is made public.

Knowledge of climate variability, change, impacts, and adaptation options is a fundamental input to both internal and external adaptation. Further research and modeling to address knowledge gaps, such as socioeconomic considerations and refining information at local scales, will lead to better and more targeted adaptation. Although our climate variability and change knowledge is incomplete, there is now enough information to implement adaptation measures.

2. Building adaptive capacity to respond and helping Canadians take action

The federal government plays a key role in helping to build the capacity of the private sector, other levels of government, communities, and organizations to assess and manage the risks and complexities of a changing climate and to take effective and sustainable action. These efforts should continue. The federal government is particularly well-positioned to support the development and dissemination of climate change information, guidance, and tools that help Canadians to adapt.

The federal government's ability to facilitate collaboration amongst many different stakeholders can be leveraged to build broad-based awareness and understanding of climate change in order to motivate and promote action at all levels across the country. For example, the government could engage stakeholders and facilitate expert discussions on assessing the need for adaptation and ways to adapt within their domains and providing decision-making tools that others can use [1]. Further, collaborative action across governments, economic sectors, communities, and disciplines can increase the effectiveness and efficiency of adaptation measures.

3. Integrating adaptation into federal policy and planning (mainstreaming)

Managing the potential impacts of climate change is also part of an organization's risk management considerations. According to the Treasury Board of Canada Secretariat's

Framework for the Management of Risk, “Effective risk management equips federal government organizations to respond actively to change and uncertainty by using risk-based information to enable more effective decision-making.” While there are some anticipated benefits, impacts from climate changes are projected to be mostly negative and could affect all aspects of Canadian society. As such, it is the responsibility of each federal organization to apply its experience in risk management to the climate change issues that could affect its continued ability to deliver on its mandate. In this way, federal organizations can build the capacity to proactively manage uncertainty that stems from climate change and make informed decisions about how best to minimize negative impacts and maximize opportunities.

As Canada’s largest organization, with operations in all regions of the country, an effective way for the federal government to advance adaptation efforts across Canada is to lead by example, specifically by building resilience into federal assets, programs and services against the impacts of climate variability and change. This means ensuring that climate change considerations are integrated into federal activities, such as policy and planning processes. Factoring climate variability and change into policy, programs, and operations is one of the most important ways the government can contribute to adaptation and is consistent with the government’s risk management approach of enhancing the protection of public assets and resources and strengthening planning and decision making. Experts agree that integrating climate variability and change information into policy, planning, and decision-making is more effective and more cost-efficient than addressing adaptation in isolation.

Via integrating adaptation into federal policy, planning, and operations adaptation planning and decision-making will become part of ongoing management processes, rather than an independent policy or program domain, and will be accomplished within existing government structures. By integrating adaptation, the government itself adapts, and in so doing can mobilize its authorities, investments, and economic instruments in support of adaptation actions across the country. Integration will require building internal capacity, disseminating information, and developing new knowledge.

Criteria for identifying federal priorities

In carrying out the federal role, it is recommended that federal departments and agencies give consideration to the following criteria when identifying climate change adaptation priorities:

1. Nature of impacts and vulnerability

Adaptation should be a priority where negative impacts are most severe or beneficial impacts are of the greatest potential. Severe impacts can occur in a number of ways, such as via a large impact on a small group (e.g., northern communities), or a small impact on a large group.

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity [2]. The nature of the resulting profile of potential vulnerabilities is an important input to adaptation decision-making. There may be thresholds where risks from impacts change, irreversible losses occur, or where impacts cease to be beneficial.

2. Appropriateness of federal action

Several criteria are useful for guiding priority setting and decision making for determining when and where it is appropriate for the federal government to act. These criteria should be considered in the order they are presented.

I. Unique federal role and responsibility

The nature of federal responsibility is a factor in setting priorities. Greater attention should be accorded to areas of sole federal responsibility (e.g., First Nations and Inuit, oceans, inter-provincial, and international matters), where the federal government has fiduciary or other direct responsibilities, is better positioned to act than other groups (e.g., gathering and disseminating climate change adaptation information, guidance, and tools), or has legislative authority (e.g., mainstreaming adaptation into federal policy and planning).

II. Unique federal capabilities

Greater consideration should be accorded to areas in which the federal government has the levers, assets, and capabilities that others do not have to generate knowledge, products, and services (e.g., decision-making tools, future climate data) necessary for adaptation in Canada.

For example, at present, the federal government operates some unique climate, oceans and freshwater monitoring networks and has expertise unparalleled in Canada in climate modeling. The resulting environmental data are key inputs to adaptation planning in organizations across Canada.

III. Timeliness of action

It is important to take cost-effective action in situations where inaction would result in increased negative impacts, including associated costs or forgone opportunities. Implementing adaptation should be a priority when existing provisions lock-in conditions inadequate for predicted future changes in climate. For example, costs associated with future climate related failures in infrastructure could potentially be avoided by changing current infrastructure design protocols to become more resilient to predicted future changes in climate.

IV. Effectiveness of action

Federal action on adaptation should be directed towards areas where intervention is effective and efficient. Indicators of effectiveness and cost efficiency are collaboration, which leverages federal investment, and broadly applicable products, services, policies, or actions.

3. Mainstreaming ability

Climate change adaptation must become the new business-as-usual for individuals and organizations across Canada. Knowledge and tools must support independent action and the integration of adaptation into existing objectives, strategies, policies and processes at all levels and stages. Policies and programs will need to be evaluated and revised as conditions change over time and new knowledge is generated.

4. Collaboration potential

The federal government should focus on priority-driven partnerships in order to integrate plans and actions among partners and support a coherent, targeted response in the key domains of health and communities, the economy, infrastructure, and natural systems.

Memorandum of Cooperation between the Government of Canada and the Government of the State of California of the United States of America concerning Climate Action and Nature Protection

The Government of Canada and the Government of the State of California, hereinafter referred to as "the Participants",

Considering that the twin challenges of climate change and biodiversity loss are a global threat to the lives and livelihoods of individuals and communities, and that there is an urgent need for collaboration on solutions to mitigate and adapt to climate change, as well as to prevent and halt biodiversity loss;

Considering that vehicles and transportation fuels are a significant source of greenhouse gas and air pollutant emissions in both Canada and California and, that cutting transportation emissions is one of the most readily achievable and economically beneficial ways to mitigate climate change, while building cleaner and more resilient communities and economies;

Considering that the Department of the Environment of Canada (Environment and Climate Change Canada - ECCC) and the California Air Resources Board have an existing Memorandum of Understanding to promote and carry out cooperative activities on policy and regulatory measures that reduce emissions of greenhouse gases and air pollutants including from: vehicles, engines and fuels;

Considering that there are further opportunities to collaborate and share information on light-, medium-, and heavy-duty vehicles, off-road equipment, clean and renewable fuel standards and charging infrastructure;

Considering that the development, adoption and scale up of clean technologies such as hydrogen, carbon capture, utilization and storage, clean energy, among others, is critical to meet their emission reduction goals;

Considering that Canada and California are implementing a range of complementary voluntary and regulatory actions spanning the plastics lifecycle in order to address the threats of plastic waste and pollution, including microplastics, on the health of the environment and ecosystems, including wildlife, rivers, lakes and oceans, and to accelerate the adoption of innovative technologies and advance the transition towards a circular economy for plastics that will reduce pollution and have positive economic impacts;

Considering that both Canada and California are experiencing more frequent extreme weather events, such as wildfires, stronger storms and droughts, eroding coastlines and floods, as well as experiencing increasing social and economic losses from current and future impacts of climate change and that urgent action is needed to adapt and build resilience, including through the use of nature-based solutions;

Considering that Canada is developing a National Adaptation Strategy and California has recently updated its Climate Adaptation Strategy;

Considering that both Canada and California are working to accelerate action on biodiversity conservation in the face of the climate crisis, in particular through Canada's commitment to conserve 30 percent of its lands and waters by 2030 and California's similar commitment to conserve 30 percent of its lands and coastal waters by 2030;

Considering that Indigenous knowledge, including customary practices and cultural values, is essential in the fight against climate change, land degradation and biodiversity loss and that both Canada and California have committed to engaging Indigenous peoples;

Considering that further collaboration between the Government of Canada and the Government of California would help them to achieve their climate change mitigation, adaptation and biodiversity objectives;

Have reached the following understanding:

1. **Objective**
    a. The objective of this Memorandum of Cooperation (MOC) is to establish a flexible framework for the Participants to promote and carry out cooperative activities in order to advance their respective policies and regulatory measures aimed at reducing pollution, adapting to climate change and conserving nature according to the Participants' respective competencies and based on principles of equality, reciprocity, information exchange and mutual benefit. In doing so, the Participants share the following common objectives:
        i. Facilitate collaboration on their zero emission transport goals, including light-duty vehicle ZEV sales and emission reduction targets, related incentive programs, and efforts to reduce the carbon intensity of fuels and to reduce and eliminate emissions from medium- and heavy-duty vehicles and off-road engines;
        ii. Promote the use of clean technologies to meet their emission reduction and Canada's net zero goals, California's carbon neutrality and to build resilience;
        iii. Share information, lessons learned and best practices on climate adaptation, nature-based solutions, circular economy and plastics to support their respective policy and regulatory development.
2. **Areas of cooperation**
    a. The Participants intend to advance their respective policies and regulatory measures aimed at preventing pollution, adapting to climate change and conserving nature through initiatives focused particularly on the following areas of cooperation:
        i. Clean Transportation;

ii. Clean Technology and Innovation;
iii. Biodiversity Conservation;
iv. Climate Change Adaptation;
v. Circular Economy, including Plastics Management;
vi. Any other areas of cooperation they may jointly decide upon.

3. **Cooperative activities**

a. The Participants may carry out the following cooperative activities:

i. Collaboration and sharing of technical information and/or best practices on regulatory development and administration, research, and policy and program development related to their respective regulations for greenhouse gas and other emissions and ZEV targets for light-, medium-, and heavy-duty vehicles and off-road equipment, as well as incentive programs, and low-carbon fuels among others;

ii. Collaboration and sharing of information and/or best practices related to advancing innovation, investment, adoption and scale up of clean technologies, including measures that drive emissions reductions by 2030 and net zero emissions by mid-century, as well as exploring collaboration opportunities with academia and private sector and to exchange information on strategies with respect to emerging clean technologies;

iii. Sharing of information and best practices on biodiversity conservation in the face of the climate crisis, such as: understanding the impact of climate change and other stressors on biodiversity; protecting areas that are important for biodiversity, including climate refugia; accelerating biodiversity conservation efforts; conserving 30% of lands and waters by 2030; developing robust monitoring and evaluation programs to track progress toward biodiversity conservation goals; and meaningfully engaging stakeholders and indigenous peoples in biodiversity conservation (including approaches for considering and co-applying Indigenous Knowledge where made available by and with consent of knowledge holders);

iv. Sharing of information and best practices to advance climate adaptation and build resilience to the impacts of climate change such as rising sea levels, flooding, extreme heat, wildfires and droughts, including, for example, knowledge exchange on nature-based solutions and their potential benefits such as public health and safety, economic prosperity, food and water security, and carbon sequestration;

v. Sharing of information and best practices on circular economy initiatives, approaches and methods beyond traditional recycling;

vi. Collaboration and seeking areas of harmonization in policies and regulations related to circular economy as well as reducing plastic waste and pollution, where appropriate, to prevent plastic pollution including from microplastics and commonly littered single-use plastics; address misinformation regarding the recyclability and compostability of plastics; advance plastic pollution science and performance measures or indicators; strengthen demand for recycled plastics; and share information and best practices on research and policy measures such as the implementation of strategies and action plans.

4. **Implementing authorities**
The Participants respectively designate ECCC and the California Environmental Protection Agency to establish a work plan to implement the objectives of this MOC and commit to report back on progress annually.
5. **Points of contact**
    a. The Participants designate the following as their point of contact for communication and information exchange, as well as any notice required to be submitted under this MOC:
        i. For ECCC:
        Jeanne-Marie Huddleston,
        Director General,
        Bilateral Affairs and Trade Directorate,
        International Affairs Branch
        ii. For the California Environmental Protection Agency:
        Shereen D'Souza,
        Deputy Secretary for Climate Policy and Intergovernmental Relations
6. **Availability of personnel and resources**
    a. The Participants understand that:
        i. this MOC does not involve the exchange of funds, nor does it represent any obligation of funds by either Participant;
        ii. all costs that may arise from activities covered by, mentioned in, or pursuant to this MOC are expected to be assumed by the Participant who incurs them, unless otherwise jointly decided upon in a separate instrument;
        iii. all activities carried out pursuant to this MOC are subject to the availability of funds, personnel and other resources of each Participant.
    b. The Participants understand that their personnel is expected to work under their respective orders and any other organization or institution to which the personnel already belongs, at all times maintaining any preexisting employment relationship only with them and the organization or institution, and not with any other Participant.
7. **Respect of applicable laws**
The Participants understand that they will carry out the activities and understandings outlined in this MOC in accordance with their respective laws.
8. **Intellectual property**
If, as a result of the activities developed in accordance with this MOC, intellectual property issues arise, the Participants intend to address them in a separate and appropriate instrument.
9. **Differences in interpretation and application**
The Participants intend to resolve any difference in the interpretation or application of this MOC through consultations.
10. **Status**
This MOC is a voluntary initiative and is not legally binding. In addition, the commitments in this MOC are not conditioned upon reciprocal actions by the other Participant; each

Participant retains full discretion over implementation of its commitments in light of the Participant's individual circumstances, applicable law, and policies; and each Participant is free to withdraw from this MOC.

11. **Final dispositions**
    a. This MOC is intended to take effect on the date of its signature by the Participants and to remain valid for five years. The Participants may extend this MOC upon their mutual written consent.
    b. The Participants may modify this MOC at any time upon their mutual written consent.
    c. Either Participant may, at any time, terminate this MOC by providing a written notice to the other Participant. A Participant who intends to terminate this MOC is expected to endeavor to provide notice of such withdrawal to other Participants 30 days in advance.
    d. The Participants understand that termination of this MOC is not expected to affect the conclusion of the cooperative activities that may have been initiated during the time MOC was in effect, unless the Participants jointly decide otherwise.

Signed in duplicate at Los Angeles on this 9th day of June 2022, in the English and French languages, both versions being equally valid.

For the Government of Canada

Steven Guilbeault
Minister of Environment and Climate Change

For the Government of the State of California of the United States of America

Jared Blumenfeld
Secretary for Environmental Protection

How Can Technology Help Combat Climate Change

Jul 12, 2021

Climate Change

- **After setting climate targets, countries and companies will need to quantify, reduce and monitor their emissions.**
- **This process can be complex, time-consuming and prone to errors, especially for novices.**
- **The right technology can simplify this process and make it more efficient, transparent and effective.**
- **Here are three ways climate change technology solutions – particularly AIoT.**

As society pressures leaders for a more environmentally-friendly agenda, governments responsible for 63% of world emissions have committed to net zero with corporate net-zero commitments covering 12% of the global economy (representing $9.81 trillion in revenue).

However, it is not uncommon to see large disconnects between targets and actual emissions – when the talk and the walk must go hand-in-hand in terms of effective emission-reduction progress. In June 2021, when the G7 decided to make climate risk disclosure mandatory, seven of the most influential global economies indicated that carbon reporting and disclosures would play a vital role in ensuring that emission reduction targets are in fact met.

Setting a target is just the first step; the second is to understand and quantify the real emission baseline into measurable units. Next, a clear definition of the emissions reduction strategy must be built. Finally, near real-time monitoring of targets vs actual progress should be in place. Ultimately, if countries and companies are to achieve net zero, they need to monitor, reduce and, in some cases, offset the emissions they generate.

The journey can be complex for beginners; it can be time-consuming, very manual, and prone to errors. That should not prevent companies from joining the decarbonization wave. After all, beyond satisfying consumers and political leaderships, committing to net zero might also prove economical, as access to capital will prove increasingly difficult for those not embracing the energy transition. As 'carbon tax' or 'cap-and-trade' schemes become the most likely path forward, and as and access to capital is reduced for those who fail to embrace the energy transition, early net-zero movers will have a competitive financial edge over laggards.

Carbon-management process

Carbon management can be broken down into three main categories: emission measuring and reporting, abatement, and offsetting.

1. Measuring and reporting carbon footprint

The first step is to measure carbon emissions. The carbon reporting process involves the collection of CO_2 data, organising by emission type and geographical segment. The data is then measured against internationally recognised carbon-accounting standards such as GHG protocol or ISO 14064-1. Currently, emission data may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, mass balance, stoichiometry (the calculation of reactants and products in chemical reactions), or other methods for acquiring data from specific activities in the company's value chain. Challenges associated with measuring and reporting commonly include the laborious data collection process, difficulty reviewing carbon footprints across business units and assets, as well as validating underlying assumptions of emissions.

2. Abatement planning and management

Abatement planning involves identifying key sources of emissions and implementing measures to reduce them. By categorising emissions in step one, businesses can then pinpoint and measure which processes emit the highest volumes of CO2 and optimise their carbon-abatement plan. To achieve this, abatement roadmaps set out targets and KPIs to reduce emissions, focusing on changing emission-heavy processes and implementing new technologies to reduce emissions. Due to the multiple variables that need to be considered in such planning, the process can be uncertain and complex. Furthermore, tracking the performance and progress of abatement programmes is laborious. Organizational challenges include a lack of both transparency regarding marginal cost-benefit of abatement programmes, and resources for managing and executing this abatement journey.

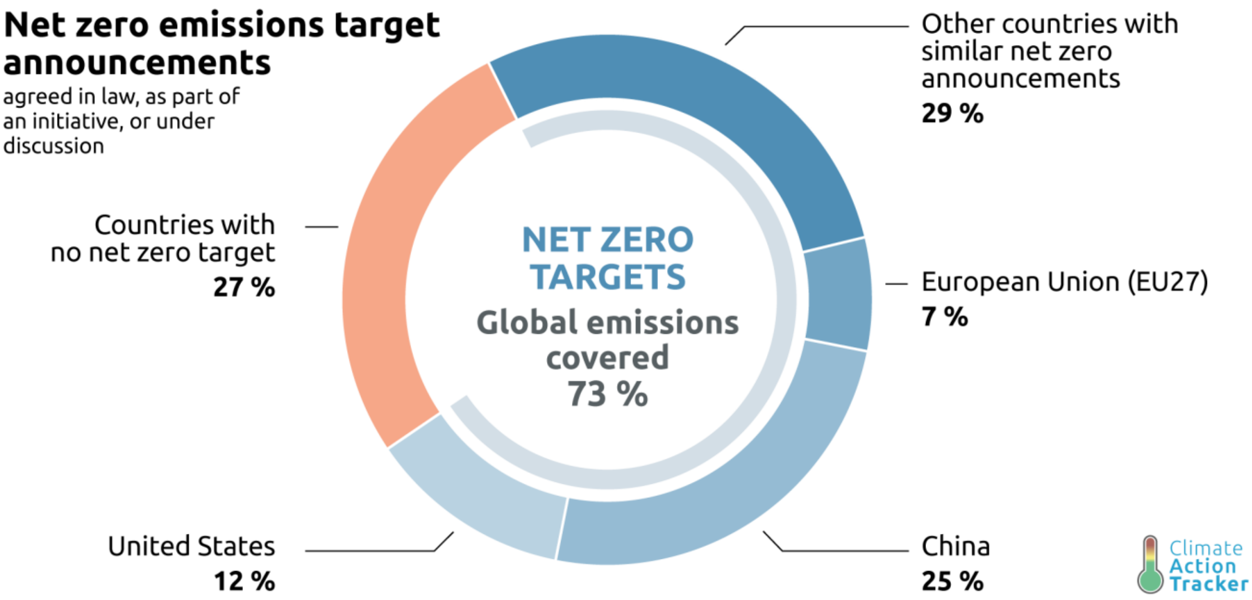


Image: Climate Action Tracker

3. Carbon offsetting

Carbon offsetting is considered the option of last resort once all abatement efforts and decarbonization investments have been exhausted. It is a way of taking responsibility for unavoidable carbon emissions by paying for others to reduce or absorb CO2. Multiple types of projects are used for carbon offsets, ranging from environmental projects such as reforestation, to carbon-capture technologies and renewable energy production. Carbon credits are measurable, verifiable emission reductions and have been used as a means for governments and companies to offset carbon emissions. Further methods include the use of RECs (renewable energy certificates) to offset energy consumed from non-renewable sources. However, offsets also come with challenges, from accurate measurement to transparency and verification to ease of trade.

How technology can fight climate change

Artificial intelligence of things (AIoT) solutions are integral to tackling some of the challenges associated with carbon management. There are three main areas of focus to make carbon management more efficient, transparent and effective.

1. AIoT – integration into measurement and reporting

With a myriad of databases and systems involved with different carbon-producing assets, the labour required to simply categorise and organise the data from multiple business units and assets is immense. AIoT integration enables seamless sourcing of real-time activity level data and asset inventory data from a variety of systems. This provides an organization with the capability to efficiently structure, collect and transform data into reports for accurate emissions-monitoring and measurement, reducing overall efforts around data collection and enhancing data quality and report resolution.

2. Abatement intelligence – predictive analytics to simulate emissions over time

Abatement planning is a challenge primarily due to the lack of accurate measures for determining the emissions derived from certain processes. AIoT technology tackles this challenge by creating insights from real-time data to better predict process emissions. By analysing and learning through data from multiple processes, AIoT can refine the performance evaluation of abatement measures and optimise emissions predictions. Beyond optimising abatement strategies, this technology also lowers the overall marginal abatement costs.

3. Carbon offsetting and offset integration

Although a last resort, the carbon offset market plays an essential role towards achieving global net-zero emissions goals for countries and organizations, with an estimated addressable market size of $200 billion by 2050. However, verification of carbon offsetting and difficulty in trading plagues the industry. Technology can support validation of RECs in near real-time and offer a marketplace for affordable and fast carbon offsetting. Offset integration would provide a global pool of offsets to an organisation, improving ease of trade and emissions planning, reducing organizational hassle, and optimising the timings of REC purchases and retirement.

Carbon management solutions are essential to meeting the G7's mandatory climate risk disclosures. More importantly, they provide the technology to actively manage and reduce carbon emissions and achieve the net-zero pledges made by governments and corporations. Driven by strong political, societal and economic agendas, carbon management solutions will be an integral part of emission reductions. For that, real-time measurement, abatement, and offset integration will help ensure companies not only talk the talk but also walk the walk and transparently meet their net-zero targets.

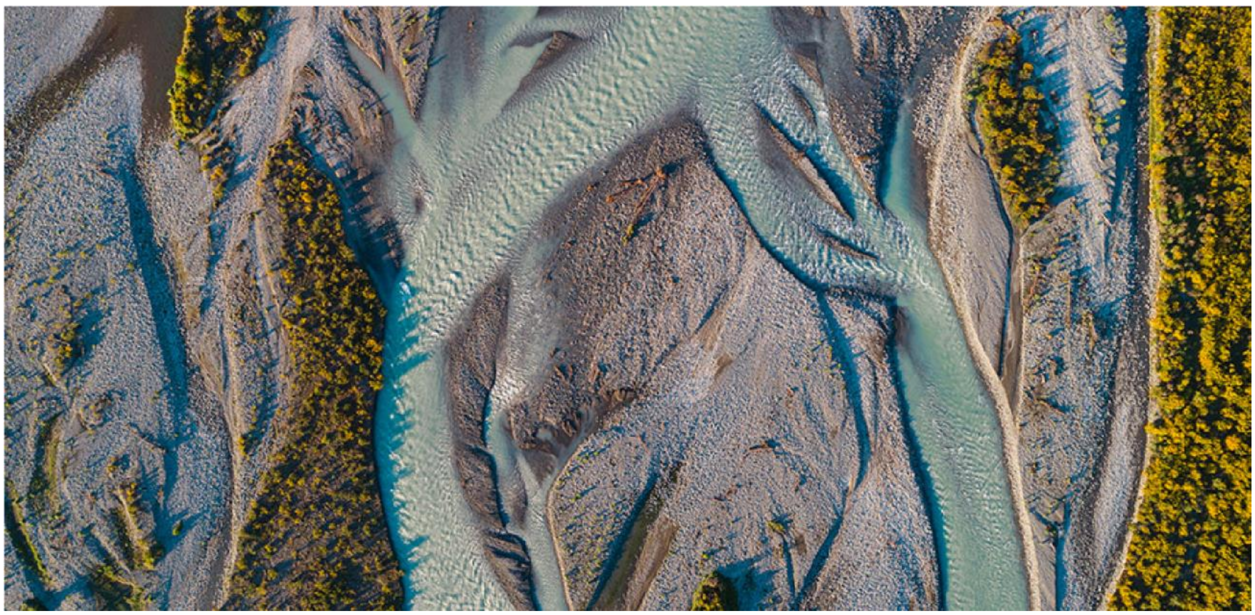
Carbon Sequestration

University of California – Davis, 2021

What is Carbon Sequestration?

Carbon sequestration secures carbon dioxide to prevent it from entering the Earth's atmosphere. The idea is to stabilize carbon in solid and dissolved forms so that it doesn't cause the atmosphere to warm. The process shows tremendous promise for reducing the human "carbon footprint." There are two main types of carbon sequestration: biological and geological.

What is Carbon?



In many ways, carbon is life. A chemical element, like hydrogen or nitrogen, carbon is a basic building block of biomolecules. It exists on Earth in solid, dissolved and gaseous forms. For example, carbon is in graphite and diamond, but can also combine with oxygen molecules to form gaseous carbon dioxide (CO2).

Carbon dioxide is a heat trapping gas produced both in nature and by human activities. Man-made carbon dioxide can come from burning coal, natural gas and oil to produce energy. Biologic carbon dioxide can come from decomposing organic matter, forest fires and other land use changes.

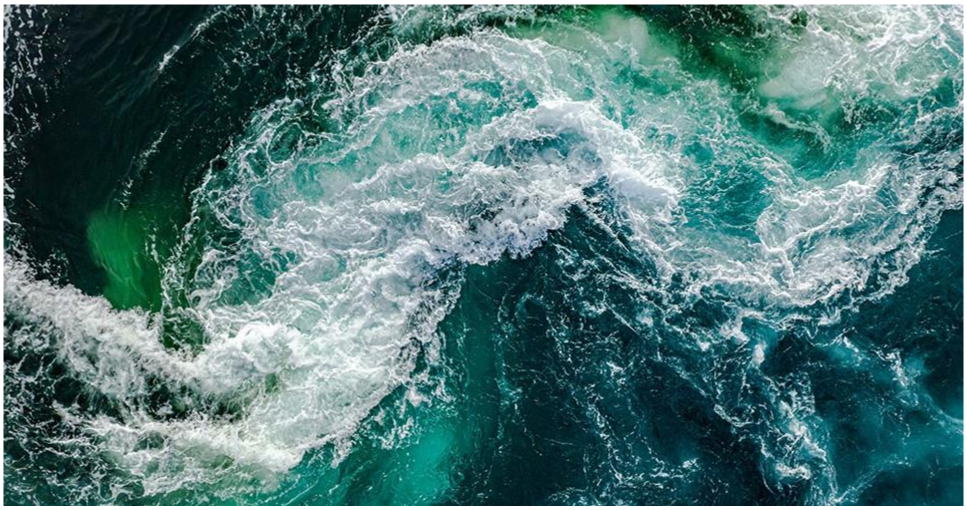
The build-up of carbon dioxide and other **'greenhouse gases' in the atmosphere can trap heat and contribute to climate change**.
Learning how to capture and store carbon dioxide is one way scientists want to defer the effects of warming in the atmosphere. This practice is now viewed by the scientific community as an essential part of **solving climate change**.

Types of Carbon Sequestration

Biological

Biological carbon sequestration is the **storage of carbon dioxide in vegetation such as grasslands or forests**, as well as in soils and oceans.

Biological Carbon Found in the Oceans

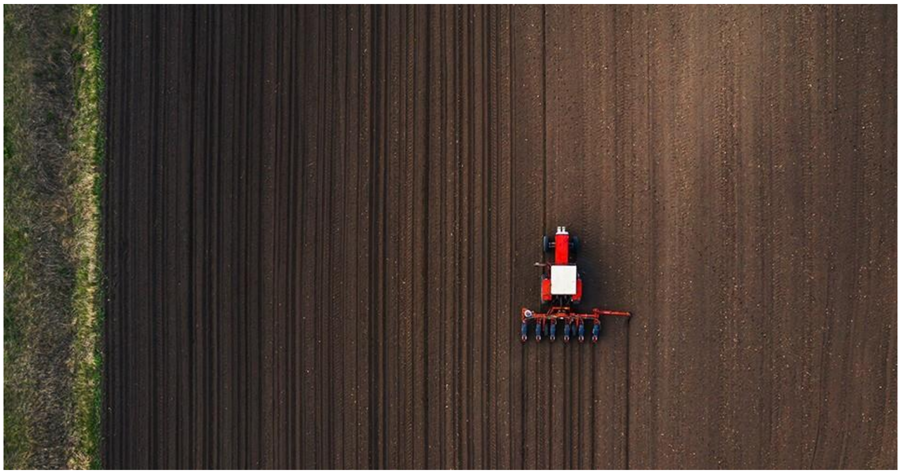


Oceans absorb roughly 25 percent of carbon dioxide emitted from human activities annually.

Carbon goes in both directions in the ocean. When carbon dioxide releases into the atmosphere from the ocean, it creates what is called a positive atmospheric flux. A negative flux refers to the ocean absorbing carbon dioxide. Think of these fluxes as an inhale and an exhale, where the net effect of these opposing directions determines the overall effect.

Colder and nutrient rich **parts of the ocean are able to absorb more carbon dioxide** than warmer parts. Therefore, the polar regions typically serve as carbon sinks. By 2100, most of the global ocean is expected to be made up of carbon dioxide, potentially altering the ocean chemistry and lowering the pH of the water, making it more acidic.

Biological Carbon Found in Soil



Carbon is sequestered in soil by plants through photosynthesis and can be stored as soil organic carbon (SOC). Agroecosystems can degrade and deplete the SOC levels but this carbon deficit opens up the opportunity to store carbon through new land management practices. Soil can also store carbon as carbonates. Such carbonates are created over thousands of years when carbon dioxide dissolves in water and percolates the soil, combining with calcium and magnesium minerals, forming "caliche" in desert and arid soil.

Carbonates are inorganic and have the ability to store carbon for more than 70,000 years, while soil organic matter typically stores carbon for several decades. Scientists are working on ways to accelerate the carbonate forming process by adding finely crushed silicates to the soil in order to store carbon for longer periods of time.

Biological Carbon Found in Forests

About 25 percent of global carbon emissions are captured by plant rich landscapes such as forests, grasslands and rangelands. When leaves and branches fall off plants or when plants die, the carbon stored either releases into the atmosphere or is transferred into the soil. Wildfires and human activities like deforestation can contribute to the diminishment of forests as a carbon sink.

Biological Carbon Found in Grasslands

While forests are commonly credited as important carbon sinks, California's majestic green giants are serving more as carbon sources due to rising temperatures and impact of drought and wildfires in recent years. Grasslands and rangelands are more reliable than forests in modern-day California mainly because they don't get hit as hard as forests by droughts and wildfires, according to research from the University of California, Davis. Unlike trees, grasslands sequester most of their carbon underground. When they burn, the carbon stays fixed in the roots and soil instead of in leaves and woody biomass. Forests have the ability to store more carbon, but in unstable conditions due to climate change, grasslands stand more resilient.

Geological

Geological carbon sequestration is the process of storing carbon dioxide in underground geologic formations, or rocks. Typically, carbon dioxide is captured from an industrial source, such as steel or cement production, or an energy-related source, such as a power plant or natural gas processing facility and injected into porous rocks for long-term storage.

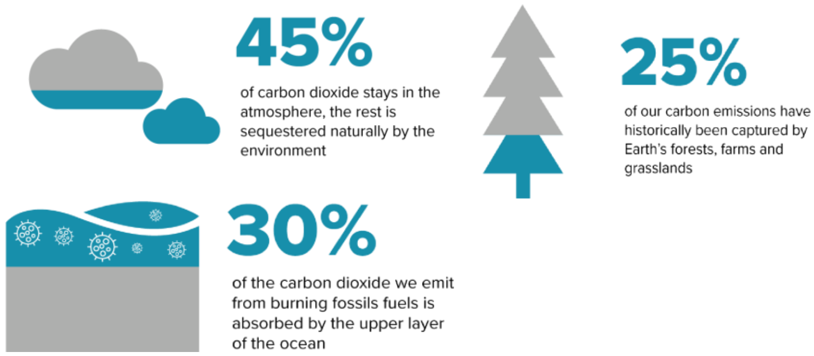
Carbon capture and storage can allow the use of fossil fuels until another energy source is introduced on a large scale.

Technological

Scientists are exploring new ways to remove and store carbon from the atmosphere using innovative technologies. Researchers are also starting to look beyond removal of carbon dioxide and are now looking at more ways it can be used as a resource.

Graphene production: The use of carbon dioxide as a raw material to produce graphene, a technological material. Graphene is used to create screens for smart phones and other tech devices. Graphene production is limited to specific industries but is an example of how carbon dioxide can be used as a resource and a solution in reducing emissions from the atmosphere.
Direct air capture (DAC): A means by which to **capture carbon directly from the air using advanced technology plants**. However, this process is energy intensive and expensive, ranging from $500-$800 per ton of carbon removed. While the techniques such as direct air capture can be effective, they are still too costly to implement on a mass scale.
Engineered molecules: Scientists are engineering molecules that can change shape by creating new kinds of compounds capable of singling out and capturing carbon dioxide from the air. The engineered molecules act as a filter, only attracting the element it was engineered to seek.

Sequestration Facts



The Future of Carbon Sequestration

Scientists are exploring **new ways to remove and store carbon** from the atmosphere using innovative technologies. Researchers are also starting to look beyond removal of carbon dioxide and are now looking at more ways it can be used as a resource.

Graphene production: The use of carbon dioxide as a raw material to produce graphene, a technological material. Graphene is used to create screens for smart phones and other tech devices. Graphene production is limited to specific industries but is an example of how carbon dioxide can be used as a resource and a solution in reducing emissions from the atmosphere.

Impacts of Carbon Sequestration

- About 25% of our carbon emissions have historically been captured by Earth's forests, farms and grasslands. Scientists and land managers are working to keep landscapes vegetated and soil hydrated for plants to grow and sequester carbon.
- As much as 30% of the carbon dioxide we emit from burning fossils fuels is absorbed by the upper layer of the ocean. But this raises the water's acidity, and ocean acidification makes it harder for marine animals to build their shells. Scientists and the fishing industry are taking proactive steps to monitor the changes from carbon sequestration and adapt fishing practices.

September 2021

NBjobs.ca

Table of Contents

Note: This profile includes data from a variety of sources that use different methodologies and are subject to periodic retroactive revisions. As a result, data from one source may not match with data from other datasets. Information about the sources and methodologies used are available upon request. In some instances source data points have been suppressed. Where this occurs, the data values presented have been inferred from non-suppressed data. Also, some totals may not equal the sum of their components due to rounding.

Sector Definition

For the purpose of this profile, the Natural Resources sector includes the following sectors:

Agriculture, Forestry, Fishing and Hunting: This sector consists of establishments that are primarily engaged in growing crops, raising animals, harvesting timber, harvesting fish and other animals from their natural habitats and providing related support activities. Establishments primarily engaged in agricultural research or that supply veterinary services are not included in this sector.

Mining, Quarrying, and Oil & Gas Extraction: This sector consists of establishments that are primarily engaged in exploration for and/or extracting naturally occurring minerals. These can be solids, such as coal and ores; liquids, such as crude petroleum; and gases, such as natural gas.

The scope of this profile includes North American Industry Classification System (NAICS 2017) sectors 11 and 21.

Legend

Natural Resources sector

New Brunswick

All sectors

Canada

Male

Female

Current Business Environment

GDP* and Productivity

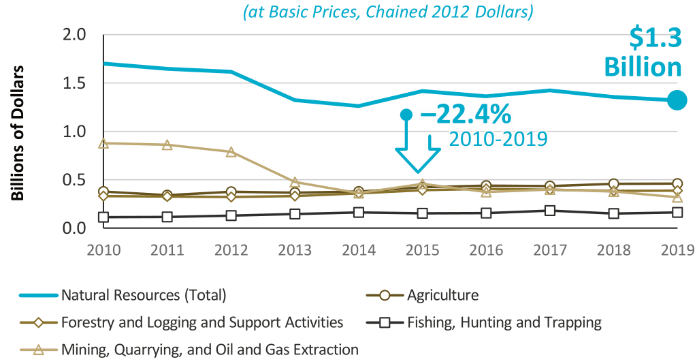
In 2019:

- The Natural Resources sector represented 4.5% of New Brunswick's (NB) GDP, contributing $1.3 billion *(chained 2012 dollars)*[1, 2]
- NB Labour Productivity[2, 3] *(a measure of productivity based on GDP per hour worked in the sector)*:
    - This sector – $49.07 output per hour of work *(chained 2012 dollars)*
    - Average of all sectors – $48.47 output per hour of work *(chained 2012 dollars)*

** Gross Domestic Product*

Proportion of GDP in NB: 2019[1]
Natural Resources Sector

Real GDP[2]
NB Natural Resources Sector
(at Basic Prices, Chained 2012 Dollars)



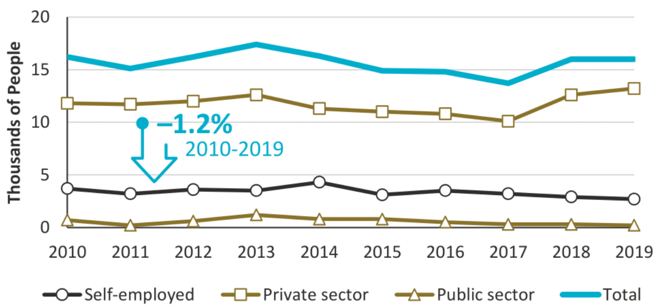
Employment in New Brunswick

In 2019:

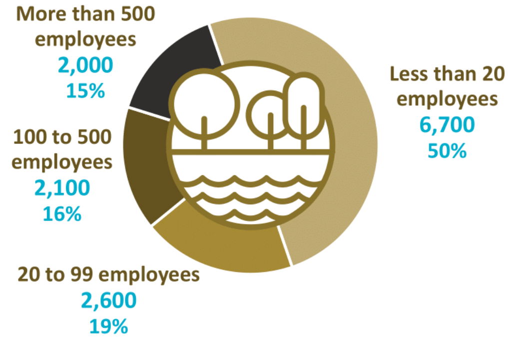
- 16,000 were employed in the NB Natural Resources sector [4]
- 4.4% of all employed in NB worked in this sector[4]
- 7.5% of employees in this NB sector were part of a union and/or covered by a collective agreement – versus 29.1% of all employees in the Province[5]

Employment: 2019[4] NB Natural Resources Sector					
Sector	Employed	% Change from 2010	Full Time	Part Time	Unemployed (Unemployment Rate)
All sectors (Total)	**361,100**	**+1.0%**	**85.0%**	**15.0%**	**31,900 (8.1%)**
Natural Resources (Total)	**16,000**	**-1.2%**	**93.8%**	**6.3%**	**3,100 (16.2%)**
Agriculture	5,800	-3.3%	86.2%	13.8%	1,100 (15.9%)
Forestry and Logging and Support Activities	3,600	-2.7%	97.2%	2.8%	500 (11.9%)
Fishing, Hunting and Trapping	2,400	+33.3%	95.8%	4.2%	900 (28.1%)
Mining, Quarrying, and Oil and Gas Extraction	4,200	-12.5%	100.0%	0.0%	600 (12.5%)

Employment: 2009-2019[6]
NB Natural Resources Sector



Employment by Size of Employer: 2019[7]
NB Natural Resources Sector



Human Resources Profile

Demographics

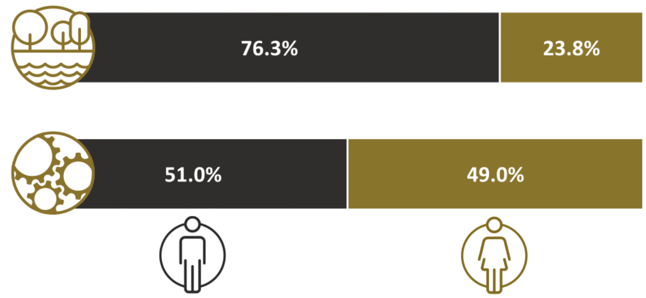
In 2019:

- 19,100 people were part of the labour force in the NB Natural Resources sector, of which 16,000 were employed[4]

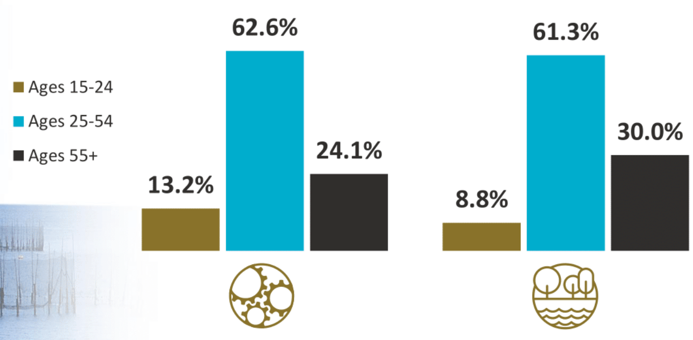
From 2010 to 2019:

- The percentage of females employed in the sector increased from 21.0% to 23.8%[4]
- The percentage of workers employed in this sector:[4]
    - Ages 15-24 decreased 1.1 percentage points
    - Ages 25-54 decreased 4.8 percentage points
    - Ages 55 and over increased 5.9 percentage points

NB Employment by Sex: 2019[4]
Natural Resources Sector vs All Sectors



NB Employment by Age: 2019[4]
Natural Resources Sector vs All Sectors



Major Occupations

In 2019:

- 33.2% of those working in the NB Natural Resources sector worked in one of the five National Occupation Code (NOC) occupations listed in the table to the right[8]
- These 4,300 employees represented 1.2% of all employed in NB[8]

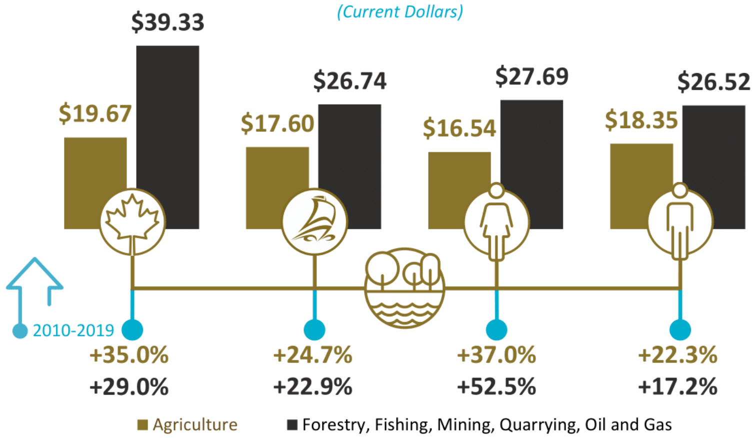
Major Occupations: 2019[8] NB Natural Resources Sector		
Occupation	Employed	NOC
General farm workers	1,500	8431
Managers in agriculture	1,200	0821
Fishermen/women	900	8262
Logging and forestry labourers	400	8616
Transport truck drivers	400	7511

Wage and Salary Information

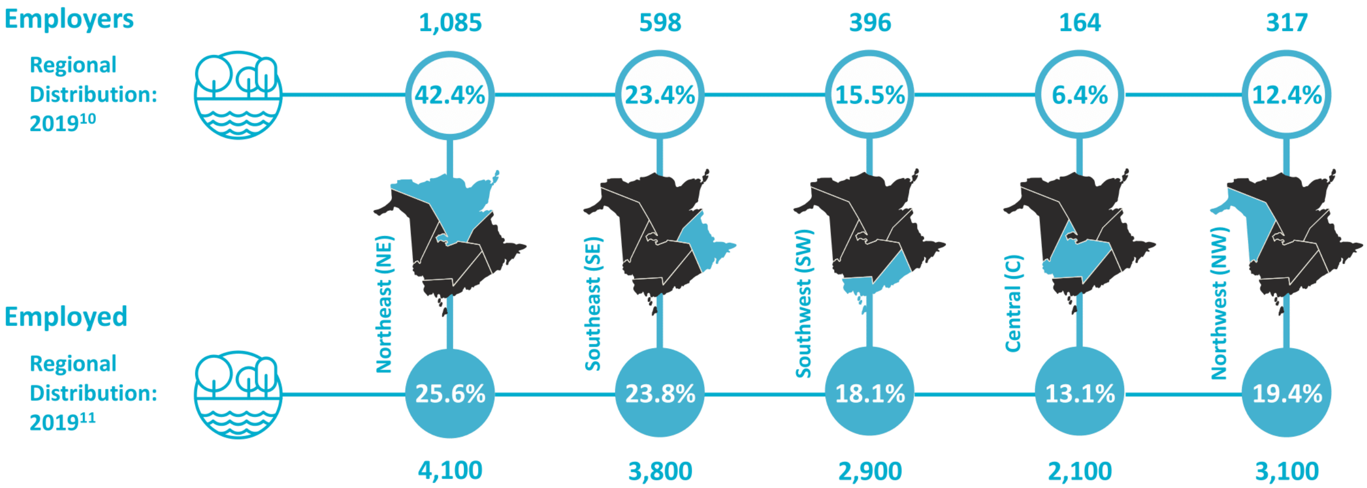
In 2019:

- The average wage in the NB Agriculture sector ($17.60) was less than than the average NB wage across all sectors ($23.49)[9]
- The average wage in the NB Forestry, Fishing, Mining, Quarrying, Oil and Gas sector ($26.74) was greater than than the average NB wage across all sectors ($23.49)[9]

Average Hour Wage: 2019[9]
Natural Resources Sector
(Current Dollars)



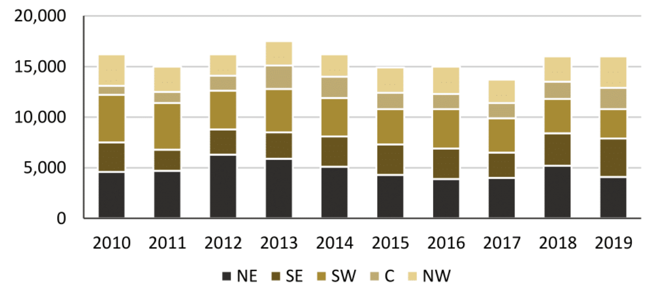
Regional Highlights



Number of Regional Employers by Employment Size: 2019[10]
NB Natural Resources Sector

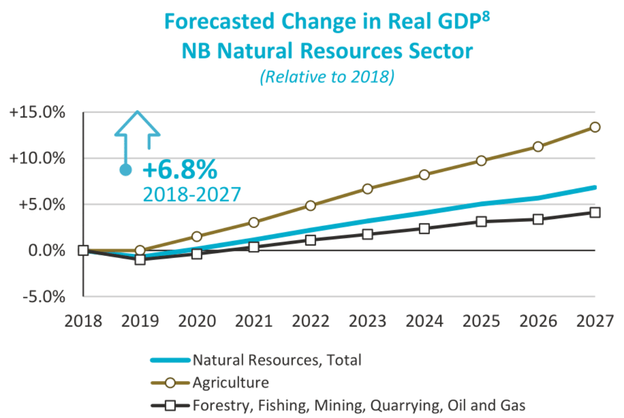
Region	1-9	10-49	50-199	200+	Total
NE	1,007	70	8	0	**1,085**
SE	561	33	3	1	**598**
SW	343	48	1	4	**396**
C	140	22	2	0	**164**
NW	231	79	6	1	**317**
Unknown	30	7	0	0	**37**
TOTAL	**2,312**	**259**	**20**	**6**	**2,597**

Employment by Economic Region: 2010-2019[11]
NB Natural Resources Sector

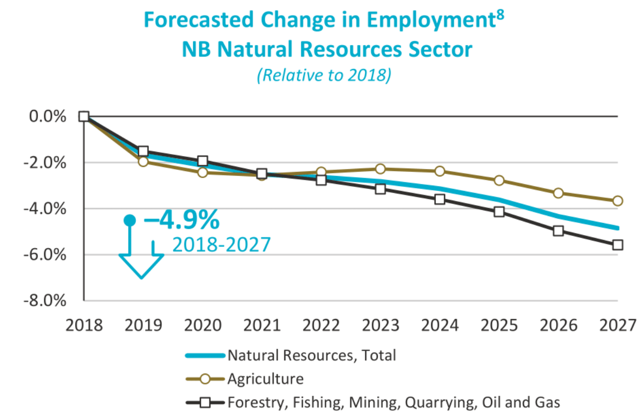


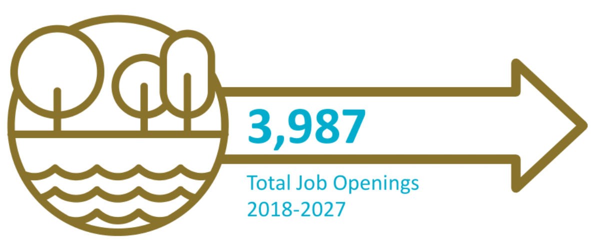
Business Outlook 2018-2027

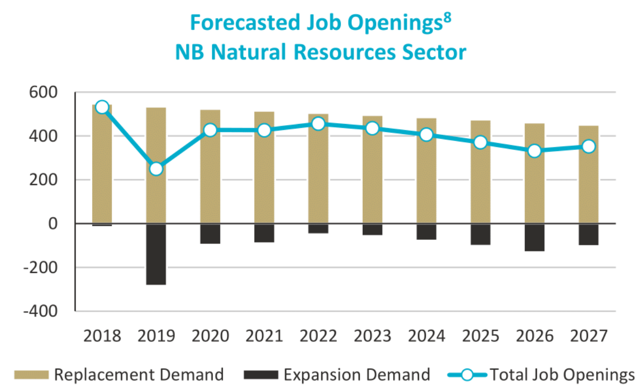
GDP Forecast



Employment Forecast







Links for Further Information

Government Sources

- NBjobs.ca
- Labour Market Information
- Sector Definitions - North American Industry Classification System, 2017 (NAICS)
- Classification of Occupations - National Occupational Classification, 2016 (NOC)

Sector Associations

- Association of Registered Professional Foresters in New Brunswick
- Canada Beef
- Canadian Institute of Forestry
- Canadian Institute of Mining
- G3 Canada
- Grand Manan Fishermen's Association
- Maritime College of Forest Technology
- Mining Association of Canada

For Additional Information Contact:

New Brunswick Department of Post-Secondary Education,
Training and Labour

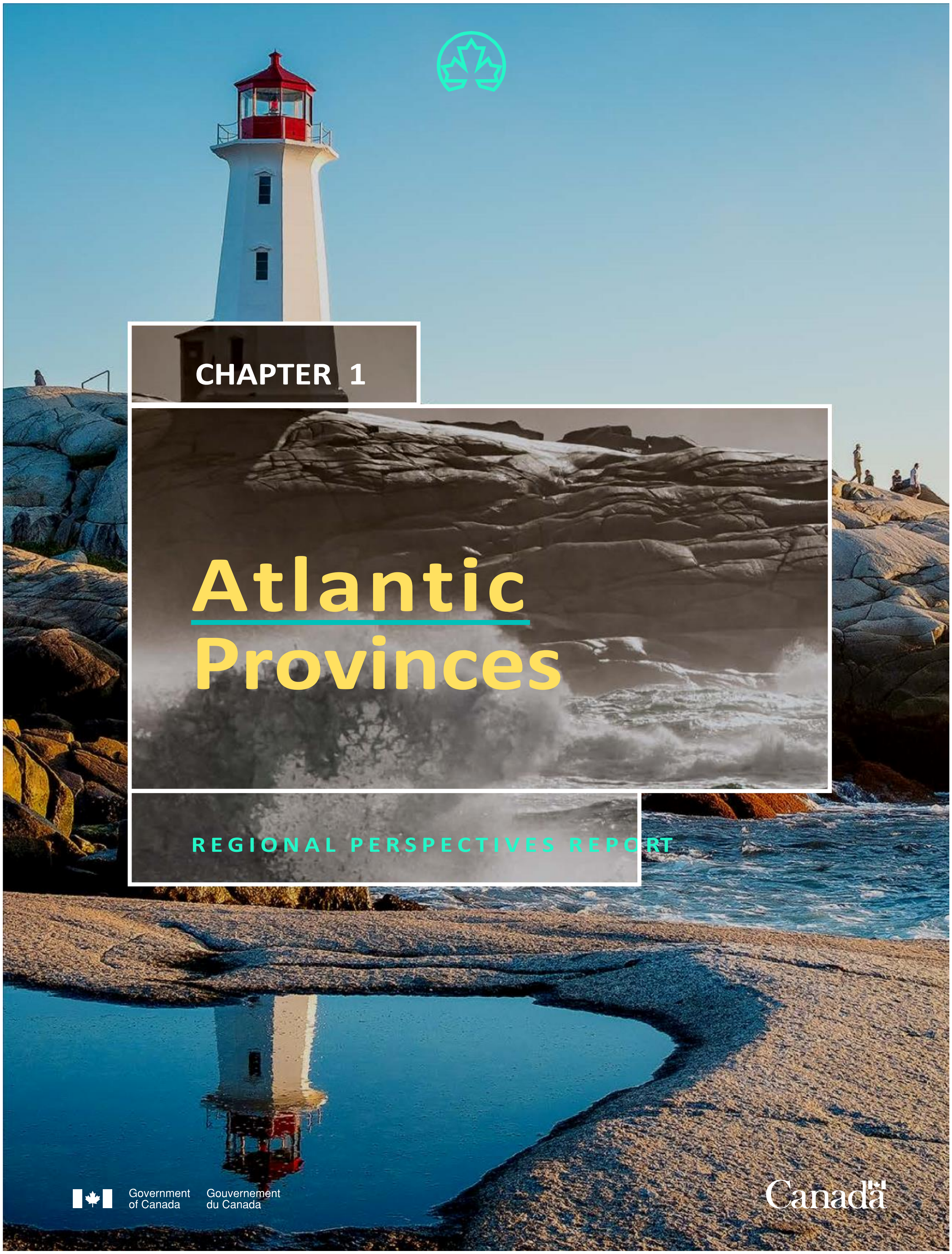
lmi@gnb.ca

Prepared by:

INPRO SOLUTIONS

Data Sources

[1] Statistics Canada, Table 36-10-0400
[2] Statistics Canada, Table 36-10-0402
[3] Statistics Canada, Table 36-10-0489
[4] Statistics Canada, Table 14-10-0023
[5] Statistics Canada, Table 14-10-0070
[6] Statistics Canada, Table 14-10-0027
[7] Statistics Canada, Table 14-10-0068
[8] Stokes Economics, Customized New Brunswick Forecast
[9] Statistics Canada, Table 14-10-0064
[10] Statistics Canada via the Community Data Program
[11] Statistics Canada, Table 14-10-0392


CHAPTER 1
Atlantic Provinces
REGIONAL PERSPECTIVES REPORT
Government of Canada
Gouvernement du Canada
Canada

1.1 Introduction

Atlantic Canada comprises the provinces of New Brunswick (N.B.), Nova Scotia (N.S.) and Prince Edward Island (P.E.I.) (collectively referred to as the Maritimes), as well as Newfoundland and Labrador (N.L.). Situated on the east coast of the country, Atlantic Canada spans three different climate regions that include cool humid-continental, sub-Arctic and Arctic tundra (Vasseur and Catto, 2008) and consists of regions and communities that differ in many ways, including population densities, natural resources, key industries and cultures. With approximately 42,000 km of coastline (Lemmen and Warren, 2016), Atlantic Canada is characterized by diverse coastal systems including sandy beaches, estuaries, intertidal flats, salt marshes, cobble beaches, cliffs, bluffs, rock shores and more (van Proosdij et al., 2016). This chapter does not include Nunatsiavut in Newfoundland and Labrador, as this region is discussed in the Northern Canada chapter.

1.1.2 Economy

Key industries in Atlantic Canada include agriculture, fisheries and aquaculture, forestry, tourism, marine transportation, shipbuilding, information technology, mining, oil and gas, renewable energy, manufacturing, aerospace and bioscience (Nova Scotia Business Inc., 2020; Government of Newfoundland and Labrador, 2017; Government of Prince Edward Island, 2016). Some of these sectors may experience new opportunities from climate change—for example, higher temperatures can lead to longer tourism and growing seasons. Negative climate change impacts, however, are expected to predominate, particularly in sectors that are sensitive to projected changes in climate due to their reliance on natural resources and marine and coastal infrastructure, such as fisheries, aquaculture, agriculture, forestry, transportation and offshore oil and gas (Vasseur and Catto, 2008)

1.5 Forestry, agriculture and fisheries are vulnerable to climate change

Atlantic Canada's natural resource industries are vulnerable to the impacts of climate change. While examples of adaptation are found in each sector—forestry, agriculture, fisheries and aquaculture—there **remains a lack of collaboration amongst stakeholders to reduce risks from climate change.**

Foresters, farmers and fishers are interested in understanding the projected climate changes in the short, medium, and long terms to improve their planning and decision making. The challenges presented by climate change for Atlantic Canada's natural resource industries are numerous, but also divergent among the different resource sectors of forestry, agriculture, fisheries and others.

1.5.1 Introduction

Atlantic Canada's natural resource industries play a crucial role for the region's economies, and are vulnerable to the impacts of climate change. The forestry, agriculture and fisheries sectors have made progress on adaptation, and benefited from collaborations between multiple levels of government, practitioners and communities (e.g., Nova Scotia Federation of Agriculture, 2020; Halofsky et al., 2018; Steenberg et al., 2011). Natural resource industries are also considering potential opportunities (e.g., longer growing season, harvesting of newly arrived species), in parallel with negative impacts (e.g., invasive species). A commonality amongst the various natural resource sectors is a strong need for research, monitoring and education, as well as a need for increased progress on action. Rigorous monitoring programs are central to climate change adaptation across all sectors in order to reduce uncertainty and inform the development of new policies and regulations.

1.5.2 Forests

The changing climate will have significant impacts on Atlantic Canada's forests (*see* Figure 1.15; Taylor et al., 2017), with implications for the forest sector, as well as natural areas, including urban forests. Short-term concerns include increases in natural disturbances, such as storm events and pest outbreaks, increased fire risks and invasions by non-native species (MacLean et al., 2021; Taylor et al., 2020). In the longer term, warmer temperatures will lead to shifts in the ranges of tree species. As important species in the region (such as Red Spruce, Black Spruce and Balsam Fir) are projected to decline in growth or abundance (Steenberg et al., 2013a), there will be significant socioeconomic impacts in the forest sector and in forest-dependent communities, including many Indigenous communities. Without action, these impacts could lead to a reduction in timber supply, employment, traditional Indigenous wood products, recreation, aesthetics and other ecosystem services (Ochuodho et al., 2012; *see* also Ecosystem Services chapter of the National Issues Report). Proactively adapting to these changes helps protect against losses, and also has the potential to generate benefits through new and enhanced wood products and services (Halofsky et al., 2018; Steenberg et al., 2011).

Planned and proactive adaptation is important for the forest sector, in part because of the long time horizons of the sector. Adaptation to date has focused primarily on research and planning to integrate the effects of climate change on forest ecosystem dynamics into modelling used for planning and policy development.

Figure 1.15: Managed Acadian forests in Nova Scotia. Photo courtesy of Jane Kent, Nova Scotia Department of Lands and Forestry.

Regional integrated assessments have emerged as a key planning tool for Atlantic Canada's forestry sector. The Maritime Regional Integrated Assessment (MaRIA), which began in 2017, involves provincial governments and forestry industries working together to assess forest vulnerability and integrate climate change considerations into forest management planning frameworks, with an emphasis on forest modelling tools (Taylor, 2021). As part of MaRIA, in New Brunswick, growth and yield curves that were developed using climate change scenarios are being used to project future wood supply (Steenberg, 2021). Additionally, a climate-change-dependent forest succession model will be developed that can be used in the provincial forest planning model to predict the forest regeneration response after harvests. The outcomes support the integration of climate change into the provincial five-year forest management planning cycle. Nova Scotia is similarly developing new protocols to integrate both forest carbon and climate change impacts into its strategic and landscape-level forest modelling and management planning (Steenberg, 2020), while Newfoundland and Labrador has supported similar research (Searls et al., 2021). More recently, the Nova Scotia Department of Lands and Forestry, in collaboration with Nova Scotia Environment and Climate Change, initiated the Climate Adaptation Leadership Program (CALP). The purpose of this program is to develop a climate change adaptation strategy for the province's Department of Lands and Forestry, with funding from the Province and from Natural Resources Canada through the Building Regional Adaptation Capacity and Expertise (BRACE) program (Natural Resources Canada, 2021).

Other examples of forest management adaptation include intermediate silviculture treatments, like precommercial thinning to favour species expected to flourish through a changing climate

(Thiffault et al., 2021) and adjusting urban forest management to reflect climate change impacts (*see* Case Story 1.10). Assisted species migration and diversification offer yet another approach to adaptation being used in the forestry sector, which includes provenance trials, the planting of genetically improved seedlings, and restoration silviculture (Halofsky et al., 2018).

Case Story 1.10: Halifax's Urban Forest Master Plan

A healthy and vibrant urban forest can alleviate some climate change impacts—such as urban heat islands and increased stormwater runoff—by directly shading buildings and infrastructure, lowering ambient

temperature, removing water from the soil, and slowing stormwater flow and decreasing runoff (Duinker et al., 2015; *see* also the Ecosystems Services and Cities and Towns chapters of the National Issues Report). A desire to maximize these and other beneficial ecosystem services in Halifax has led to many improvements in the urban forest management.

Halifax Regional Municipality's urban forester and municipal planners worked with Dalhousie University researchers to develop the city's first Urban Forest Master Plan (UFMP), which was adopted by Regional Council in 2012. Using adaptive management to address the uncertainty of climate change is a core principle of the UFMP (Steenberg et al., 2013b). The UFMP prescribes an increased rate of tree planting to ensure that this outpaces tree mortality, and also recommends a transition from reactive tree maintenance to a proactive pruning program. Since 2013, over 8,800 trees have been planted on municipal property, an initiative that can be directly attributed to the UFMP (Foster and Duinker, 2017; Steenberg et al., 2013b). Planting prescriptions included measures to increase species diversity and build resilience to climate change. The cyclical pruning program is intended to promote tree health and to prevent conflicts with infrastructure, ensuring a healthier urban tree canopy.

The Halifax experience of urban forest management highlights the importance of partnerships between researchers, municipal staff, and citizens, from the time of inception of a project. Public consultations informed the UFMP, and it was clear from these that most people want more trees in the city. This support allowed the municipality to increase spending on the urban forest, which is an important contributor to increasing climate resilience.

1.5.3 Agriculture

The net impact of climate change on agriculture in Atlantic Canada will be determined by the balance between opportunities and challenges (Ochuodho and Lantz, 2015). In a project called AgriRisk (Nova Scotia Federation of Agriculture, 2020), the opportunities identified included an extended growing season and the ability to grow higher-value crops, while the challenges included the risks associated with a greater frequency of extreme events, damage to crops and/or infrastructure, uncertainty in global markets, and potential changes in pest spectrum and incidence of disease. In Nova Scotia, a diverse group of researchers through the Nova Scotia Federation of Agriculture (NSFA) carried out a risk assessment focused on the wine grape industry. The goal was to “integrate and make use of the best available data sets and key variables associated with risks along the grape and wine value chain to help contribute to achieving the outcome of a risk-aware grape and wine industry.” The project developed models and interactive climate tools to help users explore current and future climate conditions in the province (Nova Scotia Federation of Agriculture, 2020).

For agriculture, adaptation approaches at the farm level (*see* Figure 1.16) have focused mainly on reducing non-climatic stressors through management practices. For example, farmers are planting cover crops, changing crop rotation and altering tillage practices to make the soil less vulnerable to erosion (Russell, 2018). Producer decisions are supported by the Alternative Land Use Services (ALUS) Program in Prince Edward Island (ALUS Canada, 2020). The program provides financial incentives to farmers for projects that support sustainable agriculture practices. For example, farmers are compensated for each acre of land used to create soil conservation structures like grassed waterways, terraces or berms. Other farm management adaptation options include flood control, shifting crop varieties, soil management, pest management, artificial cooling in livestock buildings (Arnold and Fenech, 2017; Wall and Smit, 2005), crop diversification and enhancing biodiversity for resilience (Wall and Smit, 2005);

Figure 1.16: Agriculture operations on Prince Edward Island. Photos courtesy of Don Jardine.

1.5.4 Fisheries

The vulnerability of fisheries to climate change is a major socioeconomic and ecological concern in Atlantic Canada, and the need for investment in adaptation has been well identified (Hutchings et al., 2012; Rice and Garcia, 2011). Many rural and coastal communities are highly dependent on fisheries. Given the scale and complexity of marine systems, climate change impacts are highly uncertain and potentially severe (*see* Sector Impacts and Adaptation chapter of the National Issues Report). Examples of important indicators of marine climate change include rising sea levels, increased ocean temperatures, hypoxia and acidification (Greenan et al., 2019), all of which affect marine ecosystems and fish stocks. Climate change can also increase sedimentation, which can result in fish habitat degradation and population declines

(Bernier et al., 2018). More extreme weather also presents technical and safety issues for fishery fleets (Rezaee et al., 2016). In 2017, a lack of available food for right whales in the Bay of Fundy may have contributed to their relocation into the Gulf of St. Lawrence, where the interaction of whales with fixed-gear fisheries led to a significant number of whale deaths, and resulted in the development of gear that is less detrimental to whales (Murison, 2017).

Changes to marine biodiversity present socioeconomic risks for those directly and indirectly connected to the fisheries sector (*see* Figure 1.17). For example, in the Outer Bay of Fundy, water temperatures have affected the hydrodynamics of ocean currents competing to enter the Bay of Fundy, resulting in an influx of warm Gulf Stream water (Drinkwater et al., 2003). This extreme change in temperature interacts with pH changes and more frequent heavy rainfall events, resulting in severe cumulative impacts on marine biodiversity (Bernier et al., 2018).

Impacts on fisheries infrastructure are another area of concern, with severe storm events placing a tremendous burden on the wharves that the fisheries depend on. Adaptation efforts in the fisheries sector on Grand Manan Island, New Brunswick, for instance, were informed by assessments of future needs under different climate change scenarios (Signer et al., 2014). Improvements to key fisheries infrastructure will help ensure that they can withstand future storm events.

Figure 1.17: Lobster fishing traps in the Gulf of St. Lawrence. Photos courtesy of Don Jardine.

1.5.5 Aquaculture

The marine stages of aquaculture production face a number of challenges related to climate change, including temperatures that approach or exceed the upper thermal limit of species, low water oxygen levels (hypoxia), acidification, more frequent and severe storms, and algal blooms (Reid et al., 2019a, b).

The primary finfish reared in the Atlantic region is the Atlantic salmon (Salmo salar), and several academic/ industry research partnerships are addressing challenges from climate change to help the industry to adapt over the next few decades. These include the following: Modules J and K of the Ocean Frontier Institute ("Improving Sustainability and Mitigating the Challenges of Aquaculture" and "Novel Sensors for Fish Health and Welfare," respectively), the "Mitigating the Impact of Climate-Related Challenges on Atlantic Salmon Aquaculture (MICCSA)" project, the "Addressing the Challenges Faced by Atlantic Salmon at Cold Temperatures" project, and the newly funded Atlantic Salmon Gill Health initiative. The “Mitigating the Impact of Climate-Related Challenges on Atlantic Salmon Aquaculture” (MICCSA) project involves several universities, the Huntsman Marine Science Centre, and industry partners including the Centre for Aquaculture Technology Canada, Somru Biosciences and AquaBounty, Canada. To date, this large project has defined the upper thermal tolerance of Atlantic salmon of the Saint John River stock (Gamperl et al., 2020; Leeuwis et al., 2019), examined the effects of elevated temperature and hypoxia on salmon production (Gamperl et al., 2020), examined pathogen-host interactions as affected by temperature (Zanuzzo et al., 2020), and directly measured Atlantic salmon behavior, distribution and physiology during summer sea-cage conditions (Gamperl et al., 2021). Further, the MICCSA research team is currently working on identifying genetic markers that will allow for the selection of broodstock with enhanced resistance to disease, sea lice and temperature (Beemelmanns et al. 2021a, b and 2020). The Ocean Frontier Institute has also funded projects at Memorial University (Model J.2) and Dalhousie University (Module K) that are advancing knowledge of how salmon and their populations are affected by adverse environmental conditions (Zanuzzo, 2022; Gerber et al., 2021, 2020; Stockwell et al., 2021). The industry is also exploring technological improvements to increase the depths of their sea cages, in compliance with ISO standards (International Organization for Standardization, 2015) to help ensure that these structures can withstand major storms, which are increasing in intensity as a result of climate change.

The primary molluscan aquaculture species in Atlantic Canada are blue mussels and Eastern oysters, which comprise approximately 35% of all Atlantic Canadian farmed organisms (Statistics Canada, 2021).The impacts of climate change on primary and secondary production have been investigated since the 1990s, and the general consensus is that infrastructure, primary productivity, seed supply, feeding physiology and carrying capacity are changing rapidly in Atlantic Canada and in many coastal regions (e.g., Reid et al. 2019a, b; Foster et al., in preparation). There has been an increase in disease and pest prevalence, an extension of the range of predators, and increasing challenges related to invasive organisms (Best et al., 2017, 2014; Lowen et al., 2016). Recent research has indicated that ocean acidification is affecting natural food supply dynamics, thereby affecting shellfish productivity at the larval and post-larval stages (Kong et al., 2019; Clements et al., 2018; Clements and Hunt, 2017; Clements and Chopin, 2016).

In the aquaculture sector, ocean dynamics, ice cover and changes in seasonal patterns of food supply are being addressed through the adoption of newer green technology by producers, and by using equipment that is storm resistant, well-engineered, better sited, and better suited to withstand the changing coastal conditions in summer and winter (International Organization for Standardization, 2020; Government of Newfoundland and Labrador, 2019). Hatchery production of the main cultivated mollusks (oysters, mussels) has been developed as a risk mitigation measure against spurious natural seed supplies and as a way of selecting strains that will perform better under changing conditions. For instance, three molluscan shellfish hatcheries have been constructed since 2018 in Atlantic Canada—two oyster hatcheries (Bideford Shellfish Hatchery, Prince Edward Island, and Maison BeauSoleil Oyster Hatchery in Neguac, New Brunswick), and one mussel hatchery and nursery in Borden, Prince Edward Island Atlantic Canadian shellfish hatcheries are being employed to reduce dependence on variable natural seed recruitment by producing a more reliable seed source that can grow under the warming climate (Guo et al., 2009). Finally, the use of algae, mollusks and echinoderms in reducing both the impacts of marine finfish farming and climate change is beginning to come to the forefront in Atlantic Canada, across Canada and globally (Clements and Chopin, 2016).

CHAPTER 4: PERSPECTIVES ON CANADA'S EAST COAST REGION

Lead Authors:
Jean-Pierre Savard (*Ouranos*), Danika van Proosdij (*Saint Mary's University*) and Stéphane O'Carroll (*Géo Littoral Consultants*)

Contributing Authors:
Trevor Bell (*Memorial University*), Pascal Bernatchez (*Université du Québec à Rimouski*), Norm Catto (*Memorial University*), Anthony Charles (*Saint Mary's University*), Claude Desjarlais (*Ouranos*), Susan Drejza (*Université du Québec à Rimouski*), Thomas James (*Natural Resources Canada*), Liza Leclerc (*Ouranos*), Nathalie Martel (*Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs du Québec*), François Morneau (*Ouranos and Ministère de la Sécurité publique du Québec*), Chantal Quintin (*Université du Québec à Rimouski*), Christina Robinson (*Memorial University*) and Anne Warburton (*Elemental Sustainability Consulting*)

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TABLE OF CONTENTS

KEY FINDINGS

Canada's East Coast region is geographically, ecologically and socially diverse, resulting in a wide range of climate change effects and responses. Analysis of existing literature and ongoing adaptation initiatives leads to the following key findings:

- **Air temperatures, sea-surface temperatures and ocean acidity have all increased in the region during the past century, while sea-ice cover has decreased.** Projected climate changes through the 21st century include continued warming of air and water temperatures, and increased precipitation, acidification and water stratification. Sea level will rise, with significant regional variability. Sea ice will decrease in area, thickness, concentration and duration, with volume likely to be reduced by more than 95% by the end of the 21st century.
- **Sea-ice cover and sea-level rise are key determinants of coastal erosion rates.** Increases in coastal erosion have been documented along many coasts in the region during years characterized by mild winters and low ice coverage. Future coastal-erosion rates will likely increase in most areas.
- **There are many adaptation measures that promote the resilience of coastal areas.** These include protection, revegetation and stabilization of dunes; maintenance of sediment supply; and provision of buffer zones, rolling easements or setbacks that allow the landward migration of the coastline.
- **Although hard coastal defence structures may be necessary to address sea-level rise and coastal flooding in some situations, particularly in urban areas, such structures disrupt coastal processes** and can exacerbate erosion, sedimentation and coastal squeeze, leading to degradation and loss of coastal habitats and ecosystem services. Retreat, sand nourishment and managed realignment represent alternatives to hard coastal-defence structures.
- **Experience in the East Coast region has shown that mechanisms such as setbacks, which control or prohibit coastal development, can be challenging to implement.** However, it is often even more difficult to remove and relocate buildings from an eroding coastline or flood-susceptible area. Selection of appropriate adaptation options may be particularly challenging in unincorporated areas where summer cottages, secondary homes or principal dwellings are established parallel to the shore in a ribbon fashion.
- **Provinces and communities across the region have made advances in identifying vulnerabilities to climate change impacts through collaboration with academia, the private sector and nongovernmental organizations.** Many have begun planning for adaptation, while others have moved from planning to implementation of adaptation strategies, although this remains a challenge for many. Few are engaged in ongoing monitoring of the effectiveness of implemented adaptation strategies.

1 INTRODUCTION

For this report, Canada's East Coast region includes the marine coasts of the Atlantic Provinces (New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador) as far north as Hamilton Inlet, Labrador, as well as the marine coasts of Quebec along the estuary and Gulf of St. Lawrence up to the city of Québec (Figure 1). The region has been inhabited by aboriginal populations for at least 9000 years (Chapdelaine, 1996), with European colonization beginning in the early 17th century. Today, more than 70 ethno-linguistic communities are represented on the coast, including the First Nations peoples. The current coastal population of the region, about 3 million people, resides in a few large cities and many small towns and tiny hamlets. Population density is lowest along Quebec's North Shore and the coast of Labrador.

The East Coast region features a great variety of landscapes consisting of rich and diversified ecosystems. Coastal communities benefit from the services provided by these ecosystems (e.g., food supply and protection against wave erosion), which contribute to both regional and national economic prosperity. Resource sectors, such as fisheries, aquaculture, transportation, tourism, mining and industrial development, rely either on marine resources or on the transportation services facilitated by the marine environment.

Climate change will affect many coastal processes, as well as adjacent terrestrial and oceanic environments, in the East Coast region. Changes in sea level, storm surges and heavy precipitation events can result in failure of coastal infrastructure, shoreline erosion, coastal and inland flooding, ice pile-ups, and saltwater intrusion into surface water and groundwater. Climate change impacts also include increasing water temperature, changes in duration of ice cover, acidification and oxygen depletion that, in turn, impact marine resources and ecosystems. If severe storms (e.g., tropical or extra-tropical storms, hurricanes) increase as a result of climate warming, the potential for wind, wave and water damage will also increase. These impacts would be further exacerbated by rising sea level. Although it is widely recognized that many natural hazards related to climatic events will increase on a global scale as a result of climate warming, there is less confidence about projected changes at the regional scale (*see* Chapter 2; IPCC, 2012).

FIGURE 1: Geographic extent of the East Coast region.

Climate change will result in long-term and permanent changes in coastal regions. The impacts of climate change on marine, terrestrial and coastal ecosystems affect human communities located close to the shore, as well as those that depend on coastal ecosystems. The vulnerability of a coastal community to climate risks depends on the physical characteristics of the coast and on the management of human activities within this changing environment. These changes will impact the lifestyles, economies and sustainability of coastal communities, presenting both risks and opportunities for economic activities. Coastal communities can reduce risks and take advantage of opportunities by adapting to these evolving conditions.

This chapter begins with an overview of observed and projected changes in climate and physical and biological coastal processes in the East Coast region (Sections 2–4). This provides a foundation for understanding climate change impacts on, and vulnerability of, coastal communities and key economic sectors, which are discussed in Section 5. It concludes with a discussion of the process of adaptation and our capacity to undertake actions that reduce climate impacts and benefit from possible opportunities (Section 6). Adaptation is framed in the context of multiple drivers of change, recognizing that communities, ecosystems and industry are continually evolving in response to a wide range of pressures, most of which are unrelated to climate. Adapting to climate change is a challenge that requires leadership, imagination and inclusion of a wide variety of participants, including communities, governments, industry, academia, coastal scientists, engineers, planners and civil society.

2 OBSERVED AND PROJECTED CLIMATE CHANGES

Canada's East Coast region is already affected by the changing climate (Vasseur and Catto, 2008). The strongest climate trend relates to increased air temperatures during the last century, a trend that climate models project to continue or accelerate for the coming century (Bush et al., 2014). Other climate variables, such as precipitation, evaporation, fog, winds and snow, may also be changing, but the trends are less strong than those for temperature.

This section reviews trends and projected changes in selected key climate parameters for the East Coast region: air temperature, precipitation and ocean-water temperature, because of their global application as indicators of long-term climate change; and wind and storms, due to their strong influence on climate impacts along coasts. Further information on observed and projected climate change in Canadian coastal areas is provided in Chapter 2 (at a national scale) and in the Atlantic Large Aquatic Basin assessment (DFO, 2012b). Changes in sea level, sea ice and wave climate are discussed in Section 3 in the context of their impacts on physical coastal processes.

2.1 AIR TEMPERATURE AND PRECIPITATION

A statistically significant increase in mean annual air temperature for the period 1900–2010 is evident throughout the East Coast region (Figure 2). The data demonstrate a general warming trend with high interannual and interdecadal variability (*see* Chapter 2 for discussion of climate variability). The average warming for the East Coast region as a whole during the 110-year period of record was 0.90 ±0.37°C (Figure 2a). Stations located along the Atlantic Ocean warmed 0.75 ±0.34°C (Figure 2b), whereas those located along the Gulf of St. Lawrence coast warmed 1.12 ±0.43°C (Figure 2c). Other studies (Finnis, 2013; Galbraith and Larouche, 2013) similarly denote an increasing spatial temperature-change gradient from the southeast to the northwest across the East Coast region. Temperature increases in the region are similar to, or greater than, global average warming during this same period (e.g., IPCC, 2013).

Climate-model projections indicate that historical trends of change in near-surface air temperature are expected to continue and become more pronounced (Table 1). Average precipitation, which does not show a clear historical trend, is expected to increase in winter and spring, and remain stable or decrease slightly in summer and fall. Seasonal changes in both mean near-surface air temperature and precipitation for the East Coast region are projected to be greatest in winter (Ouranos, 2010).

2.2 OCEAN-WATER TEMPERATURE

The main ocean-water bodies in the East Coast region are made up of three distinct layers: the surface layer, a cold intermediate layer and a deeper layer (Galbraith and Larouche, 2013). Local variations are observed in many areas, especially in fiord embayments, such as Smith Sound, NL and Fjord du Saguenay, QC. Rising air temperature (Section 2.1) has changed the temperature of surface marine and coastal waters (Han et al., 2013). During the period 1945–2010, the surface-water temperature of the northwest Atlantic Ocean increased 0.32°C, with the largest increase occurring in the Labrador Sea (Han et al., 2013). Increases in surface-water temperature in the Gulf of St. Lawrence are similar to those in air temperature over the same region (Galbraith et al., 2012). On the Atlantic coast, increases of +1.04°C and +0.89°C in surface-water temperature were observed for the Labrador Sea and the Scotian Shelf, respectively, during the period 1982–2006 (Sherman et al., 2009), with a similar warming trend (+0.38°C/decade) observed for the Labrador Sea during the period 1981–2010 (Han et al., 2013).

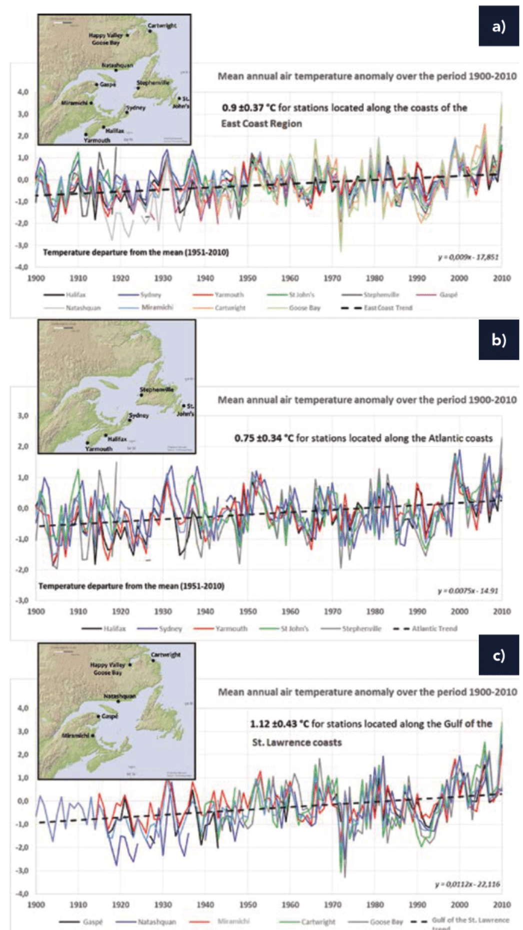

FIGURE 2: Mean annual air temperature anomaly (departure from the 1951–2010 mean) at **a)** meteorological stations in the East Coast region as a whole, **b)** stations located along the Atlantic Ocean, and **c)** stations located along the Gulf of St. Lawrence coast. The confidence interval is 95% for all plots. Positive values indicate that mean annual temperature is higher than the average temperature for the 1951–2010 time period. The 1951–2010 period was chosen as a reference period because of the availability of homogenized data (Vincent et al., 2012). Source: Ouranos (*modified from* Savard et al., 2008).

TABLE 1: Anticipated change of near-surface air temperature and precipitation in the East Coast region for 30-year periods, centred on 2020, 2050 and 2080, relative to the 1970–2000 period, based on results of the Coupled Model Intercomparison Project (CMIP 3) using *Special Report on Emissions Scenarios* (SRES) scenarios (IPCC, 2007). See Ouranos (2010) for details on methodology.

Season	Climate Parameters	Change by 2020	Change by 2050	Change by 2080
Winter	Temperature Precipitation	1.4 to 2.2°C 2.8 to 9.7%	2.5 to 3.8°C 6.5 to 15.4%	3.4 to 5.0°C 12.6 to 22.9%
Spring	Temperature Precipitation	0.8 to 1.5°C 0.3 to 8.1%	1.6 to 2.7°C 3.1 to 11.5%	2.2 to 4.1°C 8.8 to 18.5%
Summer	Temperature Precipitation	0.9 to 1.6°C –1.9 to 5.2%	1.7 to 2.7°C –1.4 to 5.7%	2.2 to 3.8°C –4.0 to 7.1%
Autumn	Temperature Precipitation	1.1 to 1.6°C –2.8 to 3.6%	1.9 to 2.8°C –2.0 to 7.1%	2.3 to 4.1°C –0.9 to 10.1%

Global-climate projections generally indicate widespread warming (1 to 3°C by 2100 under an intermediate-emissions scenario) of the upper ocean around Canada during the 21st century, with substantial seasonal and spatial variability (Meehl et al., 2007; Capotondi et al., 2012). Warming is expected to be more limited in the North Atlantic south of Greenland, due to a likely reduction in the northward ocean transport of heat by the Atlantic Meridional Overturning Circulation (Drijfhout et al., 2012; Hutchings et al., 2012). It is unclear whether this projected ocean-temperature anomaly will extend westward into the Labrador and Newfoundland coastal waters, as global models have difficulty resolving ice-ocean variability in the Labrador Sea (de Jong et al., 2009).

2.3 WIND AND STORMS

Trends in wind velocity and direction, and in storms during the 20th century, are difficult to determine conclusively, in part because datasets are not as complete as for air temperature. Wind is very sensitive to local topography, and any relocation of wind stations (even if moved a short distance) or replacement of instrumentation or equipment can introduce significant changes in a time series that are not related to climate change. The most reliable databases start only in 1961 or 1979 (when satellite observation data became available). Analysis of the density of intense storm centres over North America for the period 1961–2000 indicates that the northwestern Atlantic Ocean, the Labrador Sea and the Gulf of St. Lawrence are some of the stormiest areas in North America (Figure 3; Savard et al., 2014).

Climate projections indicate that significant changes in wind speed are unlikely as a result of climate warming, but there is likely to be a northward shift in storm tracks that will affect storm frequency in the East Coast region (Loder et al., 2013).

3 CHANGES IN PHYSICAL PROCESSES AND COASTAL GEOMORPHOLOGY

Coasts are a naturally dynamic environment (*see* Chapter 2). They are in a state of constant flux that involves sediment movement, changes in coastal morphology and shifts in the organisms that inhabit these systems. Although coastal systems may be considered as being in dynamic equilibrium, this depends on the ability of the system to transport sediment alongshore by longshore currents, or seasonally onshore and offshore through wave action. In normal conditions (excluding storms), sediment is transported alongshore through the process of littoral drift, generally within the boundaries of a littoral cell (*see* Chapter 2). Erosion or deposition rates depend on a range of natural (e.g., riverine sediment supply and formation of ice foot [ice along the shoreline]) and anthropogenic processes (e.g., dredging and shore protection).

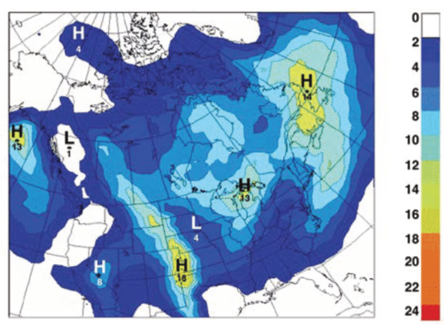

FIGURE 3: Spatial distribution of the annual average density of storm tracks for the 1961–2000 time period from ERA-40 reanalysis (a reanalysis of the global atmosphere and surface conditions for a period of 45 years, extending from September 1957 through August 2002, by the European Centre for Medium-Range Weather Forecasts; *modified from* Savard et al., 2014)

Rising air and sea-surface temperatures will lead to shorter sea-ice seasons, which in turn cause an increase in total wave energy dissipated on the coast (Neumeier et al., 2013). Combined with rising sea levels, this will affect the risk of storm-surge flooding and will exacerbate coastal erosion and sedimentation in areas already sensitive to these processes. Climate change will also affect processes, such as freeze-thaw cycles, input from inflowing rivers and ice scouring, that influence sediment balance and contribute to the changing nature of the coastal landscape.

In the following sections, the main climate change–related drivers of change in coastal geomorphology are discussed in more detail. These include the changes in sea level, storms and ice conditions that affect extreme water levels and waves.

3.1 CHANGES IN RELATIVE SEA LEVEL

Recent findings on sea-level rise (SLR) are given in global assessments, such as the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Church et al., 2013; IPCC, 2013). Global sea-level change is the vertical change of the sea surface relative to the Earth's centre, averaged for all oceans on the planet. In contrast, 'relative' sea-level change is the change in mean sea level relative to solid ground at any specific point on the coast (*see* Chapter 2).

During the 20th century and the first decade of the 21st century (i.e., 1900–2009), the trend of global sea-level rise was 1.7 ±0.2 mm/year. The rate of global sea-level rise between 1993 and 2009 increased to 3.2 ±0.4 mm/year (from satellite altimetry) or 2.8 ±0.8 mm/year (from tide-gauge records; Church and White, 2011). The IPCC (2013) projects a range of global sea-level rise of 26–98 cm by the year 2100, based on the representative concentration pathway (RCP) emissions scenarios (*see* Chapter 2). Collapse of a sector of the West Antarctic Ice Sheet has the potential to add another few tens of centimetres of global sea-level rise, but its probability of occurrence is uncertain (Church et al., 2013).

In Canada's East Coast region, spatial differences in vertical land motion, largely associated with glacial isostatic adjustment, produce regional differences in relative sea-level change (*see* Chapter 2). Glacial isostatic adjustment is the delayed response of the solid Earth to the surface unloading that occurred at the end of the last ice age. Vertical land motion measured at GPS stations in the East Coast region (*see* Chapter 2) shows sinking land across the southeastern part of the region. Sinking land contributes to relative sea-level rise. In the northwestern part of the region, the land is rising and relative sea-level change is reduced compared to global values.

Recent projections of relative sea-level change on Canadian coasts (James et al., 2014), based on the results of the IPCC Fifth Assessment Report, are described in Chapter 2. The projections include the steric effect (thermal expansion of the surface layer of the ocean); meltwater from mountain glaciers and ice caps, and the Greenland and Antarctic ice sheets; projected changes in dynamic oceanography; and other smaller sources (*see* Chapter 2). For much of the East Coast region, a projected reduction in the strength of the Gulf Stream contributes 10–20 cm to sea-level rise by 2100, due to dynamic oceanographic effects (Yin, 2012).

Projections for the East Coast region are presented in Figures 4 and 5. For the high-emissions scenario, James et al. (2014) projected the mean elevation of sea level to be 80–100 cm higher at 2100, relative to 1986–2005, in the southeastern part of the region (Atlantic coast of Nova Scotia and New Brunswick) and on the southern side of the Gulf of St. Lawrence (Figure 4). In the northwestern part of the East Coast region (i.e., on the North Shore of the Gulf of St. Lawrence in Quebec), sea level is projected to be about 20–40 cm above its current position by the year 2100. In Newfoundland, projections indicate sea-level will rise 60–80 cm by 2100. This variability is due largely to differences in vertical land motion, which range from nearly 2 mm/year of subsidence for some locations in Nova Scotia to nearly 5 mm/year of uplift on the North Shore of the Gulf of St. Lawrence. Other factors also play a role. Based on the range of estimated maximum contributions presented in the literature and summarized by Church et al.

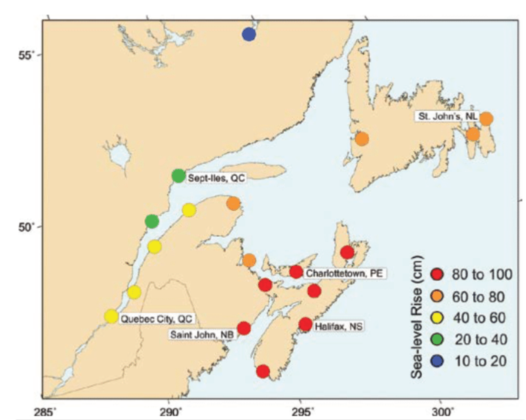

FIGURE 4: Projections of relative sea-level rise by the year 2100 for the median value of the high-emissions scenario (RCP8.5; after James et al., 2014). *See* Chapter 2 for additional information on sea-level projections. Sea-level projections through the 21st century are given in Figure 5 for the six labelled communities.

(2013), James et al. (2014) estimated additional sea-level rise associated with potential collapse of a portion of the West Antarctic Ice Sheet could contribute up to an additional 65 cm of global sea-level rise. This additional contribution has the potential to increase relative sea-level rise to more than 1.5 m by 2100 for some locations in the East Coast region (Figure 5).

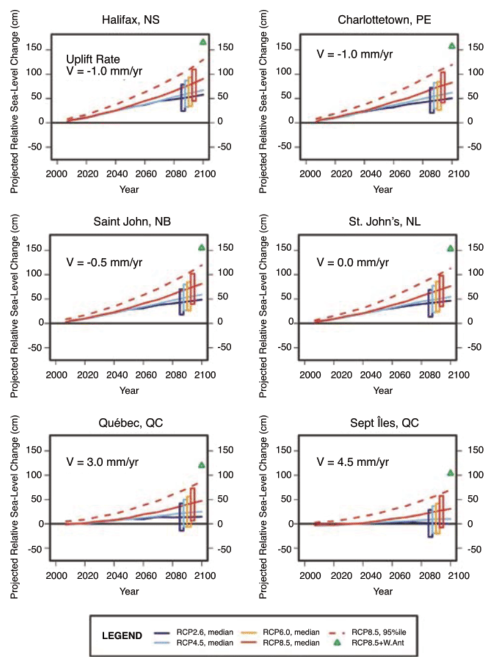

FIGURE 5: Projected sea-level change through the 21st century for selected communities in the East Coast region (after James et al., 2014, 2015). RCP2.6 is a low-emissions scenario, RCP4.5 and 6.0 are intermediate-emissions scenarios and RCP8.5 is a high-emissions scenario. The projected value at 2100 is also given for the high-emissions plus Antarctic ice-sheet reduction scenario, an augmented scenario in which the West Antarctic Ice Sheet contributes an additional 65 cm to the median projected value of the high-emissions scenario (RCP8.5+W.Ant; green triangle). Rectangles show the 90% confidence interval (5–95%) of the average projection for the period 2081–2100 and include RCP6.0. The dashed red line gives the 95th percentile value for the high-emissions scenario. Vertical land motion (V) is given to nearest 0.5 mm/year in each panel. *See* Chapter 2 for further explanation of scenarios. Projections for additional sites are given in Appendix A.

3.2 STORM SURGE AND EXTREME WATER LEVELS

Storm-surge elevation is the difference between the observed water level during the surge and the level that the tide would normally rise to in the absence of storm activity. Storm surges result from variations in atmospheric pressure and wind (*see* Chapter 2; Forbes et al., 2004; Thompson et al., 2009). Storm surges can occur over one or several tidal cycles (Figure 6), depending on the speed of the low-pressure system moving through an area. When a surge occurs at the same time as a high tide, lands and infrastructure located in low-lying areas can be flooded (Case Study 1).

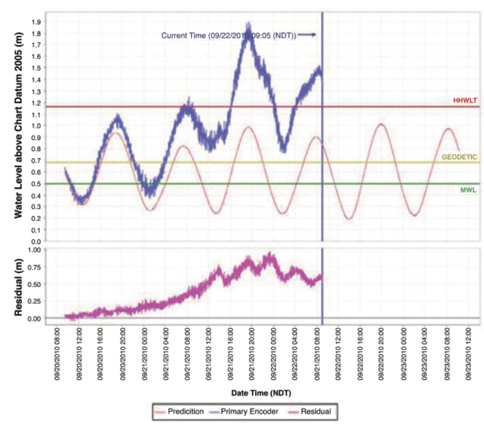

FIGURE 6: Example of surge caused by Hurricane Igor (October 2010) over several high-tide cycles in St. John's, NL. The higher high water large tide (HHWLT) was exceeded on at least three occasions (Canadian Hydrographic Service, Atlantic Region). Abbreviations: MWL, mean water level; NDT, Newfoundland Daylight Time.

CASE STUDY 1
THE GROUNDHOG DAY STORM

The 'Groundhog Day' storm of February 2, 1976 is a classic example of the impact of a storm occurring coincident with high tides to produce a large surge. Significant damage (representing more than $10 million at the time) and coastal flooding were reported in southwestern Nova Scotia and southern New Brunswick, where water levels rose more than 2.5 m above the predicted tides, heavily eroding shorelines (Parkes et al., 1997; Desplanque and Mossman, 2004). Strong south-southeast winds blowing for 5–6 hours resulted in a large storm surge in areas of the Bay of Fundy. Water levels rose to 3.2 m above predicted tides in 15 minutes (Desplanque and Mossman, 2004), and new tide-height records were set at Yarmouth, NS and Saint John, NB harbours (Amirault and Gates, 1976). Fortunately for those farther up the Bay of Fundy, the tide was an apogean spring tide (lower than average tide because the moon was most distant from Earth in its monthly orbit). Therefore, although a surge of 1.46 m was recorded and dikes were overtopped, the damage was limited. Had the storm occurred 16 days later during the perigean spring tide (higher than average tide because the moon is closest to Earth in its monthly orbit), the damage would have been much greater (Desplanque and Mossman, 2004). It is estimated that, if the Groundhog Day storm had occurred on April 16, 1976, it "would have had the potential of causing calamity on the scale of the Saxby Tide" (Desplanque and Mossman, 2004; *see* Chapter 2).

In Charlottetown, PE, the two largest recorded storm surges between 1911 and 2000 (1.43 m on December 19, 1963 and 1.41 m on March 12, 1991) did not flood the historical waterfront properties of the city, as both storm surges occurred during low tide. However, during the same time period, six smaller storm surges were sufficiently high, when combined with the tide height, to flood the waterfront area of the city, registering a maximum water level of 3.6 m or more above chart datum (Parkes and Ketch, 2002). Historically, relative sea level has been rising in Charlottetown at the rate of 3.2 mm/year since 1911 (Parkes et al., 2002). If sea levels had been at today's height, both the 1963 and 1991 storm surges would have resulted in flooding of the historical waterfront.

Using long-term tide-gauge data, Xu et al. (2012) studied the recurrence frequencies of extreme storm surges for five sites in the estuary and Gulf of St. Lawrence, and on the Atlantic coast: Lauzon, QC; Rimouski, QC; Charlottetown, PE; Halifax, NS; and St. John's, NL. Although the study concluded that there was no observed trend in storm-surge heights (i.e., no net increase or decrease) for the entire East Coast region, there were site-specific increases in storm-surge recurrences at St. John's and Rimouski during the 1922–1951 to 1981–2011 periods (Xu et al., 2012). The relative degree of negative impact on a coastal community from storm surge is also associated with the frequency of occurrence of a storm of that magnitude. Communities and coastal ecosystems that are frequently impacted by surge events are more likely to have evolved coping responses. For example, a 1 m storm surge is a relatively rare event in the Placentia, NL and Ferryland, NL areas, and could therefore pose a threat to coastal communities, whereas a 1 m storm surge in Lauzon, QC is a yearly event that may have little effect on the well-being of coastal residents.

On Quebec coasts, Bernatchez et al. (2012a) identified 30 storm-surge events that caused significant damage at a regional scale between 1950 and 2010, including 14 events that caused flooding. In the Bas-Saint-Laurent area, run-up during the storm of December 6, 2010 caused water levels to reach a little more than 2 m above the high tide (Quintin et al., 2013), corresponding to a once-in-150-years event (Bernatchez et al., 2012a). The average amount of erosion of low-lying sandy coasts as a result of this storm was 3.7 m, with a maximum erosion of 15 m measured at one site (Quintin et al., 2013).

Climate change affects storm surge and associated flooding as a result of sea-level rise, possible changes in storm frequency and intensity, and other ocean-dynamics factors. For example, tidal resonance in the Bay of Fundy is projected to increase the tidal range and lead to greater water-level extremes, although it will not affect mean sea levels (Greenberg et al., 2012). This contribution to water-level extremes has been estimated to be on the range of 5–20 cm by 2100 in the Bay of Fundy, compared with close to zero in Halifax, NS. The magnitude of changes in sea level is fairly well understood, but less is known about potential changes in other factors. Modelling allows analysis of potential storm-surge impacts under future climate conditions (e.g., Bernier et al., 2006).

3.3 WAVE CLIMATE AND SEA ICE

Wave-climate modelling (e.g., Swail et al., 2006) is used in coastal vulnerability assessments and in the planning and design of offshore and coastal infrastructure (e.g., drilling platforms, wharves, jetties, breakwaters, and offloading and loading structures). It has also contributed to an improved understanding of coastal evolution (i.e., sediment dynamics and water currents), changes in wave characteristics over time (i.e., period, height and wavelength) and possible future wave conditions in a changing climate.

Modelling of the wave climate of the estuary and Gulf of St. Lawrence for the period 2071 to 2100 indicates an increase in wave height of between 5 cm and 1 m, for a return period of 50 years, and a slight increase in overall mean wave energy due to decreasing sea-ice cover (Neumeier et al., 2013).

The East Coast region includes the most southward extent of winter sea ice in Canada's coastal waters. The average annual sea-ice cover in the East Coast region has decreased by 0.27% per year since the Canadian Ice Service began collecting data in 1968–1969 (*see* Figure 7 for trend since 1980–1981; Senneville et al., 2014). For the period 1998–2013, the average decrease was 1.53% per year (Senneville et al., 2014; note that both 2014 and 2015 had ice cover exceeding the 1980–2010 median). Warmer average winter temperatures have reduced the percentage of ice cover, shortened the duration of the ice season and decreased ice thickness. These trends are projected to continue, with modelling indicating that sea ice will be almost completely absent in most of the Gulf of St. Lawrence by 2100 (Senneville et al., 2014).

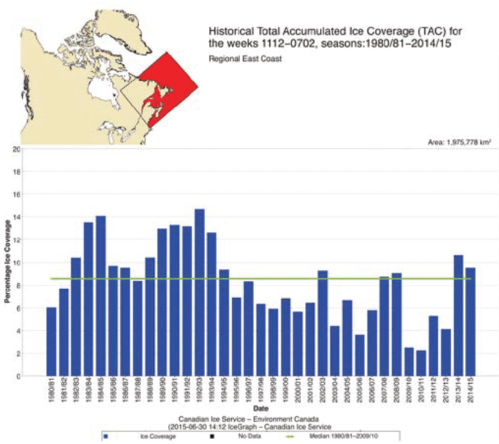

FIGURE 7: Historical total accumulated ice coverage for the weeks December 11 to February 7 from 1980 to 2015 in the East Coast region (Environment Canada, 2015).

Since ice cover impedes wave formation, the shortening of the ice season increases the total energy of storm waves developing in an ice-free water body, such as the Gulf of St. Lawrence (Neumeier et al., 2013). This, in turn, will modify the coastal sediment balance, activating shore erosion in some areas while reducing erosion in others as material is redistributed (Jones et al., 2009; Overeem et al., 2011).

In the Gulf of St. Lawrence, the period of wave inhibition by sea-ice decreased by 30% for the period 1995–2007 (average ice-covered period of 55 days/year) relative to the period 1960–1995 (average ice-covered period of 80 days/year; Savard et al., 2008). In comparing future conditions (2041–2070) to the recent past (1982–2011), modelled simulations suggest that the period of sea-ice cover will decrease by 36 days and the number of days that the ice foot completely protects the coast will decrease by an average of 33.4 days (Senneville et al., 2014). Ice-foot development currently occurs during some winters along coastlines in the southern Gulf of St. Lawrence and around the Avalon Peninsula, NL, and more frequently along the Quebec North Shore, in northeastern Newfoundland and in Labrador.

3.4 GEOMORPHOLOGY, SEDIMENT SUPPLY AND COASTAL DYNAMICS

The East Coast region has a diverse geomorphology. Mountain and fiord coastal areas are common in parts of Newfoundland and Labrador, while topographically low to moderately high, resistant bedrock cliffs, occasionally interrupted by unconsolidated coasts, are found along the northern and eastern shores of the Gulf of St. Lawrence, the Bay of Fundy coast of New Brunswick, and the exposed Atlantic shores of Nova Scotia and Newfoundland. Soft erodible cliffs are widespread along the southern and western shores of the Gulf of St. Lawrence (Prince Edward Island, New Brunswick and the Îles de la Madeleine). Resistant cliffs in the region retreat slowly, at annual rates of less than a centimetre per year (e.g., Davidson-Arnott and Ollerhead, 2011). Coastal cliffs in unconsolidated materials and in soft, nonresistant rocks are more dynamic (Bezerra et al., 2011) and therefore more sensitive to climate change. Unconsolidated, low-lying coasts consisting of salt marshes, sandy barrier islands and beaches occur mainly along the St. Lawrence estuary and western shores of the Gulf of St. Lawrence (Quebec, Prince Edward Island and New Brunswick) and on the Îles de la Madeleine, as well as along the Bay of Fundy, especially at its head. Extensive, fine-grained tidal flats and salt marshes are exposed at low tide in the upper Bay of Fundy, where tides may exceed 14 m.

During the last glaciation, large quantities of sediment were deposited offshore because sea level was substantially lower than at present (Shaw et al., 2002). Subsequent glacial isostatic adjustments (*see* Chapter 2) resulted in increasing sea levels that reworked these sediments to form many of the beaches, spits and barrier islands seen today along the shorelines of the East Coast region (Davidson-Arnott and Ollerhead, 2011). However, apart from most of Newfoundland and Labrador, the abundant sediment resources contained on the continental shelf have largely been exhausted throughout the region, so most of the sediment presently supplied to the coastal beaches is sourced from shoreline erosion, the reworking of coastal sediments by littoral currents, and materials transported to the coast by rivers and streams. This leads to a chronic sediment deficit, which can be further exacerbated by the armouring of coastlines that is frequently associated with coastal urbanization (O'Carroll et al., 2006; Bernatchez et al., 2008b; Bernatchez and Fraser, 2012).

There is presently a generalized landward retreat of the coasts (Table 2) that will continue in the future. It is important to note that, apart from Prince Edward Island and sections of the New Brunswick coast, erosion rates have not been calculated in a consistent manner or with the same standards of measurement for comparison. Progradation (seaward advance of the coast) is occurring in some localized areas, often as a result of erosion along other shoreline areas (Forbes et al., 2004; O'Carroll et al., 2006; Jolicoeur et al., 2010; Davidson-Arnott and Ollerhead, 2011). The rate of shoreline erosion is associated with the lithology of the underlying bedrock (Davidson-Arnott and Ollerhead, 2011), coastal landforms or ocean-climate factors (e.g., storm surge, tidal stage and sea-level rise).

Rates of coastal erosion will also vary depending on the type of coastal landform. For example, rates of erosion in New Brunswick are highest in beach-dune systems (averaging 0.78 m/year) and lowest for cliffs (0.26 m/year; Table 3). Coastal landforms, such as beaches, dunes or marshes, have the capacity to re-establish following major erosion events (O'Carroll et al., 2006; Ollerhead et al., 2006), whereas a cliff or bluff will only recede. Eroded material plays an important role in supplying sediment to the rest of the coastal system within a littoral cell (*see* Chapter 2).

Human actions, such as coastal armouring (e.g., Finck, 2012), sediment extraction (e.g., Hunter, 1975; Taylor and Frobel, 2009) and building of dams (e.g., van Proosdij et al., 2009), interact with natural factors to influence sediment supply and coastal dynamics. For example, a study of barrier and non-barrier beaches along the head of South Bay Ingonish and Black Brook Cove, NS showed that seasonal sand accumulation resulted in fluctuations in beach width of 10–20 m at both sites. However, backshore areas varied significantly in their ability to repair themselves (Tibbetts and van Proosdij, 2013). At Ingonish beach, it took roughly 6–10 years to rebuild the crest elevation, whereas sites where the backshore areas were excavated and lowered by human activity still had not recovered 26 years later (Taylor and Frobel, 2009). A major challenge in projecting future changes in coastal geomorphology is the complex relationship between climate, coastal dynamics and human activity (Case Study 2 and *see* Chapter 2).

TABLE 2: Examples of historical bluff or cliff rates of retreat throughout the East Coast region. These rates may not be directly comparable due to differences in methodologies and types of measurements.

Location	Retreat rate	Time period	Reference
Quebec — Unconsolidated bluffs, Gulf of St. Lawrence coast	Up to 3.45 m/year	Various	(Bernatchez and Dubois, 2004)
New Brunswick — Till bluffs, Northumberland Strait	0.26 m/year (average)	1944–2001	(O'Carroll et al., 2006)
Prince Edward Island — Sandstone and till, entire island	0.28 m/year (average)	1968–2010	(Webster, 2012)
Prince Edward Island — Till bluffs, Gulf of St. Lawrence coast	Up to 2.24 m/year	1935–1990	(Forbes and Manson, 2002)
Prince Edward Island — Till bluffs, Northumberland Strait coast	0.74 m/year (average)	1935–2000	(O'Carroll, 2010a)
Newfoundland and Labrador — Unconsolidated bluffs, northeastern Avalon Peninsula	0.1 to 0.3 m/year	Undetermined	(Catto, 2011)
Nova Scotia — Till drumlin, Cape Breton	1.38 m/year (average)	2000–2007	(Force, 2012)
Nova Scotia — Till bluff, Bras d'Or Lakes	0.33 m/year (average)	1939–2014	(O'Carroll, 2015)
Nova Scotia — Basalt-sandstone bedrock, Bay of Fundy	0.06 to 0.8 m/year	Undetermined	(Desplanque and Mossman, 2004)
Nova Scotia — Till drumlin, Gulf of St. Lawrence coast	0.27 to 0.85 m/year	1939–2007	(Utting and Gallacher, 2009)
Nova Scotia — Till bluff, Northumberland Strait coast	0.4 m/year (average)	1964–2005	(Finck, 2007)

TABLE 3: Varying rates of erosion depend on coastal landform and geography in New Brunswick. Coastal erosion has been systematically monitored in the province for 45 years (New Brunswick Department of Energy and Mines, 2015). Abbreviation: N/A, not available.

Landform	Chaleur (m/year)	Northeast (m/year)	Northumberland (m/year)	All New Brunswick (m/year)
Cliff	0.18	1.17	0.26	0.26
Dune	0.35	1.20	0.85	0.80
Beach	0.32	1.01	1.00	0.76
Salt marsh	0.17	N/A	0.30	0.28

CASE STUDY 2

INTERACTIONS BETWEEN PHYSICAL, BIOLOGICAL AND HUMAN ASPECTS OF COASTAL DYNAMICS, MIDDLE COVE, NL

To better assess the vulnerability of a coastal site, location or community, a baseline study describing the links between the physical, biological and human aspects should be carried out. Middle Cove beach, located approximately 15 km north of St. John's, NL, is a prime spawning ground for capelin (capelin rolls) and is also a sought-after tourist site during the summer. The head of the cove and the beach were characterized as extremely sensitive to erosion by Catto and Catto (2014) due to the physiography of the coast; the fact that the cove faces the north to northeast storm-wave direction; the frequency of storm events (especially since 2001); the documented effects of storm activity since 1989; and the general absence of sea ice and limited snow cover.

The physical characteristics of Middle Cove beach (a moderate-wave-energy beach composed of relatively well-rounded, medium to coarse pebbles) make it an ideal spawning site for capelin (*Mallotus villosus*; Catto and Catto, 2014). Middle Cove is also one of the most heavily used beaches on the Avalon Peninsula. On warm summer days and evenings, and during capelin rolls season, more than 150 people can be found at Middle Cove beach. This visitor pressure results in gradual flattening of the upper parts of the beach, which alters the profile, destroys or restricts cusp development and results in compaction of the sediment.

The profile of Middle Cove beach, as is the case for most beaches, evolves on a seasonal basis, adjusting to coastal conditions. Of particular importance are the winter months, at which time a convex beach profile develops when waves are unable to reach the upper beach because of snow or an ice-foot cover. During winters where an ice foot is absent, the profile becomes concave (Catto and Catto, 2014). A steeper beach profile, caused by successive storm events or the absence of winter ice-foot protection, results in coarser beach material that is less favourable for capelin spawning. Warmer air and water temperatures in future will further impede winter ice-foot development (which has not been significant since the early 2000s), while relative sea-level rise could render the upper part of the beach more susceptible to scour and thinning. This will result in a beach even less favourable to capelin spawning during the roll season, and could also have economic and cultural effects.

4 CHANGES IN BIOLOGICAL PROCESSES AND COASTAL ECOSYSTEMS

Healthy coastal ecosystems provide a range of ecological services that are essential to the well-being of coastal communities. Enhancing and sustaining ecosystem resilience is of both ecological and socio-economic importance. Coastal ecosystems are integrated across terrestrial and marine environments, exchanging nutrients valuable for overall ecosystem function and providing habitats for species across a range of life-cycle stages. Direct economic benefits arise from a range of traditional and commercial activities, including fishing, shellfish harvesting and tourism. In addition, ecosystems such as wetlands, coastal dunes, spits and barrier islands enhance the sustainability of the built environment by acting as buffer zones that protect against severe wave and storm activity (e.g., Duarte et al., 2013).

Together, changing climate and increased anthropogenic pressures have led, and will continue to lead, to modifications to coastal habitats, affecting species distribution and dynamics, as well as altering and/or impairing ecosystem structure and function (Day et al., 2008; Rabalais et al., 2009; Michel and Pandya, 2010; Rabalais et al., 2010).

The following sections examine the ecological implications of changes in ocean climate (sea temperature, hypoxia, acidification and salinity), and the interaction of climate and human activities affecting water resources and ecosystem dynamics.

4.1 IMPLICATIONS OF CHANGES IN SEA TEMPERATURE

Sea temperature affects a range of biological processes (e.g., metabolic processes and growth rates) as well as species distribution and abundance (e.g., Hoegh-Guldberg and Bruno, 2010; Pankhurst and Munday, 2011). Global ocean primary productivity has declined since the early 1980s, with most of this decline linked to increased sea-surface temperatures in high and northern latitudes (Gregg et al., 2003; Hoegh-Guldberg and Bruno, 2010; Nye, 2010).

Primary productivity in the East Coast region is also affected by the scope and duration of sea-ice cover. In the Gulf of St. Lawrence, winter sea-ice contributes to water-convection processes, an important driver of primary production by phytoplankton (Le Fouest et al., 2005; Dufour and Ouellet, 2007). As sea-ice forms, it releases the salt content of the water in the form of denser brine, which sinks. This displaces less dense, nutrient-rich deeper waters toward the surface, causing upwelling and feeding nutrients to primary producers. Sea-ice melt also plays a major role in triggering phytoplankton blooms (Hoegh-Guldberg and Bruno, 2010). The likely cessation of winter sea-ice formation in the Gulf of St. Lawrence this century will affect phytoplankton abundance, timing and distribution, and alter primary production functions in this semi-enclosed marine basin (Dufour and Ouellet, 2007).

Ice also plays an important role in the redistribution and colonization of salt-marsh cordgrass (*Spartina alterniflora*) seeds and rhizomes in the East Coast region (van Proosdij and Townsend, 2006), and is an important contributor to the sediment budget of the high marsh (Dionne, 1985, 1989; Troude and Sérodes, 1988; Drapeau, 1992; van Proosdij et al., 2006). Ice in tidal flats is also important in the dispersal of macro-invertebrates and in the dynamics of spatially separated populations of the same species (Drolet et al., 2012).

Small changes in average seawater temperature have been associated with changes in abundance and distribution of coastal vegetation, finfish and shellfish (Burkett and Davidson, 2012). For fish such as salmon and eels, which use coastal habitats (salt-marsh creeks, estuaries and rivers) during part of their life cycle, temperature-induced changes will have great effects on some of their life stages and growth (Todd et al., 2008). Spawning is of special concern, as small increases in water temperature can reduce survivorship by affecting egg mortality and hatching (Pankhurst and Munday, 2011). Increased maximum summer water temperature was an important factor in the disappearance of marine eelgrass (*Zostera*) along Chesapeake Bay (east coast of the United States), near the southern distribution limit of this species (Burkett and Davidson, 2012). The condition of eelgrass beds is also a concern for Canada's East Coast region, as it is considered a prime indicator of overall coastal-ecosystem health.

Invasive species are another risk to ecosystems associated with warming water temperatures, with potential impacts on individuals, species' genetics, population and community dynamics, and ecosystem processes (Rockwell et al., 2009). These impacts can be localized or felt more broadly across the region (DFO, 2012a). Invasive alien species can disrupt food webs, resulting in a decrease in productivity for species such as oysters and eelgrass that are important in maintaining the structure of coastal ecosystems and habitats (Rockwell et al., 2009). Some studies attribute a marked decline in eelgrass health in Nova Scotia to an increase in invasive species such as the European green crab (*Carcinus maenas*; Garbary et al., 2014.) However, direct evidence of the effects of climate change on both eelgrass and invasive species such as green crab are still limited. Many of the invasive alien species that have already entered marine waters of the East Coast region are tunicates (filter feeders) that attach themselves to rocks or other surfaces of the sea floor. The shellfish aquaculture industry (e.g., mussel, oyster) is especially vulnerable to invasion by alien tunicate species, which can form significant colonies on the cultivated shells (Klassen, 2013). Examples include Club tunicate (*Styela clava*), observed in the Gulf of St. Lawrence and off Prince Edward Island; Diplosoma tunicate (*Diplosoma listerianum*), observed in eastern Canada; and European sea squirt (*Ascidiella aspersa*), observed off the coasts of Nova Scotia.

4.2 HYPOXIA

Hypoxia (also termed the 'dead zone') can result from eutrophication of coastal waters through overloading of nutrients (i.e., nitrogen, phosphorus, silicon and organic matter), leading to a depletion of the dissolved oxygen content of the water. Hypoxia can result in fish kills and mortality losses in other species, altered physiological development and growth (including reproductive abnormalities), altered migration patterns, loss of habitat for bottom-dwelling fishes and other benthic fauna, and habitat compression for pelagic fishes. These altered conditions result in reduced fish stocks, including those of valuable finfishes and crustaceans (Rabalais et al., 2010).

Hypoxia can also be related to large-scale ocean-water circulation. Historical data reveal that hypoxia is progressively worsening in the deep waters of the Gulf of St. Lawrence, especially at the heads of the Laurentian, Anticosti and Esquiman channels (Figure 8; DFO, 2010). Oxygen levels in these areas have declined since 1932 as a result of a higher influx of warm, oxygen-poor North Atlantic water and a reduced input of oxygen-rich cold water from the Labrador Current (DFO, 2012a). Hypoxic conditions drive away many fish, mollusc and crustacean species that cannot survive in oxygen-depleted conditions. In the St. Lawrence estuary, 5% of the Atlantic cod (*Gadus morhua*) tested died within 96 hours of exposure to 28% saturation, whereas half of the fish died within 96 hours when exposed to 21% saturation (DFO, 2012a). Cod almost completely avoid those areas of the estuary and Gulf of St. Lawrence where near-bottom levels of dissolved oxygen are less than 30% saturation (DFO, 2012a).

As surface-water temperatures increase due to climate change, it is likely that water stratification will strengthen, worsening hypoxia where it currently exists and facilitating its formation elsewhere. In areas of increased precipitation, increases in fresh-water discharge may result in increased

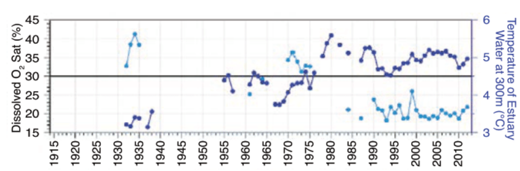

FIGURE 8: Dissolved oxygen saturation (O_2 Sat; light blue dots) and temperature (T; dark blue dots) between 295 m and the bottom in the deep central basin of the St. Lawrence estuary; 30% saturation marks the threshold of hypoxic conditions (DFO, 2010).

runoff of nutrients to coastal waters. The cumulative effect of increasing nutrient concentrations and enhanced water-column stratification will aggravate and accelerate hypoxia (Global Environment Facility Scientific and Technical Advisory Panel, 2011).

4.3 ACIDIFICATION

Increasing ocean acidification on a global scale is a major finding of the IPCC Fifth Assessment Report (IPCC, 2013). Effects of acidification include (Pörtner et al., 2014):

- dissolution of corals and carbonate exoskeletons;
- changes in benthic-invertebrate and fish productivity;
- increased growth of certain seaweeds and sea grass;
- changes in species composition and dominance;
- societal and economic impacts; and
- other potential impacts that presently remain unknown.

In the East Coast region, monitoring in the Gulf of St. Lawrence indicates that there has been no significant change in the pH of surface waters since 1934 (DFO, 2012a). In the St. Lawrence estuary, waters at greater than 100 m depth are acidifying faster than the surface waters because of *in situ* processes; this trend is not directly related to increased greenhouse gas emissions (Scarratt and Starr, 2012). In the Scotian Shelf area, pH has declined by about 0.1–0.2 units since the early 1930s (Stewart and White, 2001).

Many commercially important shellfish species harvested in Nova Scotia, such as the American lobster (*Homarus americanus*) and Atlantic deep-sea scallop (*Placopecten magellanicus*), and many aquaculture species, such as the blue mussel (*Mytilus edulis*), American oyster (*Crassostrea virginica*) and quahog clam (*Mercenaria mercenaria*), are vulnerable to acidification during the fertilization, cleavage, larval settlement and reproduction stages (Curren and Azetsu-Scott, 2013).

4.4 SALINITY

Records of ocean salinity for some areas of the East Coast region are available from the late 1940s, enabling calculation of decadal variability. Since the 1960s, for example, the Scotian Shelf area has seen oscillating periods of cold, fresh water (1960s, 1980s, 1990s) and warm, more saline water (1970s and 2000s; Breeze et al., 2002). The 1990 decadal mean surface salinities for the Gulf of St. Lawrence, the Scotian Shelf and the Bay of Fundy were the lowest ever recorded (Drinkwater and Gilbert, 2004).

Recent studies have reported a further decrease in salinity (freshening of water) off the coast of Nova Scotia (Scotian Shelf and Gulf of Maine; Drinkwater and Gilbert, 2004; Greene et al., 2008), potentially resulting from the melting of Arctic sea ice. As Arctic sea ice continues to melt in the future, the resulting pulses of fresh water will increase the strength of the southward-flowing Labrador Current and reduce sea-surface salinity. This could result in biogeographic changes of some species, such as was documented for the boreal plankton *Neodenticula seminae*, which is now common in the North Atlantic flora (Greene et al., 2008). Based on sedimentary records, this Pacific Ocean plankton species had not been present in the East Coast region for 800 000 years (Nye, 2010).

Under climate change, it is projected that the North Atlantic Oscillation (NAO; *see* Chapter 2) will be dominantly in a positive phase, shifting the warmer water of the Gulf Stream northward and increasing the volume of cold water transported by the Labrador Current (Frumhoff et al., 2007). A projected decrease in annual outflow from the Great Lakes watershed will also impact the circulation and salinity of the Gulf of St. Lawrence (Dufour and Ouellet, 2007).

Organisms can respond in several ways to these changes in temperature and salinity, but a shift in spatial distribution is the hypothesized first response (Nye, 2010). The responses of natural ecosystems are likely to be nonlinear, such that change may not occur until a threshold has been reached, at which time rapid, dramatic transitions may be expected (Dufour and Ouellet, 2007).

4.5 WATER QUALITY

Coastal water quality affects many parameters that govern the overall health and functioning of marine ecosystems (Burbridge, 2012). Water quality could suffer in areas experiencing increases in rainfall. For example, heavy precipitation events can cause problems for water infrastructure, as sewer systems and water-treatment plants can be overwhelmed by the increased volume of water. Heavy downpours can also increase the amount of runoff into rivers and lakes, washing sediment, nutrients, pollutants, trash, animal waste and other materials into water supplies, making them unusable, unsafe or in need of additional water treatment.

In the East Coast region, there has been no systematic monitoring of coastal-water quality that would enable a spatial or trend analysis of the quality of coastal marine waters (Burbridge, 2012) and possible linkages to climate change versus other human activities. Apart from data required to determine the safe levels of specified contaminants found in fish, shellfish and fish products (Stewart and White, 2001; Simms, 2002), water quality in nearshore coastal environments remains largely unknown (Mercer Clarke, 2010). Contaminant concentrations in water, sediments and/or biota have been measured in a number of provincial harbours and estuaries, as well as in the open waters of the Scotian Shelf, the Bay of Fundy and the Gulf of St. Lawrence. For most open-water sampling sites, contaminant concentrations are low (i.e., at or near background concentrations) and there is little or no indication that environmental harm can be attributed to the contaminants (CBCL Limited, 2009). Contamination has been documented at sites in proximity to urban and industrialized centres, such as Halifax Harbour, NS; Sydney Harbour, NS; Strait of Canso, NS; Clam Harbour, NS; and the area of Belledune, NB.

4.6 SALTWATER INTRUSION

Saltwater intrusion is the infiltration and mixing of seawater with fresh water stored in the pores and fractures of the underlying soil and bedrock of coastal lands. The seawater–fresh-water interface is naturally dynamic and fluctuates in response to changes in recharge, withdrawals and sea level. Displacement of fresh water by seawater occurs as seawater moves inland as a result of sea-level rise, storm surge, coastal erosion or prolonged dry periods (Phan, 2011; Loaiciga et al., 2012).

Saltwater intrusion is expected to become a more prominent issue as a result of climate change, although increasing demand for groundwater resources will be a more important driver than sea-level rise. Warmer summers are likely to lead to increased withdrawals of groundwater (Government of Prince Edward Island, 2011), particularly if this is associated with increased tourist demand. Although sea-level rise increases the risk of seawater intrusion and well contamination, the extent of this increase is not well understood (Chang et al., 2011). Increased coastal flooding associated with sea-level rise and storm surges could contaminate potable-water wells with saltwater.

A large proportion of the population of the East Coast region (nearly 100% in the case of Prince Edward Island and the Îles de la Madeleine) relies on groundwater for potable water (Rivard et al., 2008). Examples of groundwater impacts associated with natural and/or human factors are documented for every province in the East Coast region:

- **New Brunswick:** Shippagan and Richibucto (due to overpumping; MacQuarrie et al., 2012); many private wells are intermittently contaminated by seawater during storm surges in Le Goulet
- **Nova Scotia:** Upper Lawrencetown and Pictou (due to development and increased groundwater demand); Pugwash and Wolfville (Ferguson and Beebe, 2012)
- **Prince Edward Island:** Summerside (due to overpumping; Hansen, 2012); York Point and Souris West (caused by natural saltwater intrusion); Prince Edward Island is particularly vulnerable to saltwater intrusion because of its geography and dependence on groundwater for potable water (Barlow and Reichard, 2010)
- **Newfoundland and Labrador:** saltwater intrusion is well documented in L'Anse-aux-Meadows (N. Catto, personal communication, 2014); the extent of saltwater intrusion at a provincial level cannot be confirmed (Adams, 2011)
- **Quebec:** there is no documented saltwater intrusion, but drawdown saltwater cones exist beneath some wells on the Îles de la Madeleine and a migration of the saltwater interface has been reported for the Île du Cap aux Meules in the Îles de la Madeleine (Chaillou et al., 2012a, b); the Îles de la Madeleine archipelago is solely dependent on groundwater resources for its water consumption and is highly vulnerable to overpumping, particularly in summer when visitor traffic currently doubles the local population.

4.7 EFFECTS ON ECOSYSTEMS

Changes in environmental conditions often result in a shift in spatial distribution of species and ecosystems (Walther et al., 2002; Parmesan and Yohe, 2003). As waters warm, for example, populations of mobile marine organisms can change spatially as the area of favourable habitats changes (Section 4.1). This seems to have been the case for some fish species of the East Coast region during the late 1980s and early 1990s, when northern cod and capelin were detected in the northwest Atlantic (Rose et al., 2000). A study of fish stocks off the coasts of North America showed that 72% of fish species shifted their overall centre of biomass northward and increased their average depth of occurrence during the period 1968 to 2007 (Cheung et al., 2011). The temperature at which these species have been found over those same 40 years has not changed (Nye, 2010), suggesting that fish are maintaining their preferred ambient temperature range by moving to higher latitudes or to deeper waters. Distributions of some northeast Atlantic species are projected to shift northward at an average rate of around 40 km per decade (Cheung et al., 2009). Projections of changes in species distribution as a result of climate change for the Gulf of St. Lawrence and the Atlantic coasts suggest that there could be a high turnover in species (i.e., many losses and many gains; Cheung et al., 2011). Differential species responses to climate change are likely to lead to trophic mismatches and/or perturbed prey-predator relationships, breaking the ecological equilibrium and leading to community reassembly (Walther et al., 2002; Beaugrand et al., 2003; Edwards and Richardson, 2004; Collie et al., 2008).

Table 4 presents the major anticipated effects on habitats in the East Coast region arising from sea-level rise and changing storm patterns. Within intertidal areas, rising temperatures will affect different beach ecosystem components. For many beach species, range extension will be a limiting factor due to the lack of dispersal capabilities at the larval stage (peracarid crustaceans), while changes in plankton communities will also impact beach macrofauna (i.e., peracarids and insects; Defeo et al., 2009).

4.8 MIGRATION OF ECOSYSTEMS AND COASTAL SQUEEZE

Coastal ecosystems dynamically adjust to changes in sea level. Field observations, including *in situ* tree stumps and roots, and fresh-water peat layers exposed at low tide or after storm events at numerous locations (Figure 9), provide evidence of the migration of coastal ecosystems due to relative sea-level rise in the past 6000 years (e.g., Garneau, 1998; Quintin, 2010).

Beaches, dunes, sand spits, barrier islands and their associated coastal marshes can adjust to increasing sea levels by continuous landward migration (Davidson-Arnott, 2005). In sandy environments, landward migration is achieved through overtopping (where waves surmount a beach crest but do not erode it, gradually adding sediments to the crest), breaching and overwash (waves surmount and erode the beach crest, depositing sediments farther landward), tidal-inlet development (leading to the formation of tidal deltas) and wind action (strong offshore winds transporting sand in the backdune and in the marsh or lagoon; Taylor et al., 2008; Jolicoeur et al., 2010; Mathew et al., 2010; Stéphan et al., 2010; Ollerhead et al., 2013). This process, which is strongly related to storms, allows sandy features to move landward and adjust vertically as sea level rises. However, high rates of relative sea-level rise can result in drowning of coastal landforms (O'Carroll et al., 2006; Kelley et al., 2013).

FIGURE 9: Photos of *in situ* tree stumps exposed at low tide or after storm events. Photos **a)** and **b)** shows tree stumps and roots that have been uncovered by erosion and **c)** shows tree stumps that been submerged by rising water levels. Locations of photos: **a)** Le Goulet, NB; **b)** Barachois, NB; and **c)** Bras d'Or Lakes, NS. *Photos a) and b) courtesy of D. Bérubé, Department of Energy and Mines New Brunswick, and photo c) courtesy of S. O'Carroll, Geo Littoral Consultants.*

TABLE 4: Projected impacts of climate change related to sea-level rise and changes in storm patterns on the coastal habitats of the East Coast region (*adapted from* Nye, 2010).

Coastal feature	Impacts
Beaches	Large-scale morphological adjustments to absorb the wave energy, including: ▪ overwash and erosion ▪ potential formation of new beaches down-drift of erosion areas ▪ landward migration of barrier beaches
Salt marshes	More frequent tidal flooding Sedimentation and possible landward migration at a rate equal to sea-level rise, depending on sediment and organic matter supply Increased margin-edge erosion (van Proosdij et al., 2006) Changes in carbon storage (Chmura, 2011)
Fresh-water marshes	Gradually become salt marshes or migrate inland
Estuaries and tidal rivers	Increased tidal volume and exchange Further penetration of saltwater
Unconsolidated cliffs	Accelerated erosion
Species and ecosystems	Modification of coastal habitats Threatened viability from changes in numerous factors, including water temperature, salinity, sea-ice patterns, runoff and water quality

In coastal marshes, fine-grained material deposited on, and/or organic matter produced in, the marsh raises the surface, keeping it in the same position relative to sea level (Allen, 2000). Gradually, a transition from low-marsh to high-marsh vegetative communities evolves and, in ideal settings, the marsh migrates landward. Again, if sea level rises faster than the sediments can be supplied, marshes can be flooded and replaced by open water, as was observed in southeastern New Brunswick between 1944 and 2001 (Hanson et al., 2006). Changes in sediment supply will also affect marsh survival. Kirwan and Megonigal (2013) demonstrated that, under moderately rapid sea-level rise, a marsh that is stable under historical sediment loads would submerge if the sediment load is reduced. This suggests that dam construction and land construction that result in the reduction of sediment load could cause marshes to become less stable in the future, even if the rate of sea-level rise were to remain constant.

Marshes developed in areas of high tidal range and high sediment availability are generally considered more resilient to sea-level rise than those developed in areas of low tidal range and low sediment availability (Chmura et al., 2001; Paskoff et al., 2011; Bowron et al., 2012). In the East Coast region, historical rates of salt-marsh aggradation range from 1.3 mm/year along the Northumberland Strait coast of New Brunswick to 4.4 mm/year in the upper reaches of the Bay of Fundy (Chmura et al., 2001; Davidson-Arnott et al., 2002; van Proosdij et al., 2006; Bowron et al., 2012). Along the St. Lawrence estuary, average vertical accretion rates range from 1 to 2 mm/year, and as high as 3 mm/year in about 10% of cases (Dionne, 2004).

Vertical accretion rates can adjust to changes in the rate of relative sea-level rise (Kirwan et al., 2010). While cyclicity in edge erosion and progradation is part of natural marsh evolution at the decadal scale (Allen, 2000; Ollerhead et al., 2006; van Proosdij et al., 2006; van Proosdij and Baker, 2007; Allen and Haslett 2014), marshes will migrate landward if there is space for them. However, retreat cannot occur where natural slopes behind the marsh are too steep, or where the path is blocked by structures such as roads, seawalls, dikes or buildings, creating a situation known as 'coastal squeeze' (Figure 10; Doody, 2013; Pontee, 2013; Torio and Chmura, 2013).

Coastal squeeze is not exclusive to coastal marshes but can also apply to other types of coastal ecosystems (e.g., beaches, dunes) and includes natural constraints, such as cliffs, that may limit landward migration (Figure 10c; Sterr, 2008; Jackson and McIlvenny, 2011; Doody, 2013; Hapke et al., 2013). In the East Coast region, studies in the Baie des Chaleurs, NB (Bernatchez and Fraser, 2012) and in the Îles de la Madeleine, QC (Jolicoeur and O'Carroll, 2007) have shown that the presence of human infrastructure is causing the loss of coastal habitats. In the Baie de Kamouraska, QC, dikes constructed to convert marsh into farmland are squeezing the intertidal zone as sea level rises. Increasing development of the coastal zone across the region increases coastal squeeze and could lead to loss of valuable marshes, dunes and beaches in coming decades (Jolicoeur and O'Carroll, 2007; Craft et al., 2009; Bernatchez et al., 2010; Feagin et al., 2010; Doody, 2013; Torio and Chmura, 2013; Cooper and Pile, 2014).

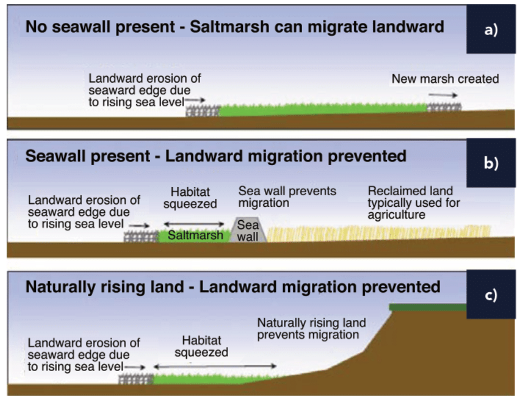

FIGURE 10: Illustration of the landward migration and prevented landward migration of coastal habitat that has been eroded by rising sea level: **a)** landward migration occurs naturally, **b)** migration has been prevented by a sea wall resulting in the 'squeeze' of habitat, and **c)** migration has been prevented by naturally rising land resulting in the 'squeeze' of habitat (Pontee, 2013 *adapted from* Doody, 2013).

4.9 IMPACTS OF HUMAN ALTERATIONS ON THE COAST

Human activities leading to changes in land use, water-courses and shorelines have already impacted nutrient and contaminant runoff, storm-water management and water quality in areas of the East Coast region. Shoreline hardening with various protection methods (walls, rip-rap, dikes, groins, pavements and landfill) and dredging have altered coastal circulation patterns and sediment transport, potentially exacerbating shoreline erosion and reducing the ability to attenuate flooding (Section 6.3.4; e.g., Hapke et al., 2013; Pontee, 2013). Changes to land cover can destroy or impair native-species habitats (Ban and Alder, 2008; Halpern et al., 2008; Burkett and Davidson, 2012). The use of hard engineering measures to protect societal assets can lead to the loss of intertidal sand habitat (Defeo et al., 2009; Leclerc, 2010; Bernatchez and Frazer, 2012; Spalding et al., 2014). Measures that promote the resilience of coastal areas include protection, revegetation and stabilization of dunes; maintenance of sediment supply; and provision of buffer zones, rolling easements or setbacks that allow landward migration of the coastline (*see* Chapter 3; Defeo et al., 2009).

Understanding how, and to what degree, a coastal system will be modified by climate change remains a challenge, given the complex interrelationship between natural and human systems. This is highly evident within the extensively diked estuaries of the Bay of Fundy, where many of the main rivers draining into the bay have been fully or partially obstructed (van Proosdij and Page, 2012). An engineering structure, such as a dike, that reduces the extent of tidal flooding, a structure that decreases the cross-sectional area of a channel or the closure of a section of an estuary will, as a consequence, change the magnitude of the characteristic tidal discharge (van Proosdij and Baker, 2007; van Proosdij et al., 2009). This can lead, in turn, to rapid sedimentation and/or alteration of the intertidal morphology of the estuary and position of intertidal habitat. The response of the system, however, depends on a large number of factors, including sediment properties, estuary morphology and the timing and sequence of engineering alterations (*see* van Proosdij et al., 2009 for comparison of Petitcodiac River, NB to Avon River, NS).

5 COMMUNITIES AND ECONOMIC SECTORS

Coastal communities and economic activity in the East Coast region will be affected by the climate-related changes described in Sections 3 and 4, especially those associated with coastal hazards, including erosion and storm-surge flooding (Hughes and Brundit, 1992; Arkema et al., 2013). The impacts associated with climate change reflect both the degree of exposure to natural hazards and the vulnerability of the system exposed (Figures 11, 12). Vulnerability, or the predisposition to be adversely affected, encompasses a variety of elements, including sensitivity to harm and the capacity to cope with changes or to adapt to them (*see* Chapter 1, Box 4 for definitions of key terms). Adaptive capacity is influenced by access to resources, as well as important social factors. Adaptation actions are undertaken with the goal of reducing risks or taking advantage of opportunities. However, many human alterations to the coast have proven to be maladaptive in that they affect coastal processes in ways that increase the vulnerability of coastal ecosystems, communities and infrastructure.

This section examines the concepts of exposure, sensitivity and capacity to adapt, using examples from the East Coast region. It then provides an overview of recent initiatives to document vulnerabilities, and highlights climate change impacts as they relate to key economic activities (e.g., fisheries, transportation and tourism) and community health, well-being, culture and heritage.

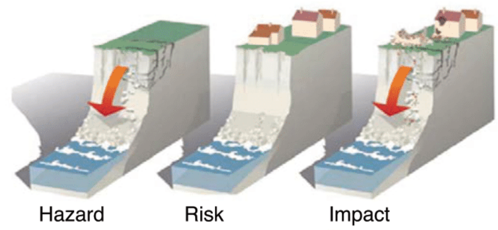

FIGURE 11: Coastal hazards, risks associated with exposure of valued assets (including ecosystem services) and impacts (*adapted from* Ministère de l'Écologie et du Développement durable de France, 2004).

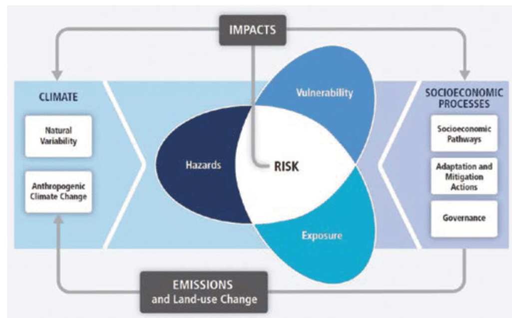

FIGURE 12: Climate impacts associated with coastal risks result from the interaction of coastal hazards and the vulnerability of exposed systems (*from* IPCC, 2014).

5.1 EXPOSURE

Exposure refers to the presence, in places and settings that could be adversely affected, of people; livelihoods; species or ecosystems; environmental functions; resources; infrastructure; or economic, social or cultural assets (IPCC, 2014). In coastal areas, exposure is influenced by physical attributes or characteristics of the coastal zone and is directly related to the likelihood that hazardous conditions will occur (Dolan and Walker, 2006; Tibbetts and van Proosdij, 2013). Settlements on a former low-lying marshland or eroding coastal bluff are more exposed to risks related to the impacts of sea-level rise, storm surge and accelerated erosion than are settlements located above the higher high tide water level or on resistant bedrock.

Exposure is often associated with the amount of wave energy reaching the coast. It is influenced by the orientation of the shoreline relative to wind and wave action, as well as features that decrease the amount of energy reaching the shoreline, such as shorefast ice, offshore sea ice, intertidal vegetation and nearshore bars. The direction of the most damaging waves varies throughout the East Coast region.

For example, winds in Prince Edward Island are mainly from the west, but the largest waves are generally from a north-northwesterly direction (Davies, 2011). In northern New Brunswick, local residents say that the most damaging wind and waves come from the northeast and refer to these winds and associated violent storms as 'les nordets' (O'Carroll, 2008). In western parts of Cape Breton, NS, damaging local winds are known as 'les suètes' and are created when a frontal inversion causes a funnelling effect over the Cape Breton Highlands. As the winds rush down the side of the highlands, strong gusts develop; these have been recorded to exceed 150 km/h.

With some exceptions, communities lying on coastlines exposed to the full swell and storm waves from the Atlantic Ocean receive the most wave energy. Wave climate and associated exposure varies throughout the year (Dufour and Ouellet, 2007) and between years (Davies, 2011). For example, the north shore of Prince Edward Island shows strong interdecadal variability, with the period 2000–2009 having more wave energy than any other decade since the 1960s (Davies, 2011). This relates, in part, to ice cover, which decreased from a mean of 103 days in the 1970s to a mean of 80 days in the 2000s (Davies, 2011) along the same shoreline.

Another factor influencing exposure is tidal range, which varies significantly across the East Coast region, from less than a metre near the Îles de la Madeleine to more than 16m in Cobequid Bay on the Bay of Fundy (e.g., Cooper and McLaughlin, 1998; Boruff et al., 2005; Rao Nageswara et al., 2008; Kumar et al., 2010; Pendleton et al., 2010; Tibbetts and van Proosdij, 2013). Coastal systems in areas with a small tidal range (microtidal) are generally less able to accommodate extreme water levels associated with storm surge, as there is a smaller area available to absorb the surge. In addition, since a storm surge would have greatest impact when it occurs at or near the high-tide level, the likelihood of damaging surge events is lower for areas with a large tidal range (macrotidal; Desplanque and Mossman, 2004).

The most common factors that reduce the flow of wave energy to coasts in the East Coast region are offshore sea ice (Section 3.3), shorefast ice (e.g., Northumberland Strait coast, Gulf of St. Lawrence, Newfoundland), sea-grass beds (e.g., Port Joli harbour, NS), foreshore marsh (salt marshes developed seaward of a dike structure; e.g., Minas Basin, NS) or dunes (e.g., north shore of Prince Edward Island), and beach barriers (e.g., spit in Bouctouche, NB or gravel barachois [coastal lagoon separated from the ocean by a sand or shingle bar] in Newfoundland). For example, coastal wave energy on the northeast coast of the island of Newfoundland can be largely muted once offshore ice cover develops, but coastlines along the southern side of the island remain vulnerable to erosion by winter storms (Taylor et al., 1997; Forbes et al., 2000; Ingram, 2004; Catto, 2011). Foreshore marshes are capable of attenuating up to 97% of incoming wave energy, depending on the size of the marsh (Möller and Spencer, 2002; Doody, 2008; van Proosdij and Page, 2012; Möller et al., 2014). Preservation and/or encouragement of foreshore-marsh habitat are examples of adaptation measures that aim to enhance and/or restore ecological processes to help decrease environmental impacts from built infrastructure (Chapman and Underwood, 2011; van Proosdij and Page, 2012).

5.2 SENSITIVITY

Sensitivity is the degree to which a system (e.g., ecosystem, community, infrastructure) is affected, either adversely or beneficially, by climate-related changes (IPCC, 2014) and is related to both the severity of the exposure and the potential consequences. Coastal settlements can be differentially sensitive to climatic risks, depending on their socio-economic and cultural characteristics, and their planning and operational structures.

Historical European settlement patterns in the East Coast region were driven largely by the need to access or transport resources such as fish, ore and wood, so infrastructure like warehouses and roads were built along or close to the shore. Throughout much of the region, communities had their beginnings providing homeports and infrastructure in support of inshore and offshore fisheries. Coastal villages were initially linked by boat transport and, when roads were built, they followed the historical pattern. Throughout French-Acadian Nova Scotia, extensive dike systems were constructed by early settlers to drain fertile salt marshes for agriculture purposes. Major ports constructed in Saint John, NB, Halifax, NS, St. Johns, NL and Québec, QC evolved to continue trade links with eastern North America and Europe.

Sensitivity to climate impacts is influenced, in part, by the persistence of these early settlement patterns despite the fact that, in some cases, contemporary industries bear little resemblance to activities of the past. This is particularly notable in diked marshlands, which were formerly harvested for highly valued salt-marsh hay (Lieske, 2012). For example, the Chignecto Isthmus region (which joins the provinces of Nova Scotia and New Brunswick) underwent a shift from a major hay-production centre to a critical transportation and communications corridor that annually moves $43 billion worth of international trade goods. Yet infrastructure throughout many of the towns and villages in the region continues to rely on approximately 33 km of the early agricultural dikes for protection against the rising tides

(Webster et al., 2012b; Wilson et al., 2012). A once-in-10-years storm surge could overtop approximately 90% of the existing dike system and temporarily inundate 20% of the Town of Sackville, NB (Lieske and Bornemann, 2012).

Contemporary development patterns are also influenced by tourism and recreation opportunities, such as cottages and seasonal rentals close to the coast. The small chalets and cabins that were once people's secondary residence are now often modified to become principal homes. This is evident along most shores of the East Coast region, particularly along the shores of Northumberland Strait, the north shore of Prince Edward Island and the southern shores of Nova Scotia. These changes significantly increase the asset value at risk from coastal hazards (Delusca et al., 2008), not only in terms of absolute dollars but also because different levels of risk are tolerated for secondary and principal residences.

Sensitivity is also related to the degree to which the hazard impacts areas of environmental, social, economic and cultural significance. For example, a community that becomes isolated from emergency services when its only transportation link has been flooded or destroyed is more sensitive than one that has more options for access to services and/or evacuation. This was illustrated in 2010, when rainfall associated with Hurricane Igor washed out roads and bridges across the Burin and Bonavista peninsulas of Newfoundland. Sensitivity is also influenced by social conditions (i.e., income, age and education), community resources and social structures (Dolan and Walker, 2006; Garmendia et al., 2010; Rapaport et al., 2013). In some areas of the East Coast region, the aging rural population and their greater sensitivity to direct (e.g., flooding and excessive heat) and indirect (e.g., inability to access social support, food and medical care) climate stressors is a particular concern (Rapaport et al., 2013). Other considerations with respect to economic sensitivity include possible impacts of extreme weather events on employment and industrial infrastructure.

5.3 CAPACITY TO ADAPT

Adaptive capacity refers to the ability of a country, region, community or group to implement effective adaptation measures (e.g., IPCC, 2007; Lemmen et al., 2008). It is influenced by a large number of social, economic, regulatory and political factors (e.g., Smithers and Smit, 1997). As change becomes more rapid, the adaptive capacity of many communities may be challenged. Extreme impacts can exceed human and financial resources to address them, and can cause physical, financial and psychological stress. Stress on local governments and service providers, and other responders to disasters, can reduce adaptive capacity to address climate change impacts in both the short and long terms (Manuel et al., 2012).

Within the East Coast region, there has been a surge in provincial and local government initiatives and community-university research partnerships during the past decade, all focused on improving adaptive capacity and moving forward on adaptation planning for climate change. For example, the Atlantic Climate Adaptation Solutions Association is a partnership among the governments of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador that is working with the Government of Canada to assist Atlantic Canadians to better prepare for, and adapt to, climate change (Atlantic Climate Adaptation Solutions Association, 2012). In Quebec, Ouranos, a joint initiative of the Government of Québec, Hydro-Québec and Environment Canada, with the financial support of Valorisation-Recherche Québec, was created as a consortium on regional climatology and adaptation to climate change and has brought together more than 400 scientists and professionals from across relevant disciplines.

Numerous initiatives have been undertaken in recent years throughout the East Coast region to develop practical tools for adaptation planning (*see* Chapter 3) and to incentivize adaptation action (Case Study 3). Many smaller communities with limited resources have benefited by collaborating with universities and colleges across the region that can provide expertise and technological innovations (e.g., Bernatchez et al., 2008a; Fedak, 2012; Lieske, 2012; Manuel et al., 2012).

CASE STUDY 3

FINANCIAL INCENTIVE FOR ADAPTATION PLANNING: THE MUNICIPAL CLIMATE CHANGE ACTION PLAN OF NOVA SCOTIA

The federal government transfers funds equivalent to a portion of the federal excise tax on gasoline to municipalities for infrastructure projects that contribute to cleaner water, cleaner air and/or reduced greenhouse-gas emissions. In Nova Scotia, terms and conditions for 'gas tax' eligibility are defined in the Canada–Nova Scotia Agreement on the Transfer of Federal Gas Tax Funds. As a requirement for funding, Nova Scotia municipalities had to submit a Municipal Climate Change Action Plan (MCCAP) by the end of 2013. The MCCAP has served as a means of identifying priority areas for adaptive action.

Service Nova Scotia and Municipal Relations, and the Canada–Nova Scotia Infrastructure Secretariat provided a guidebook (Fisher, 2011) that outlines a six-step framework to assist municipalities with the adaptation portion of MCCAP development. Each step consists of a series of questions that, cumulatively, assess if and how local climate trends and projections would introduce or exacerbate hazards, and in what ways these changing conditions may affect people's safety, municipal services and assets, and other community characteristics (e.g., local economic functions, sense of place and community well-being, emergency preparedness planning and capacity for response).

A key to successful MCCAP development for all municipalities in Nova Scotia was the document *Scenarios and Guidance for Adaptation to Climate Change and Sea Level Rise – NS and PEI Municipalities* (Richards and Daigle, 2011), which provided a common starting point with respect to climate trends and projections. Beyond this foundation document, the quality of an MCCAP was defined largely by a municipality's internal capability to interpret climate trends and projections in a local context, in order to understand what impacts are likely and the potential severity of their consequences.

A recent survey of municipal climate change adaptation around the Bay of Fundy indicated that a combination of factors, including limited staff time and expertise, stretched budgets and lack of jurisdictional authority, make it difficult for municipalities to address even well-documented vulnerabilities to climate change (Schauffler, 2014). The MCCAP process highlighted several findings, including that key factors such as geology are often excluded in land-use planning decisions. In large part, this is a reflection of the high daily demands placed on the land-use– and community-planning sector, and the lack of support to seek out and include additional information when developing long-term land-use strategies. Other challenges highlighted by the MCCAP process include the following:

- The limited jurisdiction of municipalities makes it difficult to address some key climate risks. For example, private wells are controlled provincially. Therefore, although a community may experience significant social and economic impacts from wells going dry, it is not involved in groundwater monitoring, management or well permitting. In addition, there are a number of issues (e.g., extension of water services) that fall under provincial jurisdiction where municipal units could play a greater role in shaping regional responses to climate change adaptation.
- Some of the scientific and technical information that municipalities sought was unavailable or not easily accessible. The MCCAP process highlighted what information or tools are helpful for municipalities to enhance climate resilience, and raised the question of who should be responsible for the collection and dissemination of that information. As municipalities do not have experts in coastal processes on staff, they must seek external expertise if, for example, erosion is an issue worthy of investigation.

Despite these challenges, the Nova Scotia MCCAP process can be considered a success in many ways. For example, the inclusion of emergency-management personnel on municipal climate change committees and the collaborative assessment processes renewed recognition of the relationship between land use and disaster-risk reduction and response. This prompted improvements in information exchange (i.e., mapping) and collaboration between these two facets of municipal management.

Municipalities generally came to a shared conclusion that they had an important role to play in helping residents manage their own risk by sharing what was learned about climate risks during the MCCAP process. Simultaneously, judgments were made as to when providing information may prove insufficient, and when policy is needed to control development with the aim of reducing risks. It was also recognized that seldom will 'one-size-fits-all' policies work when addressing coastal hazards, so site-specific work is needed to balance a municipal responsibility to respond to known (or suspected) risk and the desire to allow appropriate use of a property. The MCCAP process has led to notable progress at the provincial level to organize, improve upon and disseminate relevant data to municipalities.

By requiring that MCCAPs consider social and economic climate impacts, there has been a subtle yet profound shift from climate-adaptation planning being considered a one-off research topic to it becoming a process through which a municipal corporation actively gauges trends in external forces (i.e., macroeconomics, demographics, health and governance) in combination with honest self-evaluation. This is an approach that provides benefits no matter how the climate unfolds.

Advances in technology and an increased ability to translate data into knowledge have increased adaptive capacity across the East Coast region. High-resolution LIDAR (Light Detection and Ranging) topographic surveys and advanced geographic information systems have enabled inundation studies at many sites in the East Coast region (e.g., Daigle, 2006; Robichaud et al., 2011; Fedak and van Proosdij, 2012; Webster et al., 2012a; Lieske et al., 2014; Daigle et al., 2015). Effective identification of hazard areas for planning purposes has also been conducted with coarser, digital elevation models (e.g., Isle Madame, St. Margarets Bay, Cape Breton and parts of the south coast of Nova Scotia; Lane et al., 2013; Rapaport et al., 2013).

5.4 VULNERABILITY ASSESSMENTS

During the past decade, there has been a significant increase in the number of vulnerability assessments performed in the East Coast region, most in the form of technical reports. In developing this chapter, 226 individual studies conducted since the late 1990s were inventoried for the East Coast region. Many of these studies covered more than one community. The studies were grouped in broad categories in order to paint a picture of the work carried out and the focus of research so far (Figure 13). Note that the inventory is limited to publicly and readily accessible documents, and is therefore not exhaustive.

Of the studies compiled, more than 40% of those conducted in Prince Edward Island, Quebec and New Brunswick focused on coastal erosion. Vulnerability and ecosystem restoration studies are prominent in Nova Scotia, with special reference to the MCCAPs and the extensive diked areas of the province. In Newfoundland and Labrador, flooding dominated the literature examined (60%). It should be noted that the extensive province-wide assessments of erosion by Catto (2011) and Webster (2012) in Newfoundland and Prince Edward Island, respectively, are likely not adequately represented in this analysis.

Areas where communities currently lack significant assessment, such as the eastern shore of Nova Scotia, the mid-Fundy shore of New Brunswick, much of Newfoundland and Labrador, and the Quebec North Shore, are evident in Figure 13. Addressing some of these gaps may be assisted by increased accessibility of public data. For example, the New Brunswick Government is in the process of making its Coastal Erosion Databank public, so that more than 14 500 erosion rates will be accessible online via an interactive map (D. Bérubé, personal communication, 2015). Erosion data for Newfoundland and Labrador will also soon be available online as an interactive map (N. Catto, personal communication, 2015).

Although there are multiple methods for assessing coastal vulnerability, the most common methods utilize indices that simplify a number of key parameters to create a single indicator (Carrasco et al., 2012). The earliest studies of coastal vulnerability were based largely on biophysical characteristics, defining vulnerability in terms of exposure to a hazardous event regardless of impacts on social conditions (Abraham et al., 1997; Dolan and Walker, 2006). This approach has been commonly used in the East Coast region with a primary focus on coastal erosion and flooding due to sea-level rise and/or storm surge. In limited areas, two- and three-dimensional hydrodynamic modelling studies have been performed to assess the velocity of flood water versus depth (e.g., Wolfville, NS; Fedak, 2012; van Proosdij, 2013), the coupled effect of fresh-water drainage and tidal surge in an estuarine area (e.g., Oxford and River

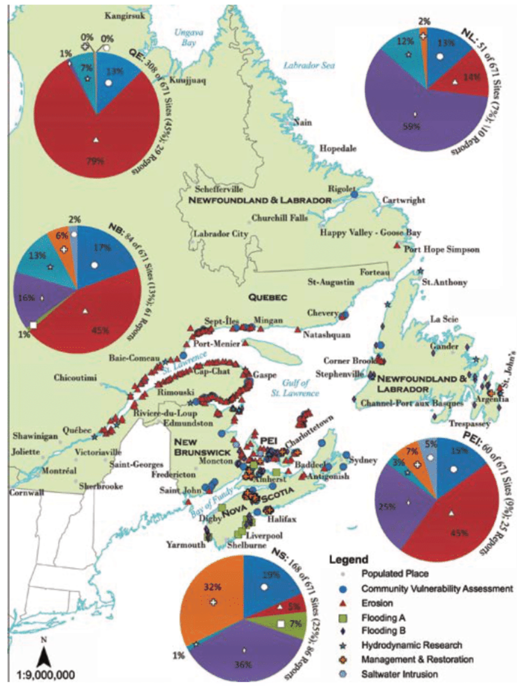

FIGURE 13: Spatial compendium of sites examined through vulnerability studies in the East Coast region. Legend categories include community vulnerability assessments, erosion (rate, shoreline adjustment, geological studies), flooding A (general extent with SLR), flooding B (SLR and/or storm surge with infrastructure and/or social variables), hydrodynamic (1-D and 2-D models and scenarios), management and restoration (shoreline restoration and management/policy assessments), and saltwater intrusion (intrusion or transition studies). The inventory was limited to publicly and readily accessible documents, and is therefore not exhaustive. Compendium compiled by B. MacIsaac and cartography by B. Perrott (Maritime Provinces Spatial Analysis Research Centre, Saint Mary's University).

Philip, NS; Webster et al., 2012b) and the effect of wave run-up (e.g., Halifax Harbour, NS; Xu and Perrie, 2012).

Coastal erosion indices have been produced for the entire coasts of the island of Newfoundland (Catto, 2011), the North Shore of the Gulf of St. Lawrence (Dubois et al., 2005), the Îles de la Madeleine (Bernatchez et al., 2012b), New Brunswick (O'Carroll et al., 2006; O'Carroll, 2008) and Prince Edward Island (O'Carroll, 2010b; Webster, 2012). Smaller, geographically focused studies of rates of coastal erosion have been conducted in Nova Scotia (Fink, 2007; Utting and Gallacher, 2009; Force, 2012), Quebec and New Brunswick (Section 3.4). Catto (2012) has advocated the differentiation of long-term (e.g., sea-level rise) versus short-term (e.g., episodic storms) drivers of coastal erosion.

Individual events, such as the January 2000 storm that impacted southwestern and southern Newfoundland (Forbes et al., 2000; Catto et al., 2006) and Hurricane Igor in 2010 (Catto, 2011), can result in extensive coastal erosion unrelated to sea-level rise or other long-term changes. Other studies that have documented significant morphological changes in response to storm conditions include those of post-tropical storm Noel (Taylor et al., 2008) and the surge associated with a February 2013 blizzard in Nova Scotia (Taylor, 2014).

With respect to future rates of change in shoreline position, most studies make inferences based on historical analyses and assume a linear relationship. Alternative approaches include those applied to Prince Edward Island, in which erosion rates and shoreline position were based on computer analyses of longshore transport within littoral cells and the derivation of a coastal-sediment budget per cell (*see* Chapter 2; Davies, 2011). This approach permits consideration of seasonal cyclicity and movement of sediment within each cell. MacDonald (2014) incorporated these processes to document changes in physical coastal vulnerability over time as the position of the coastline changes. An economic assessment of the impacts of erosion on the coastal infrastructure in Quebec revealed that, by the year 2065, 5426 buildings will be exposed to erosion if no adaptation measures are undertaken (83% of these buildings being dwellings), and 294 km of roads and 26 km of railroads will likewise be exposed. The combined value of this infrastructure is 1.5 billion dollars (Bernatchez et al., 2015).

Studies focused on the physical effects of erosion and/or inundation on residential, commercial and institutional infrastructure include those initiated in response to concerns in the communities of Le Goulet, Shippagan and Bas-Caraquet in northeastern New Brunswick, that were seeking detailed information on storm-surge levels and coastal-erosion maps to aid in the development of municipal plans (Robichaud et al., 2011; Aubé and Kocyla, 2012; Jolicoeur and O'Carroll, 2012). The studies assigned levels of risk to infrastructure based on a ratio of building height to flooding depth (Robichaud et al., 2011; Aubé and Kocyla, 2012). Maps were produced showing the intersection of flood extent and erosion zones with known infrastructure using aerial images, LiDAR surveys and available tidal and/or storm-surge data. The maps facilitated the participation of community members in identifying and agreeing to zoning-plan proposals with specific future time references (Robichaud et al., 2011; Aubé and Kocyla, 2012; Jolicoeur and O'Carroll, 2012). The five Mi'kmaq communities of the Bras d'Or Lakes recently completed a similar assessment of their coastal reservations as part of a first phase of assessing their vulnerability to climate change and identifying adaptation options (Daigle et al., 2015).

Another method for determining vulnerability involves integrated assessment of physical and social vulnerabilities. For example, an integrated team approach that combined physical-risk assessment (i.e., effects of sea-level–rise scenarios and/or storm surges on infrastructure) with social assets (i.e., beaches, parks and walking trails) and social values was used to examine avoidance, protection, accommodation and retreat options for specific locations in Yarmouth and Lunenburg, NS, and uses of community structures and spaces (Cochran et al., 2012; Johnston et al., 2012; Muise et al., 2012; Wollenburg et al., 2012). The work also tested different visualization techniques, ranging from static to interactive computer displays and a three-dimensional (3-D) physical model to depict flooding levels, in terms of their effectiveness in communicating risks. Although photo simulations were found to be the most engaging, a range of tools was considered to be beneficial (Maher et al., 2012). Coastal Impact Visualization Environment (CLIVE) is a geovisualization tool that allows users to combine data from numerous sources, including an extensive province-wide archive of aerial photographs, and the latest high-resolution digital elevation data (LIDAR) to develop analytical visualizations of coastal erosion regimes and scenarios of potential future sea-level rise (Hedley et al., submitted). The tool has been used to assess the vulnerability of coastal infrastructure on Prince Edward Island (Fenech et al., submitted).

Vulnerability assessments often emphasize the importance of incorporating the views of local residents, their experiences in dealing with past climate impacts and traditional knowledge. Community-level assessments can stimulate change, enhance community buy-in for solutions and provide a voice for those being affected, as well as record experiences of elders in the communities. Reports on the Prince Edward Island communities of Victoria, North Rustico, Mount Stewart and Souris incorporated key informant interviews with community members that included their personal historical photos and memories (Government of Prince Edward Island, 2011). In other areas, such as Sackville, NB, simple climate change adaptation tool kits have been developed for use by the local community (e.g., Marlin, 2013). The community of Cheticamp in Cape Breton, NS experienced a range of engagement activities from coastal monitoring to social media and the arts led by the Ecology Action Centre and academic and public partners (Brzeski, 2013).

5.5 IMPACTS

The effects of climate change are already being felt in the East Coast region and will continue to affect many aspects of life, ranging from health and well-being of human populations to the economy. A large number of the broad policy areas related to coastal planning and management, including economic development and public safety, will be impacted to greater or lesser degrees by climate change

(CBCL Limited, 2009). Although quantitative analysis of economic impacts is lacking for almost all sectors, ongoing research is beginning to address this gap (*see* Chapter 7, FAQ 11). This section briefly addresses three areas of impacts and associated vulnerabilities in the East Coast region: economy, public safety, and culture and heritage.

5.5.1 ECONOMY

The East Coast region's economy will experience both negative (e.g., infrastructure damage) and positive (e.g., longer tourism season) impacts as a result of climate change. Available research identifies agriculture, fisheries and tourism as being particularly sensitive to climate change, along with development and transportation of offshore oil and gas (Vasseur and Catto, 2008). A cross-sectoral concern is the potential impacts on infrastructure, including residential, commercial and institutional buildings.

While available literature focuses primarily on risks to economic sectors, one example of a potential opportunity arising from climate change is increased crop production and diversification of the agriculture industry as a result of longer growing seasons (Vassseur and Catto, 2008). This positive impact for agriculture could be partially or completely offset by negative impacts associated with insect outbreaks and other disturbances (Vasseur and Catto, 2008).

FISHERIES

The 598 small-craft harbours in the East Coast region reflect the importance of fisheries to this part of the country (Table 5). In 2010, East Coast fisheries accounted for 80% of the total volume of landings by weight and 86% of registered salt- and fresh-water fishing vessels in Canada (DFO, 2013a). In 2011, the commercial sea fishery in the East Coast region accounted for $1.82 billion in landed value and 710 530 metric tonnes (live weight) in commercial landings. The bulk of these landings were located in Nova Scotia, and Newfoundland and Labrador (Table 5).

The economic value of fisheries extends well beyond the landed value. In Nova Scotia, for example, commercial fisheries, post-catch processing and aquaculture cumulatively contributed more than $1.1 billion to the province's gross domestic product in 2006, with the majority of this being attributed to shellfish (Gardiner Pinfold Consulting Economists Ltd., 2009). The lobster fishery alone in the four Atlantic Provinces is valued at $550 million/year (Seiden et al., 2012).

Changing climate affects many aspects of fisheries ecology, including migration patterns and the timing of spawning and life-stage development, with significant economic implications. Wahle et al. (2013, p. 1571) termed 2012 "the year that drove climate change home" to the American lobster fishery. An ocean heat wave resulted in a glut of lobsters from the New England states before the close of the Canadian fishery, causing a dramatic drop in prices (Wahle et al., 2013). Changing migration patterns are resulting in mackerel (*Scomber scombrus*) arriving in the East Coast region later in the summer, such that their appearance no longer overlaps with the spring lobster and snow crab (*Chionoecetes opilio*) seasons. As mackerel is a staple bait species, the lack of bait is another stress for the local lobster-fishing industry. Bait purchased elsewhere is not cost effective for fishers, as bait prices increase with transportation and refrigeration costs (Brzeski, 2013).

In situations where capture-species populations become so depleted, whether as a result of changing climate, overfishing or other stressors, there are historical examples of fishers changing to focus on other species (Brzeski, 2013). However, regulatory regimes tend to limit this adaptation response (Charles, 2009; Miller et al., 2010), and Vasseur and Catto (2008) noted the need to make changes to licensing regulations to take into account the potential for species to migrate to new areas or disappear due to climate change.

Changing climate places additional stress on the fisheries sector as a whole. Fishers in the East Coast region already face maintenance and repair costs associated with aging infrastructure (e.g., wharves and processing plants), as well as conflicts over access, harbour management and competing land use. Existing infrastructure may become less usable with higher tides and storm surges, and/or accelerated erosion through increased wave action.

TABLE 5: Commercial fishery in the East Coast region, 2011 (DFO, 2013b, c).

Province	Small-craft harbours (fishing)	Live weight (metric tonnes)	Landed value ($)	Landed value ($/tonne)
Nova Scotia	163	258 677	731 992 000	2 829
New Brunswick	68	81 760	175 196 000	2 143
Prince Edward Island	46	30 789	111 106 000	3 609
Newfoundland and Labrador	264	283 923	641 978 000	2 261
Quebec	57	55 381	154 898 000	2 797

Breakwaters may be ineffective at certain points during the tide cycle or more susceptible to frequent surges. Fish plants located close to shore may be undermined or destabilized by erosion, or inefficient if wharves can no longer receive fish landings due to sea-level rise. A risk assessment by DFO (2012b) for the Atlantic basin identified damage to infrastructure (including harbours, breakwaters, wharves and navigation aids) as the greatest risk exposure to the department (Figure 14). The estimated impact of climate-related damages is very high and the likelihood of such damages is moderate to almost certain at the 10- to 50-year time scale (DFO, 2012b).

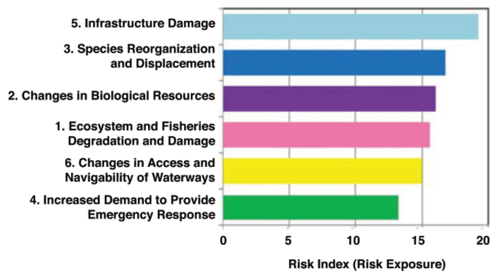

FIGURE 14: Index of climate change adaptation risks on the 50-year time scale for each of six risks identified by the Fisheries and Oceans Canada (DFO) with respect to their department operations. Risk evaluation was based on expert opinion of magnitude of impact (ranked from 0 to 5, where 5 is very high) and probability (also ranked from 0 to 5, where 5 is very high). The risk index is the product of the risk's impact and probability rankings. See DFO (2012b) for additional details on methodology.

AQUACULTURE

Climate change presents risks, and potentially some opportunities, to aquaculture, which is a rapidly growing part of the regional economy. In 2013, the East Coast region produced 49% of Canada's aquaculture by weight and 45.4% by total value ($427 million; Statistics Canada, 2014b). Newfoundland and Labrador, and Prince Edward Island are the top producers by weight, whereas Newfoundland and Labrador, and New Brunswick are the top producers by value (Table 6). Atlantic salmon (*Salmo salar*) is the most valuable species. Shellfish, particularly the blue mussel (*Mytilus edulis*), are the core of the aquaculture industry in Prince Edward Island, where the larvae are recruited from the wild and then cultured (Feindel et al., 2013).

Climate change will affect aquaculture via acidification, changes in seawater temperatures and circulation patterns, the frequency and severity of extreme events, and sea-level rise and associated ecological changes (Feindel et al., 2013; Shelton, 2014; Gurney-Smith, 2015; Reid et al., 2015). Possible operational impacts on aquaculture include infrastructure damage, loss of stock, positive and negative changes in production levels, and changing insurance costs (Table 7; Feindel et al., 2013).

Unlike wild species, cultured species cannot migrate to areas that are optimal for growth and survival. Although some environmental conditions can be moderated artificially for some species (e.g., land-based pens for Arctic char), others require *in situ* pens exposed to local oceanographic conditions of temperature, salinity, oxygen and acidity. Tolerance ranges differ greatly between species and for different conditions, and tolerance will also vary by life-cycle stage. Larvae are most sensitive to changes in optimal conditions. Some cultured species require the larvae to be harvested from the wild before being grown in compounds.

Impacts of ocean acidification are already a major issue globally for both wild and cultured populations of marine shellfish (Gurney-Smith, 2015). Negative responses have been reported in a large majority of North American studies on commercial species to date (Gazeau et al., 2013). These responses include shell deformation, low growth rates and high mortality of commercially important bivalves, such as the blue mussel (*Mytilus edulis*; Gazeau et al., 2010; Gazeau et al., 2013).

Research on Atlantic salmon has shown that an average increase in water temperature of 1°C over the production cycle will decrease time to market by approximately two months, thereby decreasing overall production costs (Reid et al., 2015). Although this suggests that small increases in average temperature could benefit aquaculture production, there are other stresses that must also be considered. For example, increased water temperatures may increase infection potential by reducing the time required for sea lice to complete their life cycle (Stien et al., 2005; Reid et al., 2015). Higher water temperatures may also lead to the introduction of pathogens to which the current genetic stocks in the East Coast region are unaccustomed (Reid and Jackson, 2014).

Selective breeding programs may be an adaptive solution (Waldbusser et al., 2010; Quinn et al., 2011), as could genomic research to select for genetic improvements within a species (Zhang et al., 2012; Millar, 2013). Otherwise, the geographic range of a species may be extended or narrowed depending on the individual species (Shackell et al., 2013). An obvious but operationally challenging option is to relocate the industry to cooler waters.

Both land-based and open-water aquaculture sites can be impacted by severe weather events, potentially rendering them inaccessible or facilitating escape of penned stock. For example, land-based pens within the Oak Bay Hatchery in New Brunswick, critical sites for egg production and brood-stock development and protection of Atlantic salmon, were flooded, and access restricted, in December 2010 (Reid and Jackson, 2014).

TABLE 6: Aquaculture production and value in 2013 in the East Coast region (Statistics Canada, 2014b). Source notes that the production and value of aquaculture include the amount and value produced on sites and exclude hatcheries or processing. Shellfish also includes some wild production. Detailed species-level data for finfish were not available for Newfoundland and Labrador or for Prince Edward Island. Abbreviation: N/A, not available for a specific reference period.

a) Production (tonnes)

Aquaculture Type	NL	PE	NS	NB	QC	All Canada
Finfish — Salmon	N/A	N/A	6 517	18 837	0	100 027
Finfish — Trout	N/A	N/A	203	0	1262	6 736
Finfish — Steelhead	N/A	N/A	0	0	0	682
Other finfish	N/A	N/A	60	0	1	696
Total finfish	22 196	N/A	6 780	18 837	1 263	130 337
Shellfish — Clams	0	0	358	0	0	2 834
Shellfish — Oysters	0	2 812	356	739	10	9 509
Shellfish — Mussels	4 354	22 894	1 051	41	448	29 080
Shellfish — Scallops	0	0	0	5	11	107
Other shellfish	0	0	203	5	22	230
Total shellfish	4 354	0	1 968	790	491	41 760
Total aquaculture	26 550	25 706	8 748	19 627	1 754	172 097

b) Value (thousands of dollars)

Aquaculture Type	NL	PE	NS	NB	QC	All Canada
Total finfish	181 833	3 229	43 386	117 334	10 854	870 346
Total shellfish	15 139	37 970	10 871	5 724	925	92 549
Total aquaculture	196 972	41 198	54 257	123 058	11 779	962 895

TABLE 7: Potential impacts of climate change on cultured species in the Atlantic Basin (*from* Feindel et al., 2013 [*as modified from* Handisyde et al., 2006] and Cochrane et al., 2009).

Drivers of change	Impacts on culture systems	Operational impacts
Changes in sea-surface temperature	▪ longer growing seasons ▪ changes in locations and ranges of suitable species ▪ reduced winter natural mortality ▪ enhanced growth and food-conversion rates ▪ decreased dissolved oxygen ▪ increased disease and parasites ▪ increased harmful algal blooms ▪ competition, parasitism and predation from altered local ecosystems, competitors and exotic species	▪ changes in infrastructure and operation costs ▪ increased fouling, pests, nuisance species and predators ▪ expanded geographic ranges for species ▪ changes in production levels
Changes in other oceanographic variables (wind velocity, currents and wave action)	▪ decreased flushing rates and food availability to shellfish ▪ changes in abundance of species used for food and fishmeal	▪ accumulation of wastes under nets ▪ increased operating costs
Sea-level rise	▪ loss of areas for aquaculture ▪ loss of areas providing physical protection	▪ infrastructure damage ▪ change in aquaculture zoning ▪ increased insurance costs
Increased storm activity	▪ larger waves ▪ higher storm surges ▪ salinity changes ▪ structural damage	▪ loss of stock ▪ facility and net-pen damage ▪ higher costs of designing new facilities and net pens ▪ increased insurance costs

TRANSPORTATION

Transportation by road, rail and ship, and the associated infrastructure, are critical elements of local and regional economies and social connectivity within and between communities. Most existing transportation infrastructure and operations were designed and constructed based on historical climate records and therefore might not be adequate to withstand future weather patterns and climate extremes (Auld and MacIver, 2007). Roads were commonly built to minimize the number of bridges required or limit the number of curves, with little consideration of coastal-erosion hazards (e.g., Drejza, 2010).

Climate change has the potential to substantially affect the effectiveness and lifespan of infrastructure in all of Canada, particularly infrastructure related to transportation and to marine and water management (Boyle et al., 2013). The exposure and vulnerability of these different types of infrastructure varies greatly. Adaptive measures can enhance climate resilience and lead to reduced costs over time. Local impacts associated with severe weather can be costly. For example, the New Brunswick Department of Transportation and Infrastructure reported repair estimates of approximately $750 000 throughout Charlotte County due to flooding on July 26, 2013 (Signer et al., 2014).

Road and rail freight in the East Coast region includes a wide range of imports and exports (Yevdokimov, 2008), with much of this traffic travelling between New Brunswick and Nova Scotia through the Chignecto Isthmus (Webster et al., 2012b). Disruption of this low-lying route stalls $50 million of trade per day (Webster et al., 2012b). Areas such as Prince Edward Island, Quebec's North Shore, Anticosti Island and the Îles de la Madeleine, and Newfoundland and Labrador are reliant on ferry or bridge connections that are very exposed to meteorological hazards. In Quebec, 60% of provincial roads in the estuary and Gulf of St. Lawrence areas are located less than 500 m from the coastline (Friesinger et al., 2013). Quebec's Department of Transportation is concerned about maintaining this essential service in light of changing coastal hazards, and has conducted several studies (Bernatchez et al., 2010). The road network is particularly important in the Îles de la Madeleine archipelago because it provides the only link between the islands and is vulnerable to being severed by major coastal erosion events (Section 6, Case Study 5).

Ports are another important element of the East Coast region's transportation network. There are 25 industrial sea ports that handle much of the import and export of bulk products and resources. Eight of those ports are managed by port authorities (Table 8). Changes in sea level, sea-ice conditions and the frequency of severe storms are likely to affect port operations in the region. Potential positive effects of climate change on commercial shipping include improved access by deeper draft vessels as water depths in harbours increase, and the reduction of sea ice in the Gulf of St. Lawrence that will increase the potential for more shipping to the Port of Montréal and the St Lawrence Seaway. Potential negative effects on shipping tend to be associated with damage to port infrastructure due to extreme weather events (Dillon Consulting and de Romilly & de Romilly Ltd., 2007).

TABLE 8: Tonnage handled by port authorities in the East Coast region (Association of Canadian Port Authorities, 2013). Port authorities account for 60% of cargo handled by Canadian ports (Statistics Canada, 2012).

Port Location	Tonnage handled (million tonnes)
Québec (QC)	29 (2011)
Sept-Îles (QC)	28 (2012)
Saint John (NB)	28 (2012)
Halifax (NS)	9.5 (2012)
Belledune (NB)	1.9 (2012)
St John's (NL)	1.4 (2012)
Saguenay (QC)	0.35 (2011)

Planning and co-ordination to address climate risks to transportation can be challenging due to the diversity of agencies involved. In Halifax, the second largest natural, deepwater, ice-free harbour in the world, for example, the federal government operates the home port and associated facilities of the Canadian Navy's Atlantic fleet and Air Command's Canadian Forces Base Shearwater, as well as bases for the Canadian Coast Guard and offices for a range of federal departments and agencies. The Halifax Port Authority, an agency of the Crown under Transport Canada, oversees operations of the Port of Halifax. Major industrial facilities, such as the Irving Shipbuilding Inc. shipyard, infrastructure of Canadian National Railway Company, the Imperial Oil Limited oil-storage facility and the Tuft's Cove Generating Station, occupy a significant proportion of the nearshore lands (Dillon Consulting and de Romilly & de Romilly Ltd., 2007).

TOURISM

International research indicates that climate change will affect a range of coastal recreational activities (e.g., beach visits, fishing and boating) both positively and negatively (e.g., Coombes and Jones, 2010). Direct and indirect tourism revenues are a significant component of the economy for many communities in the East Coast region. In New Brunswick, for example, visits to and within the province contributed almost $1 billion in tourism-related expenditures in 2008 (New Brunswick Department of Tourism and Parks, 2010), the vast majority of which were linked to the coast. In

Prince Edward Island, tourism is a critical driver of economic activity, employment and tax revenue, accounting for 6.9% of the island's GDP and $373 million in revenue in 2009 (Tourism Industry Association of Prince Edward Island, 2014). The economic contribution of the 500 000 tourists to Newfoundland and Labrador is estimated at approximately $450–470 million annually and also contributes to employment and small-business establishment (N. Catto, personal communication, 2015). In 2014, the Quebec Government unveiled an action plan (Stratégie de mise en valeur du Saint-Laurent touristique 2014-2020) to promote tourism within the St. Lawrence river, estuary and gulf regions, where tourism is already a key component of local economies (Tourisme Québec, 2014). For example, visitor traffic in the Îles de la Madeleine in the summer currently doubles the local population.

In examining approaches to adaptation, researchers have assessed the potential for collaboration between fishing and tourism industries, to improve overall economic stability within local areas. In Bonne Bay (NL), for example, the fishing and tourism sector are economically important to six small local communities. By enhancing the local experience for tourists through boat tours of the bay, improving local culinary services and offering historical interpretation of area, the economic future for both fishing and tourism sectors has improved (Lowitt, 2012). In Chéticamp, NS, a multidisciplinary research team developed a toolkit to help fisheries and tourism sectors adapt and remain competitive. The Chéticamp and Grand Étang harbour authorities are working to diversify harbour uses to enhance resilience, and the tourism association is promoting cultural tourism that provides indoor activities as an alternative to weather-dependent activities (Brzeski et al., 2013).

5.5.2 PUBLIC SAFETY

Changes to water quality, flooding and temperature extremes could impact the health and well-being of local residents. Flooding may adversely affect the ability of a geographically isolated group of residents to access emergency services, such as fire, medical and police (Muise et al., 2012; van Proosdij, 2013; Masson, 2014). In Windsor (NS), for example, a 1.2 m storm surge during an average high tide would flood road access to the hospital, including the access ramps to the major highway linking communities, whereas a 1.8 m surge would prevent emergency-response vehicles from leaving their station (van Proosdij, 2013). Even where hospitals and nursing homes may not be directly at risk from flooding, infrastructure and assets in support of daily living, such as grocery stores and pharmacies, as well as infrastructure that supports recreational, social and spiritual needs, can be directly or indirectly affected (Rapaport et al., 2013).

Costs associated with climate hazards can directly impact individual well-being. Homeowners in Canada generally cannot purchase insurance coverage for damages caused by overland flooding, including flooding from rivers, storm surges, tides and sea-level rise. In addition, erosion associated with overland flooding, including coastal erosion, is not covered under typical homeowner policies (Sandink, 2011). Behavioural changes, such as avoiding building or living in areas at high risk from such hazards, and heeding evacuation notices, would reduce the direct impact on individuals.

Major financial costs tend to be associated with extreme weather events. Flooding has been the most common type of disaster in the East Coast region, followed by hurricanes and winter storms (Public Safety Canada, 2014). Between 2003 and 2011, damage caused by three hurricanes and one major winter storm in the region resulted in insured losses ranging from $51 million to $132 million (Kovacs and Thistlethwaite, 2014). Catastrophic losses due to rising water and weather events, including more frequent rain-on-snow flooding and more frequent winter thaws that are anticipated to affect ice-jam flooding and river/estuarine drainage, will continue to increase with projected changes to climate in the East Coast region. Combined with current development pressures and practices, this may set the course for higher damages to built infrastructure and services (e.g., PIEVC, 2008).

5.5.3 CULTURE AND HERITAGE

At a global scale, the vulnerability of coastal archeological resources is well acknowledged (e.g., English Heritage, 2008; Blankholm, 2009; Marzeion and Levermann, 2014). Canada's East Coast region has a wealth of cultural and heritage resources, such as parks (national, provincial, municipal), UNESCO sites, museums, heritage architecture, undeveloped archeological sites, abandoned cemeteries, and sites of important aesthetic and spiritual value. Climate change can affect culture and heritage directly through physical damage to sites, structures and landscapes, or indirectly through impacts to economic resources that could undermine efforts to maintain and preserve cultural heritage. The prospect of loss or damage to historical and archeological resources in nearshore areas is often more significant to society than damage to contemporary structures that can be rebuilt.

Coastal erosion plays both destructive and discovery roles with respect to cultural heritage. Within the East Coast region, there are coastal and watercourse sites from all chronological periods of history (Paleo-Indian, Archaic, Woodland Ceramic, Proto-Historic/Contact and Historic). Examples include Tyron, PE; Meadford, NS; Sainte-Anne-des-Monts and Marsoui, QC; Port-au-Choix, NL; and Amherst Shore, NS (Chapdelaine, 1996; Bell and Renouf, 2003; Kirstmanson, 2011). For sites such as Pointe-aux-Vieux, PE, located on an actively eroding shoreline, the constant threat from climate impacts raises fundamental issues about the identification, protection and management of archeological sites. Although it would generally be preferable to leave portions of the archeological deposits intact for future generations to interpret, many sites, or a substantial portions of them, will eventually be lost to erosion by increments or by a catastrophic event (Case Study 4).

CASE STUDY 4

COASTAL ARCHEOLOGICAL RESOURCES AT RISK

Although coastal archeological sites have been inundated by rising water levels in many parts of Atlantic Canada for millennia (Lacroix et al., 2014), recent loss or damage by storm surges and erosion has raised the alarm for heritage managers to potential future threats (e.g., Duggan, 2011; Finck, 2011; McLean 2011). One study estimated that one-fifth of all coastal archeological sites in three regions of Newfoundland are highly vulnerable to sea-level rise during the next 15–20 years, including national historical and world heritage sites (Westley et al., 2011). A similar study is underway for Prince Edward Island (Kirstmanson, personal communication, 2014). At a more local scale, Parks Canada classified 16 of 18 areas of the Fortress of Louisbourg National Historic Site as vulnerable to impacts from sea-level rise within the next century (Duggan, 2011). The Coastal Archaeological Resources Risk Assessment (CARRA) project, based at Memorial University of Newfoundland, aims to refine and expand on the vulnerability-assessment approach for heritage managers so they can readily identify at-risk sites, prioritize those for immediate action and learn through a community of practice how best to respond (Pollard-Belsheim et al., 2014).

For the most part, the response of the heritage management community to the impacts of sea-level rise and coastal change has been reactive. Regular monitoring for erosion of coastal archeological sites is rare and typically limited to protected areas (e.g., national parks) or sites near communities. As a result, loss of or damage to many sites goes undetected. Response measures range from rescue excavation of rapidly eroding or submerging sites to protection of sites through armouring or hardening of eroding shorelines (Figure 15). Protective measures are mostly informal and have had mixed results. In Bonavista Bay, NL, for example, a gabion rock wall has effectively protected the Inspector Island site for almost 30 years, whereas wooden breakwaters at the Beaches site failed within five years of installation (Figure 16; Pollard-Belsheim et al., 2014). Proactive adaptation requires the prioritization of at-risk sites, a process that should integrate cultural values, socio-economic factors and public input (e.g., Duggan, 2011) with an assessment of physical threats and the adoption of site action plans that enable implementation of excavation, protection or abandonment.

FIGURE 15: Malagawatch Cemetery, NS, where buried human remains eroded into the sea following several storm events. Initial protection of the site involved the use of stone armouring (as seen below the cross). Subsequent storms and erosion led to temporary protection of burials using anchored hay bales and a permeable membrane (centre of photo). Planning for more permanent protection is ongoing. *Photo courtesy of Heather MacLeod-Leslie.*

FIGURE 16: Two different construction methods used to protect archeological sites in Bonavista Bay, NL: **a)** the stone gabion wall constructed at Inspector Island (Pastore, 1987) has successfully protected the site for three decades; **b)** wooden breakwaters have consistently failed at the Beaches site. *Photo b) courtesy of Anita Johnson-Henke.*

Coastal erosion can also expose previously unknown archeological and paleontological resources. For example, coastal erosion at the Joggins Fossil Cliffs, NS, a UNESCO World Heritage Site, has led to the recent discovery of fossilized footprints from the smallest known Tetrapod (*Batrachichnus salamandroides*) from the Carboniferous Period (approximately 360–299 million years ago; Stimson et al., 2012). New fossils are exposed with every storm and the challenge becomes accessing the new resources before they are washed away with the tide.

As the impacts of climate change accelerate, it will become increasingly important to determine which heritage sites are most at risk and which have the most value culturally and economically (Westley et al., 2011). For example, of the archeological sites at L'Anse-aux-Meadows, NL, 60% are considered to be of high vulnerability (mostly in Sacred Bay), 16% moderate and 24% low (Westley et al., 2011). This type of assessment can help concentrate preservation/recovery efforts or to understand the realities of abandonment.

Climate change will directly affect the assets of many parks in the East Coast region (e.g., Vasseur and Tremblay, 2014), and management plans are beginning to reflect these risks. Prince Edward Island National Park, for example, faced with a 1 m/year recession rate and with storms capable of eroding 10 m in a single event, has accepted planned retreat as an appropriate approach to adaptation, abandoning campgrounds and relocating the main coastal road landward in an effort to maintain and enhance natural coastal processes.

Most First Nations communities in the East Coast region have traditional ties to the coast. For example, Malpeque Bay (PE) has been crucial to the Mi'kmaq for food harvesting, transportation and recreation, among other uses, during a long history that spans thousands of years (Charles, 2012). Many First Nations continue to occupy areas vulnerable to climate change and to rely on coastal natural resources. The community centre of the Mi'kmaq Confederacy of Prince Edward Island on Lennox Island, for example, occupies a highly erodible island joined to the mainland by a short causeway and bridge. Concerns related to climate change include potential saltwater intrusion and threats to Mi'kmaq archeological sites in the area. These concerns are being addressed in an ongoing study led by the Confederacy: *Adapting the PEI First Nations' Coastal Residences, Infrastructure and Heritage to a Changing Climate on Prince Edward Island* (Mi'kmaq Confederacy of PEI, 2014).

6 ADAPTING TO CLIMATE CHANGE

Adapting to climate change in the East Coast region brings direct economic benefits (*see* Chapter 3) and is important for preserving vulnerable ecosystems and landscapes, and for securing sustainable regional development. In implementing adaptation, attention must be given to the multiple biophysical and socio-economic factors that together produce the complexity inherent to coasts and coastal communities, including climate, geomorphology, coastal dynamics, and environmental, legal and regulatory processes. Adaptation is a process that includes assessing risks and vulnerability at various time scales, identifying options to reduce or eliminate these risks, and assessing these options in terms of their impact on the neighborhood, on coastal ecosystems and on the economy. Often, adaptation is not an individual process but rather involves multiple levels of decision makers, including community members. Examples of maladaptation, actions that lead to increased risk of adverse climate impacts (IPCC, 2014), are also common in the region. Many factors have contributed to this maladaptation, including a frequently limited understanding of coastal dynamics, conflicts of interest and lack of knowledge about alternative options (Friesinger and Bernatchez, 2010; Novaczek et al., 2011; Graham et al., 2013; Niven and Bardsley, 2013; Cooper and Pile, 2014).

The following sections address many of the complexities of the natural and human (institutional) environment as they relate to the identification, assessment and implementation of adaptation measures in the East Coast region. Such analysis commonly forms the foundation for selecting specific adaptation options. An overview of the broad categories of adapting to coastal erosion, sea-level rise and coastal flooding, with examples from the East Coast region, precedes a summary that focuses on future directions.

6.1 THE CHALLENGE OF A CHANGING ENVIRONMENT

The preceding sections have highlighted many of the biophysical and socio-economic factors that influence changes in coastal environments (*see also* Chapters 2 and 3). Understanding the dynamics of such environments is fundamental to the development of adaptation measures (Spalding et al., 2014). With respect to changes in the coastline, the projected acceleration of sea-level rise, decreases in sea-ice and ice-foot cover, and the potential increase in effective storms suggest that historical erosion rates almost certainly underestimate future coastal retreat. In a study of three areas in the East Coast region (Îles de la Madeleine, Percé and Sept-Îles QC), Bernatchez et al. (2008a) developed three scenarios for future coastline position by the year 2050 (Case Study 5). Modelling of these scenarios contributed to the delineation of three setback zones of varying vulnerabilities to coastal erosion. A similar project undertaken along the north shore of Prince Edward Island incorporated changes in shoreline configuration due to exposure and wave stress at the coast (MacDonald, 2014).

CASE STUDY 5

PLANNING FOR COASTLINE MOBILITY IN THE ÎLES DE LA MADELEINE

Located in the centre of the Gulf of St. Lawrence, the Îles de la Madeleine is an archipelago of 10 islands (total area about 190 km^2) with a population of approximately 12 600. The living area of the archipelago is restricted, with the maximum width of rocky outcrops not exceeding 10 km and their central part often being high and steep (Figure 17). Tourism is a key component of the local economy (Section 5.5.1). The Îles de la Madeleine are vulnerable to coastal hazards, and the archipelago is particularly sensitive to erosion. Coastal infrastructure on the Îles de la Madeleine is threatened by shoreline retreat at several sites, including the main road network of the archipelago and the sewage purification ponds of the main community. In its master plan, the Municipality of Les Îles-de-la-Madeleine identified 23 areas where erosion is an issue and where action is deemed necessary (Municipality of Les Îles-de-la-Madeleine, 2010).

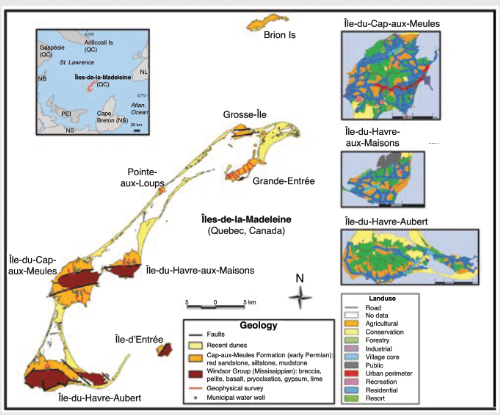

FIGURE 17: Location, geology and land use on the Îles de la Madeleine (Rémillard et al., 2012).

The archipelago is more vulnerable to relative sea-level rise than any other area in Quebec. This relates, in part, to the fact that it is a microtidal environment, with only about 1 m difference in height between low tide and high tide. With sea level around the Îles de la Madeleine in the year 2100 projected to be 50–83 cm higher than at present, and as much as 150 cm higher in the scenario involving partial collapse of the West Antarctic Ice Sheet (based on curves for Charlottetown presented in Figure 5 and Appendix A; James et al., 2014; *see also* Chapter 2), the current position of the high tide could roughly correspond to the position of the low tide in 2100. This shifting of the intertidal zone will change the position of the coastline and affect habitats, coastal ecosystems, coastal dynamics and erosion rates.

To assess the potential impacts of future changes in climate, Bernatchez et al. (2008a) proposed three possible positions of the coastline for the year 2050 (Table 9). The mapping of these scenarios along the coasts of the archipelago enabled stakeholders, scientists and members of working groups to identify adaptation options for targeted priority sites. Options considered included sand nourishment; a combination of sand nourishment, groynes and eolian sand traps where the main road is threatened; and rip-rap defence structure (armour stone) where erosion is threatening the community core (Figure 18; Savard et al., 2008).

TABLE 9: Erosion scenarios developed for communities in the Gulf of St. Lawrence and used to map the evolution of the coastline to the year 2050 (*translated from* Savard et al., 2008).

Scenarios for 2050	Description
S1: average coastline displacement rate between 1931 and 2006	Assumes that the effect of climate change will not modify the average rates of coastline retreat to 2050
S2: average erosion rates measured for a range of 10–15 years where erosion was most intense during the period 1931–2006	Considers probable accelerated coastal erosion due to climate change
S3: average values of higher-than-average rates of retreat for a range of 10–15 years where erosion was most intense during the period 1931–2006	Considers as likely a high acceleration of erosion due to climate change and aggravating anthropogenic factors

Their analysis concluded that, by 2050, the rocky cliffs of the Îles de la Madeleine could erode by about 38 m (–0.9 m/year) and sandy coasts could retreat by about 80 m (–1.9 m/year) (Bernatchez et al., 2008a; Savard et al., 2008). Under this scenario, many sites in the archipelago will be at high risk in the near future, including portions of the main road where only a single foredune ridge separates it from the westerly exposed beach and some community infrastructure and tourist sites. The overall picture demonstrates that coastal erosion exacerbated by climate change is a chronic and serious problem in the Îles de la Madeleine. Nevertheless, based on an understanding of coastal dynamics and acceptance of inevitable changes, the decision was made to leave 95% of the archipelago's territory unprotected from natural processes such as erosion and flooding. This approach preserves the natural beauty of the archipelago, which is a primary draw for tourists, and the islands are sufficiently high and large to endure shoreline retreat for many centuries. Only a few town centres with critical infrastructure are protected with a mix of hard and soft protection methods (Section 6.3.4).

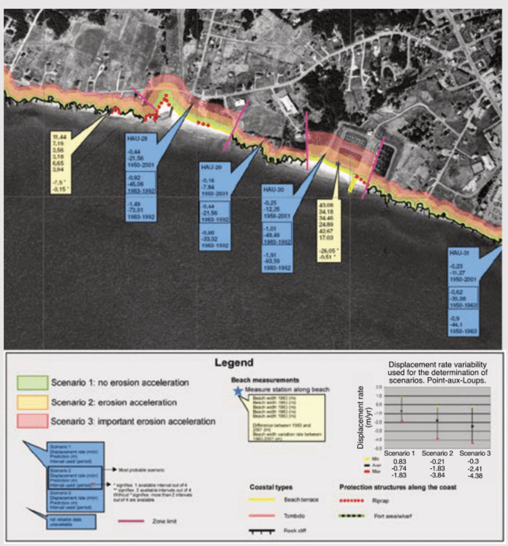

FIGURE 18: Example of digital-mapping scenarios and setbacks S1, S2 and S3 in Cap-aux-Meules, Îles de la Madeleine (*adapted from* Savard et al., 2008).

The study by Bernatchez et al. (2008a) was a first attempt to address how the local coast will evolve in the 21st century, knowing that the past does not represent an analogue for the future. Continued research and production of rigorous scientific documentation on the response of coastal systems to projected conditions will help better support decision making.

Risk management, analysis and the implementation of adaptation solutions to address changes in the coast often benefit from an approach based on uniform coastal units, usually littoral cells (*see* Chapter 2; Schéma Directeur d'Aménagement et de Gestion des Eaux du bassin Rhône-Méditerranée-Corse, 2005; de la Vega-Leinert and Nicholls, 2008; Dawson et al., 2009). Interventions made in one area of a littoral cell will impact the rest of the cell (MacDonald, 2014). Failure to take account of this important aspect of coastal dynamics can lead to maladaptation.

6.2 INSTITUTIONAL FACTORS AFFECTING ADAPTATION

The legal and institutional frameworks defining land policy in coastal regions can be key in facilitating adaptation or, in some situations, can serve as barriers to adaptation (e.g., Doiron, 2012). Policies may include defining areas with protection status for biodiversity, municipal zoning and development strategies and plans. The majority of laws, regulations and codes of practices in place today do not include consideration of changing climate and would benefit from review with a climate change lens. Indeed, much recent construction in the East Coast region has occurred in areas of high flooding risk yet is compliant with existing land-planning regulation and legislation. There are, however, important exceptions to this general characterization that reflect recent advances in adaptation planning (Case Study 6).

CASE STUDY 6

DEVELOPED WATERFRONT AND VERTICAL ELEVATION LIMITS IN HALIFAX REGIONAL MUNICIPALITY

Halifax Regional Municipality (HRM) is the capital of Nova Scotia and Atlantic Canada's largest city. The municipality covers more than 5500 km^2 and has a population of more than 414 000 (Statistics Canada, 2014a). Halifax Harbour, at the heart of HRM, is a major seaport with significant industrial, military and municipal infrastructure, including culturally important assets. In response to extreme weather events, such as Hurricane Juan, a Category 2 hurricane that caused an estimated $200 million in damage in Nova Scotia and Prince Edward Island in 2003, and a major winter storm in 2004, HRM began to actively implement climate change adaptation measures (Charles and Wells, 2010). In 2006, the HRM Council adopted the Regional Municipal Planning Strategy, which explicitly included policies to address climate change impacts. The strategy highlighted that scientific information is the foundation for adaptation-planning processes, particularly as it relates to sea-level change, storm surges and coastal vulnerability, to inform development of an area-specific land-use plan for Halifax Harbour (HRM Department of Energy and Environment, 2013).

In partnership with Natural Resources Canada, the HRM Department of Energy and Environment evaluated future sea-level rise and flooding risk around Halifax Harbour during the next 100 years for three scenarios that considered present and future sea-level rise, vertical land motion, statistics of extreme water levels (combined tide and surge), wave run-up and harbour seiche (Forbes et al., 2009). Mapping of future flood-hazard zones (Figure 19) utilized a high-resolution digital elevation model based on LiDAR data.

The scenarios of global sea-level rise used by Forbes et al. (2009) were based on projections of the IPCC Fourth Assessment Report (IPCC, 2007) and subsequent scientific literature. Although those scenarios are superseded by the projections presented in this report (Section 3.1 and *see* Chapter 2), both sets of scenarios cover a similar range. The 57 cm sea-level rise presented in Figure 19 compares with updated projections of relative sea-level rise for 2010–2100 at Halifax of 60.6 cm for RCP4.5 (median) and 84.7 cm for RCP8.5 (median; James et al., 2014, 2015). It is therefore quite a conservative scenario.

Based on available analysis, and following a precautionary approach, the Municipal Planning Strategy and Land Use By-Law for the downtown Halifax waterfront area prescribes any ground-floor elevation development to be a minimum

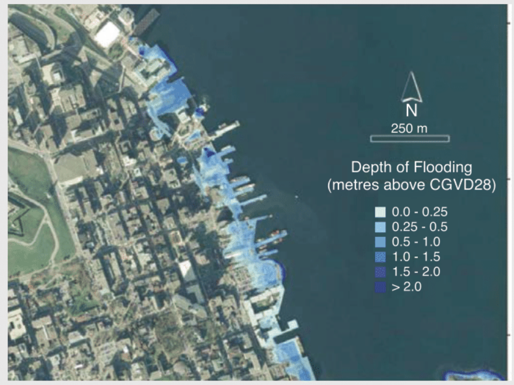

FIGURE 19: Flooding extent and depth (still-water) for a 57 cm sea-level rise with a once-in-50-years extreme-water-level event in downtown Halifax, derived using a light detection and ranging (LiDAR) digital elevation model displayed over a digital airphoto image (Forbes et al., 2009).

2.5 m above the ordinary high-water mark. Provisions were made for this figure to be adjusted based on ongoing monitoring and analysis of sea-level rise. This is an example of an adaptation measure being incrementally adjusted as new information becomes available. In the interim, HRM staff have used development agreements (i.e., bilateral contracts between the municipality and the landowner) for a number of waterfront parcels to encourage safe development while a formal adaptation plan is being completed (Charles and Wells, 2010).

Building upon the findings of Forbes et al. (2009), Xu and Perrie (2012) modelled extreme wave run-up within Halifax Harbour. Although development proponents are not presently required to demonstrate that extreme waves and wave run-up effects have been incorporated into their project design and engineering, information from this research study could be considered in amendments to land-use by-laws. For instance, development proponents could be required to conduct site-specific wave studies and demonstrate that appropriate adaptive responses have been incorporated into the overall design (HRM Department of Energy and Environment, 2013).

The availability of a high-resolution digital elevation model for a complex coastal urban landscape such as HRM has provided significant opportunities for community engagement and visualization of hazards. It assists in delineating zones of vulnerability and prioritization of sites for protection, relocation and enforcement of setbacks. Setbacks can be updated as new data and information become available.

Vertical and horizontal setbacks are useful mechanisms to promote adaptation, and their utility is not limited to large municipalities. For example, the Municipal Council of Beaubassin-Est, NB passed an updated zoning by-law in March 2011 to enhance protection of new construction in its coastal zone (Eyzaguirre and Warren, 2014). The by-law requires that the minimum ground-floor elevation of any new building be at least 1.43 m above the current once-in-100-years flood mark to account for anticipated sea-level rise (Doiron, 2012). All previous zoning conditions still apply. In Prince Edward Island, coastal setbacks are legislated based on measured erosion rates (1958, 2000 and 2010), supplemented with field observations. Wetlands and streams near cliffs must be protected by a buffer of 15 m or 60 times the erosion rate of that section, whatever is greatest (Arlington Group et al., 2013; Weissenberger and Chouinard, 2015). In Quebec, construction is prohibited below the high-tide line as part of a policy on the protection of shores, littoral zones and floodplains. Although construction in the flood plain is permitted, no living space, door or window may be located below the level of a once-in-100-years flood (Weissenberger and Chouinard, 2015).

Opportunities exist for the integration (mainstreaming) of coastal and/or climate-change adaptation elements into existing legislation, policies and practices, including building codes and codes of practice for engineers, planners and landscape architects. In most jurisdictions, municipalities and other land-management organizations identify areas at risk for erosion, landslide and flooding. Municipalities in Quebec, Nova Scotia, and Newfoundland and Labrador are required to prepare public-safety plans that are integrated in the municipality's land-policy and land-management plan. Such plans can be important in driving adaptation if they are developed with an understanding of how climate change is impacting coastal hazards.

Changing legal and regulatory frameworks tends to be a slow process. One of the earliest examples of planning for coastal change is the New Brunswick *Coastal Areas Protection Policy*, developed in 2002 in recognition of the stresses that threaten public safety, infrastructure, agricultural lands and the biodiversity of plant and wildlife within the region. This policy identifies sensitive coastal features, allowing these to continue to function naturally and maintain their buffering capacity, then identifies a 30 m limited-activity and -development buffer that begins at the farthest landward extent of the dynamic coastal zone (Figure 20; New Brunswick Department of Environment and Local Government, 2002). Although proactive and innovative at the time it was introduced, challenges in implementation have been ongoing and, as of 2013, it still did not have the force of law (Weissenberger and Chouinard, 2015). Interim measures are sometimes employed while broader regulatory changes are being considered. In Quebec, an interim regulation has been implemented to prohibit construction in areas of coastal risk on the North Shore from Québec to Blanc-Sablon (Case Study 7). The regulation is subject to review and adjustment as new scientific knowledge becomes available.

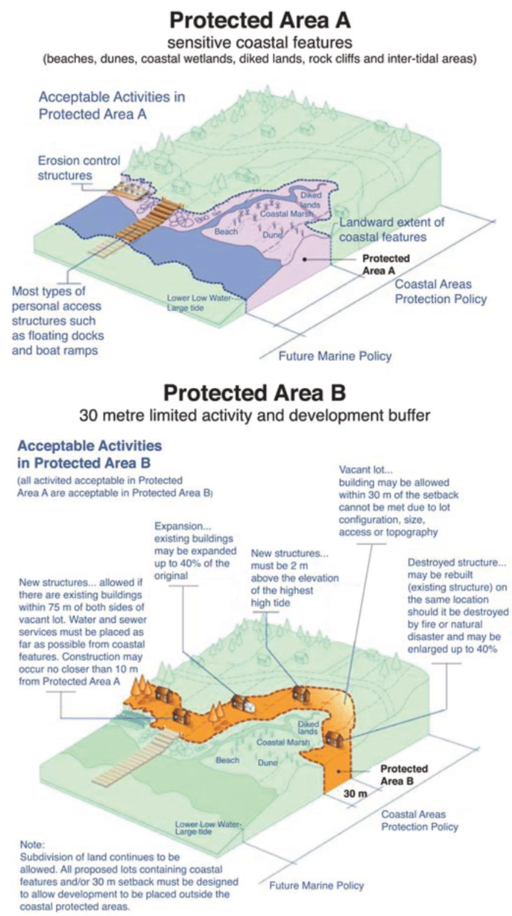

FIGURE 20: Zones A and B of the New Brunswick *Coastal Areas Protection Policy* (New Brunswick Department of Environment and Local Government, 2002).

CASE STUDY 7

ADDRESSING COASTAL EROSION IN SEPT-ÎLES, QC

The Municipality of Sept-Îles, QC has been dealing with erosion and coastal change, related to natural processes and human influences, for decades (Bernatchez and Dubois, 2004; Bernatchez and Fraser, 2012). In the late 1990s, the municipality requested a detailed study on the issue of erosion and a plan for coastal management based on integrated solutions (Dubois et al., 2005). The resulting four-year (2000–2004) scientific assessment concluded that coastal erosion had accelerated in recent decades, that human interventions at the coast were amplifying natural rates of erosion and that climate change could accelerate erosion in the future (Dubois et al., 2005). A follow-up study (2005–2008), led by the Ouranos consortium and the Quebec Department of Public Safety, assessed the vulnerability of coastal communities along the province's eastern shores, including the Municipality of Sept-Îles (Figure 21). The study used a participatory approach, taking into account the views of stakeholders and transferring climate science to decision makers to facilitate an integrated coastal-management approach and to identify adaptation options (Savard and Bourque, 2008, 2010; Savard et al., 2009). Local stakeholder representatives were invited to participate in a series of day-long workshops to identify adaptation solutions. The approach required that decision be achieved by consensus (Savard et al., 2008; Savard and Bourque, 2010).

The study highlighted that changes in storm frequency lead to significant retreat of sandy coasts; that increased winter thaws intensify freeze-thaw processes on clay cliffs; that decreases in seasonal sea-ice coverage in the Gulf of St. Lawrence increase the development of energetic winter waves that reach the coast; and that all of these climate-related factors are acting in the context of a rising sea level. The study was a catalyst for many events, meetings and consultations among community representatives, municipal and government policy makers, and members of the study's scientific committee.

The scientific documentation and the consultation with community stakeholders arising from the study were crucial in the adoption of control measures in the Sept-Rivières Regional County Municipality, measures with which the City of Sept-Îles must comply (Municipalité régionale de comté de Sept-Rivières, 2005; Natural Resources Canada, 2015). These include:

- adoption of a safety setback margin calculated over a period of 50 or 100 years, depending upon whether it is private or public land;
- development of future erosion scenarios (2050) to identify appropriate adaptation options;
- a ban on the installation of traditional protection structures (rip-rap, concrete walls, wooden walls, groynes and revetments); and
- a ban on any increase of habitable surface area for buildings in designated no-construction zones.

This regulation is now fully enacted across the Province of Quebec. Representatives of the provincial government, regional county municipality and the City of Sept-Îles are working to establish a master plan for coastal intervention, in order to deal with erosion and coastal management problems over the short, medium and long term (Natural Resources Canada, 2015). For example, the municipality decided to move part of the coastal population living on a sand cliff located along the gulf shores of the Sainte-Marguerite River estuary.

A final component of the study was a cost-benefit analysis over a 25-year period (2008–2032) of the adaptation options identified through the consultation process (Tecsult

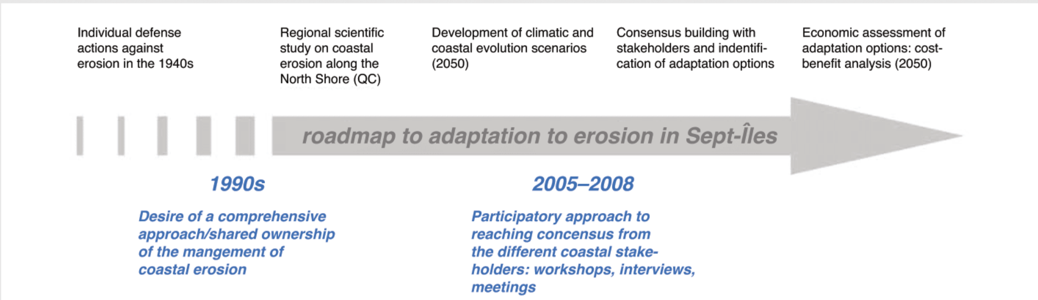

FIGURE 21: Main actions and interventions in the process leading to adaptation to erosion in Sept-Îles, QC.

Inc., 2008). The options studied, which varied from location to location, were sand nourishment, linear rock armourment, a combination of groynes and sand nourishment, revegetation, and planned relocation. The analysis showed that the optimal adaptation scenarios were those favouring sand nourishment or planned relocation. Under the Major Natural Hazards Prevention Guidelines (Cadre de prévention des principaux risques naturels), the Quebec Department of Public Safety had funds specifically earmarked for adaptation to coastal erosion. The Regional Municipality of Sept-Îles was approved for funding under this program for an $8 million sand-nourishment project, with the municipality required to provide 25% of the funding (approximately $2 million). A tax levy was proposed to raise the funds, but the local government had difficulty obtaining public support as the levy would have been applied to all residents, whereas only the ocean-front property owners were perceived to benefit from the project (Arlington Group et al., 2013).

Availability of financing is another example of an administrative control on adaptation. It is often easier to obtain financing for hard engineering projects, such as seawalls and rip-rap, than for more flexible options, such as beach nourishment and dune or marsh restorations that require ongoing financing over a long-term period (even though the cost-benefit ratio can be better than for hard protection methods; Spalding et al., 2014). Some financing may be available through avenues such as habitat compensation projects for loss of aquatic habitat due to infrastructure construction, with the primary goal of such coastal wetland restoration projects being habitat creation (Bowron et al., 2012). Lack of public support can also be a barrier to funding of implementation measures (Case Study 7).

6.3 COASTAL ADAPTATION OPTIONS

Although specific adaptation measures are diverse, adaptation options in coastal areas can be grouped into four broad categories: no active intervention, avoidance/retreat, accommodation, protection, or a combination of these approaches (*see* Chapter 3; Chouinard et al., 2008; Vasseur and Catto, 2008; Pilkey and Young, 2009; Linham and Nicholls, 2010; Nicholls, 2011; Burkett and Davidson, 2012; Arlington Group et al., 2013; Macintosh, 2013; Niven and Bardsley, 2013). Coastal settings located between urban areas and relatively natural areas can be particularly challenging with respect to determining appropriate adaptation measures. There is a large array of feasible adaptation options where the coast is occupied by low-density settlements, such as a line of cottages, houses or suburban commercial assets. Rapid linear urban expansion, often referred to as ribbon development, has occurred along many stretches of the coast in this region during the past few decades, resulting in significant economic assets being at risk from coastal hazards and exacerbating coastal squeeze (Section 4.8).

6.3.1 NO ACTIVE INTERVENTION

No active intervention can be a legitimate adaptation response when, based on a thorough understanding of the risks involved, decision makers choose to take no action at this time. No active intervention may be appropriate when there is no significant risk, when little can practically be done to avoid or reduce the impacts of coastal hazards, or when action taken now is an inappropriate allocation of resources against the potential of a future threat. As described in Case Study 5, a rigorous adaptation planning process for the Îles de la Madeleine led to the decision to make no active intervention with respect to 95% of the archipelago's territory.

6.3.2 AVOIDANCE AND RETREAT

The option of avoidance and retreat involves identifying risk areas and defining where development will be prohibited, while enabling existing housing and infrastructure at risk to be relocated to safer areas. These options are most commonly suggested for the preservation of natural landscapes and coastal ecosystems, and applied in areas with few coastal-infrastructure assets. For example, Prince Edward Island National Park acquired 12.5 km^2 of land in the mid-1970s along the landward portion of the park boundaries to compensate for the land losses along the shoreline. This land is now being managed as a buffer to gradually relocate coastal infrastructure as the shoreline moves landward (Parks Canada, 2007). In urban centres, where major assets are concentrated, retreat options are challenging because there is no room for accommodation and the cost of retreat, both economically and culturally, would be enormous.

Even outside urban centres, avoidance and retreat may not be generally preferred strategies on the basis of short-term economics. Coastal land is often a significant source of revenue for municipalities and leaving this land unoccupied by direct revenue-generating activity is often seen as a negative economic factor. Another drawback of avoidance is that facilities and people are commonly already present in the high-risk area (Lieske and Borneman, 2012; van Proosdij et al., 2014). Public consultation and information are particularly important in achieving successful adaptation through avoidance and retreat (Savard and Bourque, 2010; Drejza et al., 2011).

Avoidance and retreat in the East Coast region also includes managed realignment in diked areas, such as in the upper Bay of Fundy. There has been increasing interest in this concept during the last few years with the recognition that the cost of maintaining the existing system of dikes in Nova Scotia and New Brunswick is not sustainable (Lieske and Borneman, 2012; van Proosdij and Page, 2012; Wilson et al., 2012; van Proosdij, 2013). Although most salt-marsh restoration projects in the bay have been conducted as habitat compensation (van Proosdij et al., 2010; Bowron et al., 2012), there is growing interest in maximizing the adaptation potential of such projects while enhancing ecosystem services (van Proosdij et al., 2014). Close monitoring of selected salt-marsh restoration projects has shown rapid recolonization of vegetation, and therefore enhanced potential for wave-energy dissipation, after tidal flow is restored. The pace of this recovery, however, is not spatially uniform (Millard et al., 2013; van Proosdij et al., 2014).

6.3.3 ACCOMMODATION

Accommodation responses seek to lower the risks of climate hazards without fundamentally changing land usage by allowing for occasional short-term impacts (e.g., impacts from storm events or seasonal flooding). Accommodation is an appropriate response when the practicality of protecting coastal assets is outweighed by the economic, environmental or social costs, and/or when the effectiveness of protection measures would be limited to a relatively short period of time (*see* Chapter 3).

In the East Coast region, there are a few examples of structures planned to accommodate sea-level rise or storm surge, such as homes or other buildings constructed on stilts, or modular buildings designed to be easily moved (Vasseur and Catto, 2008; Doiron, 2012). Storm-water management that decreases runoff (e.g., vegetated swales and green space), increases conveyance (e.g., dredging channels and engineering drainage design with culverts that are appropriately sized for climate change) and increases storage (e.g., storm-water retention ponds and rain gardens) can be a very important accommodation option in addressing flooding. For example, evaluation of the 2003 storm-water management plan for Stratford, PE determined that numerous culverts within the town would not be able to accommodate projected changes in rainfall intensity associated with climate change, and that there was a need for increasing drainage capacity in order to accommodate larger runoff volumes. Increasing culvert size may not be beneficial, as larger and stronger drainage flows could lead to increased erosion. Instead, a combination of pipe upgrades, additional storage within tributary watersheds, abandonment and appropriate flood-proofing and hazard-warning systems in selected areas has been proposed to decrease damage and the threat to residents (CBCL Limited, 2012).

Accommodation includes accepting temporary inundation of noncritical infrastructure (e.g., flooding of secondary roads where alternative access routes exist for fire or other critical services). Cost-benefit studies can be used to assess the cost of modifying or displacing the road versus accepting occasional closure or repairs for several decades. Improved predictability of extreme events can enable actions such as evacuation of persons at risk and temporary protection of buildings and properties to happen in advance of a major storm.

6.3.4 PROTECTION

Protection consists of a variety of methods to defend coastal assets against the sea (erosion and flooding). It can take different forms, ranging from 'hard' methods, such as dikes, rip-rap, walls, gabions and groynes, to 'soft' or flexible methods, such as beach nourishment, revegetation and dune reprofiling, which allow coastal processes to resume naturally.

Data on the length and type of coastal protection by 'hard methods' tends to be incomplete and commonly outdated for most of the East Coast region (e.g., Bérubé, 1993; Bérubé and Thibault, 1996; Breau, 2000; Dubois et al., 2005; Bernatchez et al., 2008a; Catto, 2012). The exception is Prince Edward Island, where the entire coast was mapped by Davies (2011). Hard-protection approaches have been used for a long time, and estimates of the percentage of coast protected is usually less than 15% within local studies. Rip-rap (i.e., heavy stone or concrete) is by far the most widespread method employed. Other common types of hard protection structures in the East Coast region are seawalls of concrete or wood, bulkheads (i.e., gabions, sheet piling or wood cribs), revetments (i.e., using various materials to cover the coastal slope) and groynes made of stone, concrete blocks or wooden stakes driven in beach (Figure 22). In proximity to ports and harbours, jetties, groynes and breakwaters are the dominant structures and consist mostly of concrete dolosse or tetrapods, or heavy stone (Jennings et al., 2008).

Older homemade defence structures are still found at some locations, but their use is declining in favour of hard engineered structures (Bérubé and Thibault, 1996). Hard-protection measures for coastal defence are used to protect public infrastructure (i.e., harbours, port areas, roads and municipal frontage) and are also used by private landowners to protect their land and property from erosion. The number of individual coastal defence structures far exceeds the

FIGURE 22: Coastal-protection structures commonly used in the East Coast region (*adapted from* Jennings et al., 2008): **a)** riprap, Malagawatch ancestral burial grounds, southwestern Bras d'Or Lake, NS (S. O'Carroll, Geo Littoral Consultants); **b)** seawall, Eel River Bar First Nation, northeastern New Brunswick (D. Bérubé, New Brunswick Department of Energy and Mines): **c)** revetement, Mispec, southwestern New Brunswick (D. Bérubé, New Brunswick Department of Energy and Mines); **d)** bulkhead, Maria, Gaspésie, QC (Laboratoire de dynamique et de gestion intégrée des zones côtières–Université du Québec à Rimouski [UQAR]); **e)** groyne, Paspébiac, Gaspésie, QC (Laboratoire de dynamique et de gestion intégrée des zones côtières–UQAR); and **f)** breakwater, Pointe-Lebel, north shore of the St. Lawrence estuary, QC (Laboratoire de dynamique et de gestion intégrée des zones côtières–UQAR).

number of ports and small-craft harbours along the northern and eastern coasts of New Brunswick (Figure 23; Breau, 2000). On Quebec's North Shore, only one-third of the 91 km of artificial coasts mapped were attributed to port and harbour activities, with the remainder being public and private coastal protection (Dubois et al., 2005).

The total length of defence structures on the coast steadily increased, sometimes exponentially, during the period covered by aerial photographs. In southeastern New Brunswick, O'Carroll et al. (2006) documented that coastal armouring was 10 times greater in 1971 than in 1944, and 22 times higher in 2001 than it was in 1971. Similar trends have been observed for coastline armouring

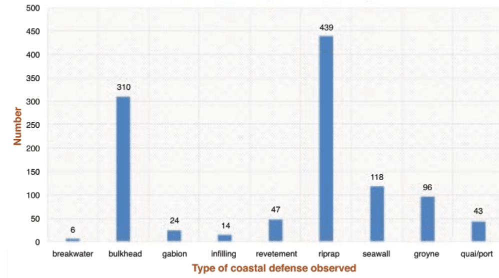

FIGURE 23: Inventory of coastal defence structures along the northern and eastern coasts of New Brunswick (Breau, 2000).

in the area of Percé (Péninsule de la Gaspésie, QC) and the residential areas surrounding Sept-Îles (Bernatchez and Fraser, 2012). Coastal armouring in the vicinity of Sept-Îles increased the most between the 1970s and the 1990s, and has since slowed considerably.

If hard-protection measures are not properly designed, placed and maintained, they can result in maladaptation: rather than diminishing vulnerability, they can actually worsen the situation, particularly for adjacent landowners. Among the most common negative effects are changes in the local sediment budget, which can result in accelerated erosion downstream, contributing to sand deficit or activating sand transfers. For these reasons, development of new sand-trapping measures such as groynes are highly restricted on crown land in New Brunswick (New Brunswick Department of Natural Resources, 2014). Other localized effects include the lowering, and sometimes the loss, of beaches and flats in front of the seawall (Bernatchez et al., 2008b, 2011; Bernatchez and Fraser, 2012). Lowering of the foreshore increases vulnerability to inundation. During storm events, surges increase the depth of water, allowing higher, more energetic waves to reach the shore. These situations can result in overtopping of protective structures such as dikes and seawalls (Bernatchez et al., 2011).

Hardening of the coastline by rigid, linear, coastal-protection structures can also lead to rapid loss of biodiversity and contribute to coastal squeeze by trapping coastal habitats and ecosystems between the rising sea and landward man-made barriers (Section 4.8). Another disadvantage of hard-protection measures is that they are generally irreversible. Once heavy stone or concrete structures are in place, it can be difficult to change the strategy of coastal protection because removal of the structures can be very expensive and often leaves the coast in an increased state of vulnerability until the equilibrium of the natural state is restored. In instances where coastal infrastructure cannot be removed, properly designed engineering approaches are warranted.

Soft-protection methods have only been used infrequently in the East Coast region. One example is the use of sand from the dredging of fishing harbours by the Quebec Department of Transportation to nourish beaches along roads threatened by erosion on the Îles de la Madeleine (Case Study 5). This method has adequately protected the roads since 2007 with no observed impact on the environment. The sand has the same characteristics as that of the local beach, since it comes from the nearby longshore drift. This reuse of dredged sand is an example of alternatives to hard protective structures. Mixed methods can also be used to reduce the wave energy, such as degradable groynes reloaded with sand (Figure 24), sand-dune–trapping devices, or protection and/or replanting of beach grass (Restore America's Estuaries, 2015).

6.4 IMPLICATIONS AND FUTURE DIRECTIONS

There are considerable opportunities in the East Coast region to increase the capacity for adapting to climate change and implementing effective adaptation measures to address coastal risks. Basic steps include increasing awareness, engaging and empowering stakeholders, reviewing and adjusting legislation and codes of practice where appropriate, enhancing interjurisdictional collaboration, and addressing regional and local differences in adaptive capacity. Adaptation is fundamentally a social process that leads to modification of long-standing habits. Progress has been made. As an example, recently developed guidelines for engineers recognize that the return period of extreme events changes over time.

Most coastal-management practices in the East Coast region were implemented before climate change was recognized as an issue and the concept of climate change adaptation was developed. The most common approaches to address coastal erosion and storm-surge flooding have been the use of hard protection methods and retreat from areas at risk. As a result of changing climate, the East Coast region is facing new challenges and will need to consider new ways of managing the associated risks. Coastal-adaptation researchers and practitioners worldwide have reported on the diverse challenges related to conflicting uses, financial fairness, integration and consultation processes, development, management of uncertainty, perceptions, political will and leadership, and regulatory framework and governance structure.

Examples of innovative ways to address these challenges are emerging. For example, with respect to consultation processes, Quebec has established a series of regional groups that serve as forums for gathering key participants around issues of managing multiple uses in the coastal areas of the estuary and Gulf of St. Lawrence (Ministère du développement durable, de l'Environnement, de la Faune et des Parcs du Québec, 2012). Ultimately, society will have to decide what constitutes sustainable development of the coast. Where cost-benefit analyses have been undertaken, there is evidence that decisions to retreat from the coast, and/or to use soft protection methods, are generally more productive in the long term. Ongoing economic analysis will also contribute to the selection of appropriate adaptation options. Where major infrastructure already exists, or where large populations are already settled in risk areas, the use of hard protection options may be more appropriate.

FIGURE 24: Hybrid living shoreline on the Shubenacadie River, Bay of Fundy, NS, illustrating gabion basket planted with marsh vegetation to reduce erosion scour. *Photo courtesy of V. Leys, August 2015.*

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Adaptation

How exactly is the climate forecast to change, and what could that mean for Canada's forests and forest management?

Canada is working to answer these questions in order to help the forest sector and society in general adapt to changing climate conditions. Today, forest managers must consider a range of possible future climates—those involving, for example, altered growing seasons, more insect infestations, more wildland fires and greater permafrost melting.

An important first step is to identify social, economic and environmental vulnerabilities to changing forest conditions. The next important step is to plan ways to reduce the impact of those vulnerabilities.

For example, projected increases in drought, fire, windstorms, and insect and disease outbreaks are expected to result in greater tree mortality. Fewer trees will reduce Canada's timber supply, which in turn will affect the economic competitiveness of Canada's forest industry. This would leave forestry-dependent communities vulnerable to job losses, closure of forestry processing facilities and an overall economic slump.

New thinking to deal with new conditions

Forest managers have traditionally assumed that the climate conditions of previous decades would be the conditions of future decades. Now, with more knowledge about climate and its patterns of change, forest managers are shifting their thinking.

Adaptation will mean taking action to minimize the negative effects of change. Yet at the same time some changes (such as longer growing seasons or moister weather patterns) may in fact offer new opportunities for the forest sector. Adaptation will therefore also be mean taking advantage of the positive impacts brought about by climate change.

The challenge of uncertainty

Many uncertainties exist about how, and to what extent, climate change will affect Canada's forests. This makes planning adaptation efforts a challenging exercise.

Dealing effectively with uncertainty requires having:

- the use of new tools and techniques for decision-making, such as scenario-planning exercises

- a good knowledge of the forest
- an understanding of risks
- the flexibility to adjust to changes

Risk management is a proven technique for identifying potential problems and then developing ways to: (1) reduce or avoid them; and (2) where they are unavoidable, respond to them to reduce negative outcomes.

In forestry, this means setting management objectives that recognize that the forests of the future will be different from those of today. By identifying the risks associated with these new conditions, forest planners and managers can then focus on finding ways to reduce or optimize the impact of those risks.

Support for adaptation from all parties

The Canadian Council of Forest Ministers (CCFM) has identified climate change adaptation as a priority for the forest sector. Many parties are working to support this priority:

- Forest scientists and forest practitioners across the country are assessing adaptation needs and adaptation options.
- The federal, provincial and territorial governments are collaborating in creating a range of products to help forest managers begin taking adaptation action.
- Provincial and territorial governments are developing approaches to addressing climate change, supporting climate research and raising awareness of the need for adaptation.
- Forest companies are beginning to address issues related to climate change in their management plans.

Practical tools aid adaptation strategies

Tools to analyze forest vulnerabilities

Forest scientists are developing a range of tools for assessing and managing climate-related risks and adaptation options. For example:

- Canadian Forest Service (CFS) researchers have developed a new software tool, BioSIM, which can predict stages in insect development during the growing season. BioSim has been used to predict how climate change might affect the risk of mountain pine beetle infestations in western Canada.
- CFS scientists have updated Canada's plant hardiness zones using recent climate data. The new map produced shows changes in the hardiness zones consistent with climate change.
- In partnership with provinces, the CFS is developing frameworks, guidebooks and tools to help forest management practitioners: better understand their readiness to adapt; and identify sources of vulnerability to sustainable forest management.

Tools to help forests and the forest sector adapt

Work is underway on several fronts to find ways to help forest stands adapt to new climatic conditions and disturbance regimes. For example:

- Researchers are looking at ways to reduce forests' vulnerability to fire and insect damage.
- Industry is exploring new markets for beetle-killed wood.
- Some forest companies have started using high-flotation tires to navigate wet areas, allowing them to extend their operating season.

Tools to inform forest management decision-making

Scientists are incorporating the data they have on changes in climate conditions into research and planning tools. This gives forest managers better information with which to make decisions. For example:

- *Seedwhere* is a geographic information system (GIS) tool that can guide planting and seeding decisions for forest regeneration. It can also help forest managers decide where to collect seeds and how far those seeds can be moved.

Looking to the long term

Forest managers need to include climate change considerations in long term planning if Canada is to maintain a competitive position in world markets. This means enhancing our ability to assess climate effects and identifying ways to adapt forests to ensure a healthy ecosystem and sustained supply of fibre.

Involving everyone in adaptation efforts—government, industry, academia, the public—will be the most effective approach. Good communication and information exchange will help Canadians address shared problems and pool resources to solve them.

Government of Canada Gouvernement du Canada

Canada's Partnership with Indigenous Peoples on Climate

Supporting Indigenous climate leadership

First Nations, Inuit, and Métis peoples have been at the forefront of the impacts of climate change. Many Indigenous leaders have reinforced the need to take action to reduce pollution, to adapt to the impacts of climate change, and to improve the ways in which the natural environment is respected and protected. In doing so, Indigenous leadership and knowledge is critical to achieving the foundational changes required to address climate change.

To help support Indigenous peoples advance their climate priorities and adapt to the changing climate, the Government of Canada is committed to renewed nation-to-nation, Inuit-to-Crown and government-to-government relationships with First Nations, Inuit, and Métis peoples, based on the recognition of rights, respect, cooperation, and partnership. The Government of Canada also supports without qualification the United Nations Declaration on the Rights of Indigenous Peoples, including free, prior and informed consent. Supporting self-determined climate action is critical to advancing Canada's reconciliation with Indigenous peoples.

Canada's strengthened climate plan, *A Healthy Environment and a Healthy Economy*, builds on the foundational principles of Indigenous climate leadership, including:

- Recognizing the unique realities, needs, and priorities of Indigenous peoples across and within distinctions;
- Respecting and promoting self-determination;
- Advancing early and meaningful engagement;
- Incorporating inclusiveness-by-design principles in all of its climate actions;
- Advancing co-development and other collaborative approaches to find solutions;
- Creating a space for Indigenous voices across and within distinctions;
- Positioning Indigenous peoples to have a say at governance tables; and,
- Supporting Indigenous approaches and ways of doing, by acknowledging traditional, local, and Indigenous Knowledge systems as an equal part in policy development, programs, and decision-making.

Since the launch of the Pan-Canadian Framework on Clean Growth and Climate Change, the Government of Canada provided over $900 million in investments to support Indigenous-led projects on adaptation planning, food security, clean energy, health, infrastructure, climate monitoring, and more.

Climate action funding for Indigenous Peoples

The Government of Canada announced more than $1.3 billion in climate action funding targeted to Indigenous peoples through Canada's strengthened climate plan, *A Healthy Environment and a Healthy Economy*, and additional investments through Budget 2021. This includes measures to:

- Support First Nations and Inuit as they manage the health impacts of climate change, such as the impacts of extreme weather events, and mental health impacts on youth ($22.7 million over five years);
- Improve food security in the north, including in Inuit Nunangat ($163.4 million over 3 years);
- Help transition rural, remote and Indigenous communities from diesel to clean energy ($376.4 million over 5 years);
- Support greener and more resilient infrastructure, including for large-scale adaptation or mitigation projects ($290 million over 12 years); and,
- Protect biodiversity through the creation of Indigenous Protected and Conserved Areas and partnerships to restore and enhance wetlands, peatlands, grasslands and agricultural lands to boost carbon sequestration (portion of $2.3 billion over 5 years for conservation, portion of $3.16 billion over 10 years for nature-based solutions, portion of $631 million over 10 years for nature-based carbon sequestration).

Distinctions-based senior bilateral tables on clean growth and climate change

In 2016, the federal government committed to strengthening its collaboration with Indigenous Peoples as partners in climate action. Following joint commitments made by the Prime Minister and the National Leaders of the Assembly of First Nations, Inuit Tapiriit Kanatami and the Métis National Council, the federal government established three distinctions-based senior bilateral tables. These tables are based on the recognition of rights, co-operation, and partnership. They help foster a collaborative approach to ongoing engagement with Indigenous Peoples, and help support Indigenous climate leadership.

Additional information on the creation of the Senior Bilateral Tables on Clean Growth and Climate Change can be found on the Process Document for Ongoing Engagement on the Pan-Canadian Framework on Clean Growth and Climate Change.

First Nations-Canada partnership

The First Nations-Canada Joint Committee on Climate Action (JCCA) was established in fall 2017. Since then, Assembly of First Nations representatives from across Canada and federal officials from various departments meet to discuss climate change priorities and collaborate on climate policy. The JCCA continues to explore opportunities for First Nations to meaningfully participate in the transition to a clean growth economy as climate leaders.

In August 2021, the JCCA released its third annual report to the Prime Minister and the National Chief of the Assembly of First Nations. The JCCA's annual report documents the positive steps taken towards reconciliation and forging a stronger climate partnership in 2020. This report highlights the Joint Committee's work in 2020 across five key areas:

- Ensuring First Nations' full and effective participation in federal clean growth and climate change programs.
- Empowering First Nations leadership in emerging opportunities for climate action.
- Enabling the meaningful participation of First Nations in the carbon pollution pricing system.
- Developing First Nations–specific indicators and criteria to report on the implementation of climate-related federal funding programs and outcomes for First Nations.

- Fostering intergenerational dialogue on climate change.

Inuit-Canada partnership

The Inuit-Canada Table on Clean Growth and Climate Change was created in 2017 to provide a forum for representatives from Inuit Tapiriit Kanatami, Regional Land Claims Organizations and federal officials from various departments to discuss and advance joint climate priorities. Since then, the Inuit Tapiriit Kanatami has shifted its focus to the National Inuit Climate Change Strategy (NICCS) that advances Inuit-determined actions to strengthen the sustainability and resilience of Inuit Nunangat in the face of a rapidly changing climate and landscape.

To support Inuit knowledge and leadership for successful climate action, the Government of Canada provided $1 million in summer 2019 to implement the NICCS. This support will help advance Inuit-led activities and initiatives under the following NICCS priority areas:

- Advance Inuit capacity and knowledge in climate decision-making;
- Improve Inuit and environmental health and wellness;
- Improve food security;
- Close the infrastructure gap with climate resilient new builds, retrofits, and Inuit adaptation to changing natural infrastructure; and
- Support regional and community driven energy solutions leading to Inuit energy independence.

Métis-Canada partnership

Since 2017, the Métis Nation-Canada Joint Table on Clean Growth and Climate Change members have built relationships and shared information on joint policy development, and identified Métis-specific considerations for designing federal programs and delivering funding.

Federal departments are working with the Métis Nation to adjust programs and policies under Canada's climate plan. This includes advancing Métis climate change and related health priorities, and shaping community-based climate monitoring initiatives. In 2020, the Métis Nation identified the following priorities to advance Métis Nation climate leadership:

- Capacity-building;
- Collecting Métis traditional knowledge;
- Conducting research & collecting data to guide Métis policy;
- Education and training opportunities in climate change:
- Environmental stewardship and nature-based solutions;
- Emergency management and disaster-risk mitigation;
- Climate change and health;
- Transportation, and;
- Renewable energy and energy-efficiency retrofits

INTERNATIONAL MODEL FOREST NETWORK
LANDSCAPES · PARTNERSHIPS · SUSTAINABILITY

RENEWABLE ENERGY BRINGS ABOUT IMPROVEMENTS IN PEOPLE'S LIVELIHOODS AND HELPS FIGHT CLIMATE CHANGE

Challenges

The Model Forest is situated in Chile's Mediterranean ecoregion, one of the 34 biodiversity hotspots in the world catalogued by "Conservation International". Agriculture, livestock, the use of trees for firewood and charcoal as well as the extraction of humus from the forest (topsoil that is rich in organic matter) are practices that have contributed to the degradation of these forests that are so characteristic of the territory. Several species of the native forest have been declared vulnerable or endangered such as the Northern Belloto (*Beilschmiedia miersii*) and the Southern Belloto (*Beilschmiedia berteroana*).

Moreover, the districts of Coltauco and Doñihue, which are part of the territory influenced by the Model Forest, have been declared by the Ministry of the Environment as areas saturated by the high

Cachapoal Model Forest, Chile
Established: 2008 | Area: 105,000 ha

Facts

- The Model Forest is located in the central part of the country, which is the area with the highest population density and where there is significant pressure on natural resources produced by a variety of forestry and agricultural activities.
- In this area, the forest is valued for the production of firewood and charcoal, the extraction of non-wood forest products such as leaves and fruit, activities such as beekeeping and tourism, and the production of services such as water and soil.

indices of suspended particulate matter in the air, as a result of slash-and-burn practices, forest fires and the misuse of firewood. Luis Martínez, Head of Chile's Special Programs Unit of the National Forest Corporation (Corporación Nacional Forestal), says that Chile could be one of the countries most affected by climate change and, accordingly, the State is concerned with adopting measures to fight and mitigate this phenomenon through lower carbon emissions and the protection of forested areas.

Finding solutions

Since the establishment of the Model Forest in 2008, its partners have been promoting a strategy to contribute to family and local development, and encourage a better relationship between people and natural resources, as well as to cut down on use of firewood as fuel and, accordingly, the emission of gases into the atmosphere. This strategy is based on promoting the use of unconventional forms of renewable energy as a way of encouraging the rational use of the area's natural resources to ensure the ecological integrity of the ecosystem, without overlooking the socio-economic development of the community.

Within the context of the Model Forest, and thanks to opportunities and alliances with several different partners, the actions involve people from the urban and rural parts of the territory who have a certain level of interest in its natural resources and, consequently, in the use of the firewood.

Solar cookers and dehydrators, as well as biodigesters for biogas production, are the main clean energy technologies being used. They make it possible to take advantage of resources such as sunlight and certain agricultural and forest products, thus minimizing the cost of living for these families. The Model Forest also works on awareness, training and the promotion of these technologies in communities, schools and local governments.

Renewable energy is energy that comes from resources that are continually replenished and inexhaustible on a human scale: solar, wind, hydraulic, biomass and geothermal.

Solar cooker and dehydrator

Solar energy can be used to heat water as well as for cooking and drying food. Solar devices such as fruit dehydrators, water collectors and solar cookers help to reduce the use of charcoal and firewood. These technologies also make it possible to take advantage of fruit and other forest materials that would otherwise be thrown away, thus creating an additional source of income and helping to lower air pollution in the communes.

Biodigester

The biodigester uses animal feces and any other degradable material to produce biogas through an anaerobic process. It helps to lower the emission of gases into the atmosphere from animal waste, and reduces the use of firewood and charcoal as fuel. The biogas is used by households for cooking and heating.

Vermiculture

Vermiculture transforms organic waste from agriculture into humus that is used as compost for crops. This practice is aimed at avoiding the extraction of humus, a recurrent practice that is extremely harmful to the regeneration of the forest. It also promotes the development of a sustainable activity for farmers.

Results and impacts

This strategy has made it possible to build alliances with public and private bodies that facilitate the leverage of funds to finance innovative projects connected with the promotion of clean energy, the collective construction of a device and community training in topics such as climate change, renewable energy, the use of firewood and the sustainable management of the native forest. The National Forest Corporation, the National Energy Commission, the Ministry of the Environment, the Foundation for Overcoming Poverty (Fundación Superación de la Pobreza), the municipalities of Doñihue, Coltauco and Las Cabras as well as local organizations such as schools, neighbourhood associations and ecological groups have been key partners in achieving this goal. According to Leonardo Duran, coordinator of the Cachapoal Model Forest, "These types of projects can only be implemented if you have built up a basic group of institutions to contribute funding, knowledge and other elements to help support these processes over time."

Since 2008 to date, approximately 200 to 250 people have benefited from high investment projects or initiatives in which every family built their own device. Using fruit dehydrators, families can sell their produce on the local market, either directly or through intermediaries. At the same time, the biogas produced by the biodigester results in savings on the monthly gas bill (the equivalent to US$80), minimizes the use of firewood, and can be used in the production of goods such as jams that generate an additional income for the family. Through these projects, a value chain is being created that is based on the promotion of clean energy. The intention is for these numbers to increase in the future, and to this end, projects are now being carried out in conjunction with several local organizations that are financed by the Ministry of the Environment's Environmental Protection Fund, in which resources are committed by the organizations and the Model Forest.

These tools help to minimize the use and extraction of firewood, which in turn helps in the upkeep of the goods and services provided by the forest, as well as in limiting the emission of gases into the atmosphere, thus contributing to the great challenge represented by climate change. These different initiatives illustrate the positive effects of unconventional renewable energy in aspects such as family economy, forest exploitation and environmental awareness. "To reinforce this work as a Model Forest, the economic and environmental impacts of the use of these technologies needs to be monitored," points out Leonardo Duran. This process enables the construction of a social fabric, a critical mass of stakeholders who already look upon the use of unconventional renewable energies as a way of life, are trained in the construction and use of these devices and are aware of the benefits for the environment, their families and local development.

"The Model Forest also seeks to have a political impact," adds Leonardo Duran, "so that in the future, clean energy and other topics may be included in the curriculum as part of environmental education as well as in development policies that are being implemented by institutions at a local level."

To find out more

- International Model Forest Network: **imfn.net**
- Video: **youtu.be/C0t1DeFUdnw**

[*The International Model Forest Network brings people together to test and apply innovative approaches to the sustainable management and use of the world's landscapes and natural resources.*]

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International Model Forest Network Secretariat
580 Booth Street, Ottawa, ON K1A 0E4 Canada
imfn@imfn.net

@modelforest | www.youtube.com/IMFNnetwork

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