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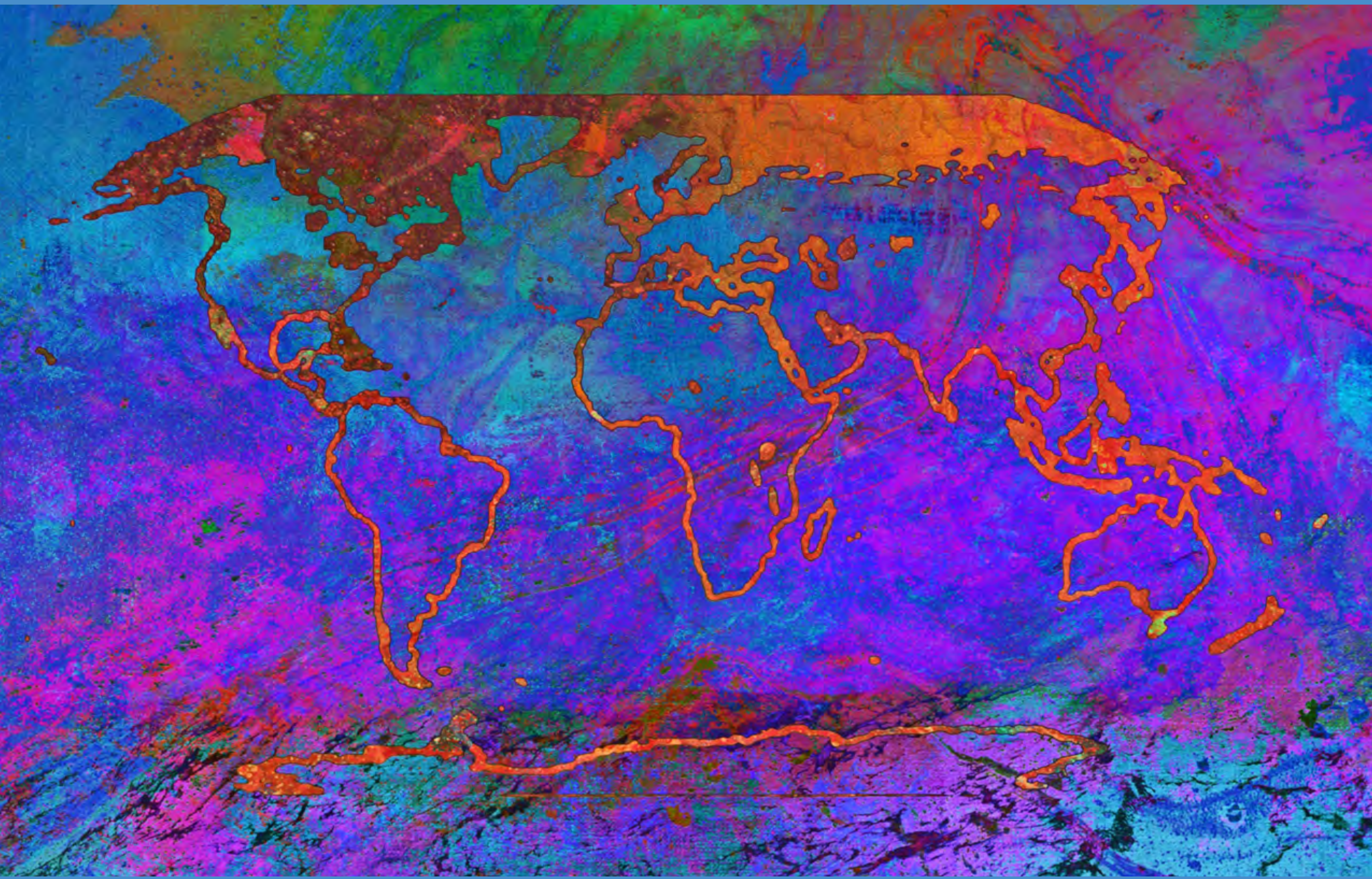
Climate Change 2021

The Physical Science Basis



WGI

Working Group I contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Summary for Policymakers

Drafting Authors:
Richard P. Allan (United Kingdom), Paola A. Arias (Colombia), Sophie Berger (France/Belgium), Josep G. Canadell (Australia), Christophe Cassou (France), Deliang Chen (Sweden), Annalisa Cherchi (Italy), Sarah L. Connors (France/United Kingdom), Erika Coppola (Italy), Faye Abigail Cruz (Philippines), Aïda Diongue-Niang (Senegal), Francisco J. Doblas-Reyes (Spain), Hervé Douville (France), Fatima Driouech (Morocco), Tamsin L. Edwards (United Kingdom), François Engelbrecht (South Africa), Veronika Eyring (Germany), Erich Fischer (Switzerland), Gregory M. Flato (Canada), Piers Forster (United Kingdom), Baylor Fox-Kemper (United States of America), Jan S. Fuglestvedt (Norway), John C. Fyfe (Canada), Nathan P. Gillett (Canada), Melissa I. Gomis (France/Switzerland), Sergey K. Gulev (Russian Federation), José Manuel Gutiérrez (Spain), Rafiq Hamdi (Belgium), Jordan Harold (United Kingdom), Mathias Hauser (Switzerland), Ed Hawkins (United Kingdom), Helene T. Hewitt (United Kingdom), Tom Gabriel Johansen (Norway), Christopher Jones (United Kingdom), Richard G. Jones (United Kingdom), Darrell S. Kaufman (United States of America), Zbigniew Klimont (Austria/Poland), Robert E. Kopp (United States of America), Charles Koven (United States of America), Gerhard Krinner (France/Germany, France), June-Yi Lee (Republic of Korea), Irene Lorenzoni (United Kingdom/Italy), Jochem Marotzke (Germany), Valérie Masson-Delmotte (France), Thomas K. Maycock (United States of America), Malte Meinshausen (Australia/Germany), Pedro M.S. Monteiro (South Africa), Angela Morelli (Norway/Italy), Vaishali Naik (United States of America), Dirk Notz (Germany), Friederike Otto (United Kingdom/Germany), Matthew D. Palmer (United Kingdom), Izidine Pinto (South Africa/Mozambique), Anna Pirani (Italy), Gian-Kasper Plattner (Switzerland), Krishnan Raghavan (India), Roshanka Ranasinghe (The Netherlands/Sri Lanka, Australia), Joeri Rogelj (United Kingdom/Belgium), Maisa Rojas (Chile), Alex C. Ruane (United States of America), Jean-Baptiste Sallée (France), Bjørn H. Samset (Norway), Sonia I. Seneviratne (Switzerland), Jana Sillmann (Norway/Germany), Anna A. Sörensson (Argentina), Tannecia S. Stephenson (Jamaica), Trude Storelvmo (Norway), Sophie Szopa (France), Peter W. Thorne (Ireland/United Kingdom), Blair Trewin (Australia), Robert Vautard (France), Carolina Vera (Argentina), Noureddine Yassaa (Algeria), Sönke Zaehle (Germany), Panmao Zhai (China), Xuebin Zhang (Canada), Kirsten Zickfeld (Canada/Germany)

Contributing Authors:
Krishna M. AchutaRao (India), Bhupesh Adhikary (Nepal), Edvin Aldrian (Indonesia), Kyle Armour (United States of America), Govindasamy Bala (India/United States of America), Rondrotiana Barimalala (South Africa/Madagascar), Nicolas Bellouin (United Kingdom/France), William Collins (United Kingdom), William D. Collins (United States of America), Susanna Corti (Italy), Peter M. Cox (United Kingdom), Frank J. Dentener (EU/The Netherlands), Claudine Dereczynski (Brazil), Alejandro Di Luca (Australia, Canada/Argentina), Alessandro Dosio (Italy), Leah Goldfarb (France/United States of America), Irina V. Gorodetskaya (Portugal/Belgium, Russian Federation), Pandora Hope (Australia), Mark Howden (Australia), Akm Saiful Islam (Bangladesh), Yu Kosaka (Japan), James Kossin (United States of America), Svitlana Krakovska (Ukraine), Chao Li (China), Jian Li (China), Thorsten Mauritsen (Germany/Denmark), Sebastian Milinski (Germany), Seung-Ki Min (Republic of Korea), Thanh Ngo Duc (Vietnam), Andy Reisinger (New Zealand), Lucas Ruiz (Argentina), Shubha Sathyendranath (United Kingdom/Canada, Overseas Citizen of India), Aimée B. A. Slangen (The Netherlands), Chris Smith (United Kingdom), Izuru Takayabu (Japan), Muhammad Irfan Tariq (Pakistan), Anne-Marie Treguier (France), Bart van den Hurk (The Netherlands), Karina von Schuckmann (France/Germany), Cunde Xiao (China)

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Table of Contents

Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group I (WGI) contribution to the IPCC's Sixth Assessment Report (AR6)[1] on the physical science basis of climate change. The report builds upon the 2013 Working Group I contribution to the IPCC's Fifth Assessment Report (AR5) and the 2018–2019 IPCC Special Reports[2] of the AR6 cycle and incorporates subsequent new evidence from climate science[3].

This SPM provides a high-level summary of the understanding of the current state of the climate, including how it is changing and the role of human influence, the state of knowledge about possible climate futures, climate information relevant to regions and sectors, and limiting human-induced climate change.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence indicated using the IPCC calibrated language[4].

The scientific basis for each key finding is found in chapter sections of the main Report, and in the integrated synthesis presented in the Technical Summary (hereafter TS), and is indicated in curly brackets. The AR6 WGI Interactive Atlas facilitates exploration of these key synthesis findings, and supporting climate change information, across the WGI reference regions[5].

[1] Decision IPCC/XLVI-2.

[2] The three Special reports are: Global warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

[3] The assessment covers scientific literature accepted for publication by 31 January 2021.

[4] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: *virtually certain* 99–100% probability, *very likely* 90–100%, *likely* 66–100%, *about as likely as not* 33–66%, *unlikely* 0–33%, *very unlikely* 0–10%, *exceptionally unlikely* 0–1%. Additional terms (*extremely likely* 95–100%, *more likely than not* >50–100%, and *extremely unlikely* 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

[5] The Interactive Atlas is available at https://interactive-atlas.ipcc.ch

A. The Current State of the Climate

Since AR5, improvements in observationally based estimates and information from paleoclimate archives provide a comprehensive view of each component of the climate system and its changes to date. New climate model simulations, new analyses, and methods combining multiple lines of evidence lead to improved understanding of human influence on a wider range of climate variables, including weather and climate extremes. The time periods considered throughout this Section depend upon the availability of observational products, paleoclimate archives and peer-reviewed studies.

A.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.

{2.2, 2.3, Cross-Chapter Box 2.3, 3.3, 3.4, 3.5, 3.6, 3.8, 5.2, 5.3, 6.4, 7.3, 8.3, 9.2, 9.3, 9.5, 9.6, Cross-Chapter Box 9.1} **(Figure SPM.1, Figure SPM.2)**

A.1.1 Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities. Since 2011 (measurements reported in AR5), concentrations have continued to increase in the atmosphere, reaching annual averages of 410 ppm for carbon dioxide (CO_2), 1866 ppb for methane (CH_4), and 332 ppb for nitrous oxide (N_2O) in 2019[6]. Land and ocean have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*)[7]. {2.2, 5.2, 7.3, TS.2.2, Box TS.5}

A.1.2 Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature[8] in the first two decades of the 21st century (2001-2020) was 0.99 [0.84-1.10] °C higher than 1850-1900[9]. Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1ºC to the updated estimate of warming in AR6[10].

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[6] Other GHG concentrations in 2019 were: PFCs (109 ppt CF_4 equivalent); SF_6 (10 ppt); NF_3 (2 ppt); HFCs (237 ppt HFC-134a equivalent); other Montreal Protocol gases (mainly CFCs, HCFCs, 1032 ppt CFC-12 equivalent). Increases from 2011 are 19 ppm for CO_2, 63 ppb for CH_4 and 8 ppb for N_2O.

[7] Land and ocean are not substantial sinks for other GHGs.

[8] The term 'global surface temperature' is used in reference to both global mean surface temperature and global surface air temperature throughout this SPM. Changes in these quantities are assessed with *high confidence* to differ by at most 10% from one another, but conflicting lines of evidence lead to *low confidence* in the sign of any difference in long-term trend. {Cross-Section Box TS.1}

[9] The period 1850–1900 represents the earliest period of sufficiently globally complete observations to estimate global surface temperature and, consistent with AR5 and SR1.5, is used as an approximation for pre-industrial conditions.

[10] Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have additionally increased the estimate of global surface temperature change by approximately 0.1 ºC, but this increase does not represent additional physical warming since the AR5.

A.1.3 The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to 0.1°C, and internal variability changed it by –0.2°C to 0.2°C. It is *very likely* that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979, and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s.
{3.3, 6.4, 7.3, Cross-Section Box TS.1, TS.2.3} **(Figure SPM.2)**

A.1.4 Globally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). It is *likely* that human influence contributed to the pattern of observed precipitation changes since the mid-20th century, and *extremely likely* that human influence contributed to the pattern of observed changes in near-surface ocean salinity. Mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s, with marked seasonality in trends (*medium confidence*). For the Southern Hemisphere, human influence *very likely* contributed to the poleward shift of the closely related extratropical jet in austral summer.
{2.3, 3.3, 8.3, 9.2, TS.2.3, TS.2.4, Box TS.6}

A.1.5 Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (about 40% in September and about 10% in March). There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability. Human influence *very likely* contributed to the decrease in Northern Hemisphere spring snow cover since 1950. It is *very likely* that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only *limited evidence*, with *medium agreement*, of human influence on the Antarctic Ice Sheet mass loss.
{2.3, 3.4, 8.3, 9.3, 9.5, TS.2.5}

A.1.6 It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and *medium confidence* that human influence contributed to this drop.
{2.3, 3.5, 3.6, 5.3, 9.2, TS.2.4}

A.1.7 Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971.
{2.3, 3.5, 9.6, Cross-Chapter Box 9.1, Box TS.4}

A.1.8 Changes in the land biosphere since 1970 are consistent with global warming: climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics (*high confidence*).
{2.3, TS.2.6}

[11] The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C.

[12] Throughout this SPM, 'main driver' means responsible for more than 50% of the change.

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Changes in global surface temperature relative to 1850-1900

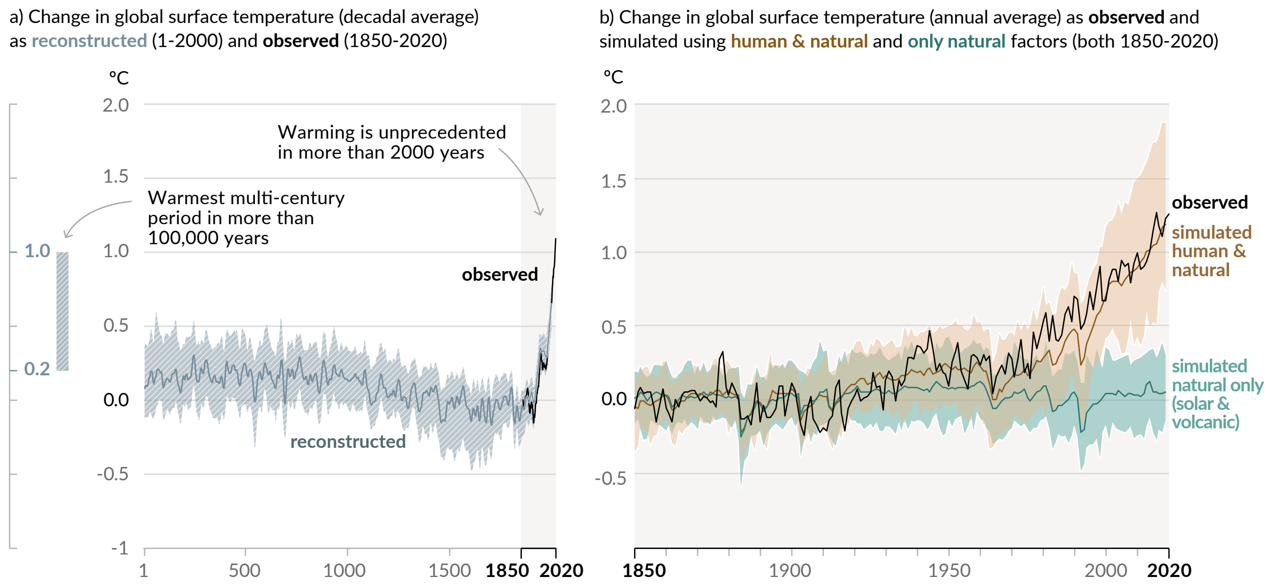


Figure SPM.1: History of global temperature change and causes of recent warming.

Panel a): Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, 1–2000) **and from direct observations** (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). The Last Interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.

Panel b): Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to CMIP6 climate model simulations (see Box SPM.1) of the temperature response to both human and natural drivers (brown), and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations. (see Figure SPM.2 for the assessed contributions to warming).

{2.3.1, 3.3, Cross-Chapter Box 2.3, Cross-Section Box TS.1, Figure 1a, TS.2.2}

Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling

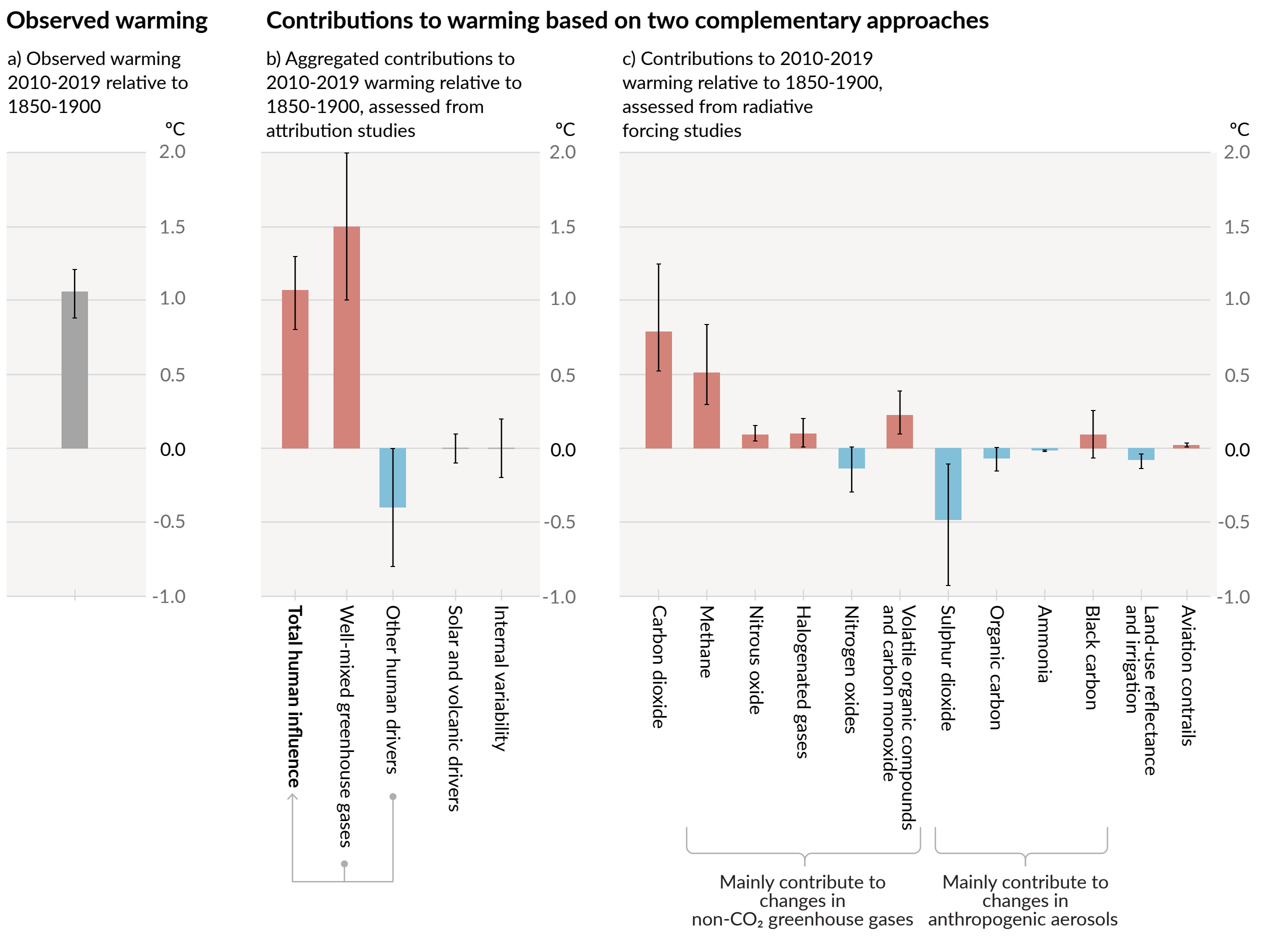


Figure SPM.2: Assessed contributions to observed warming in 2010–2019 relative to 1850–1900.

Panel a): Observed global warming (increase in global surface temperature) and its *very likely* range {3.3.1, Cross-Chapter Box 2.3}.

Panel b): Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to total human influence, changes in well-mixed greenhouse gas concentrations, other human drivers due to aerosols, ozone and land-use change (land-use reflectance), solar and volcanic drivers, and internal climate variability. Whiskers show *likely* ranges {3.3.1}.

Panel c): Evidence from the assessment of radiative forcing and climate sensitivity. The panel shows temperature changes from individual components of human influence, including emissions of greenhouse gases, aerosols and their precursors; land-use changes (land-use reflectance and irrigation); and aviation contrails. Whiskers show *very likely* ranges. Estimates account for both direct emissions into the atmosphere and their effect, if any, on other climate drivers. For aerosols, both direct (through radiation) and indirect (through interactions with clouds) effects are considered. {6.4.2, 7.3}

A.2 The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.
{Cross-Chapter Box 2.1, 2.2, 2.3, 5.1} **(Figure SPM.1)**

A.2.1 In 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years (*high confidence)*, and concentrations of CH_4 and N_2O were higher than at any time in at least 800,000 years (*very high confidence*). Since 1750, increases in CO_2 (47%) and CH_4 (156%) concentrations far exceed, and increases in N_2O (23%) are similar to, the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (*very high confidence*).
{2.2, 5.1, TS.2.2}

A.2.2 Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). Temperatures during the most recent decade (2011–2020) exceed those of the most recent multi-century warm period, around 6500 years ago[13] [0.2°C to 1°C relative to 1850–1900] (*medium confidence*). Prior to that, the next most recent warm period was about 125,000 years ago when the multi-century temperature [0.5°C to 1.5°C relative to 1850–1900] overlaps the observations of the most recent decade (*medium confidence*).
{Cross-Chapter Box 2.1, 2.3, Cross-Section Box TS.1} **(Figure SPM.1)**

A.2.3 In 2011–2020, annual average Arctic sea ice area reached its lowest level since at least 1850 (*high confidence*). Late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years (*medium confidence*). The global nature of glacier retreat, with almost all of the world's glaciers retreating synchronously, since the 1950s is unprecedented in at least the last 2000 years (*medium confidence*).
{2.3, TS.2.5}

A.2.4 Global mean sea level has risen faster since 1900 than over any preceding century in at least the last 3000 years (*high confidence*). The global ocean has warmed faster over the past century than since the end of the last deglacial transition (around 11,000 years ago) (*medium confidence*). A long-term increase in surface open ocean pH occurred over the past 50 million years (*high confidence*), and surface open ocean pH as low as recent decades is unusual in the last 2 million years (*medium confidence*).
{2.3, TS.2.4, Box TS.4}

[13] As stated in section B.1, even under the very low emissions scenario SSP1-1.9, temperatures are assessed to remain elevated above those of the most recent decade until at least 2100 and therefore warmer than the century-scale period 6500 years ago.

A.3 Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.

{2.3, 3.3, 8.2, 8.3, 8.4, 8.5, 8.6, Box 8.1, Box 8.2, Box 9.2, 10.6, 11.2, 11.3, 11.4, 11.6, 11.7, 11.8, 11.9, 12.3} **(Figure SPM.3)**

A.3.1 It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006.
{Box 9.2, 11.2, 11.3, 11.9, TS.2.4, TS.2.6, Box TS.10} **(Figure SPM.3)**

A.3.2 The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (*high confidence*), and human-induced climate change is *likely* the main driver. Human-induced climate change has contributed to increases in agricultural and ecological droughts[15] in some regions due to increased land evapotranspiration[16] (*medium confidence*).
{8.2, 8.3, 11.4, 11.6, 11.9, TS.2.6, Box TS.10} **(Figure SPM.3)**

A.3.3 Decreases in global land monsoon precipitation[17] from the 1950s to the 1980s are partly attributed to human-caused Northern Hemisphere aerosol emissions, but increases since then have resulted from rising GHG concentrations and decadal to multi-decadal internal variability (*medium confidence*). Over South Asia, East Asia and West Africa increases in monsoon precipitation due to warming from GHG emissions were counteracted by decreases in monsoon precipitation due to cooling from human-caused aerosol emissions over the 20th century (*high confidence*). Increases in West African monsoon precipitation since the 1980s are partly due to the growing influence of GHGs and reductions in the cooling effect of human-caused aerosol emissions over Europe and North America (*medium confidence*).
{2.3, 3.3, 8.2, 8.3, 8.4, 8.5, 8.6, Box 8.1, Box 8.2, 10.6, Box TS.13}

[14] Throughout this SPM, 'main driver' means responsible for more than 50% of the change.

[15] Agricultural and ecological drought (depending on the affected biome): a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general. Observed changes in meteorological droughts (precipitation deficits) and hydrological droughts (streamflow deficits) are distinct from those in agricultural and ecological droughts and addressed in the underlying AR6 material (Chapter 11).

[16] The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the Earth's surface.

[17] The global monsoon is defined as the area in which the annual range (local summer minus local winter) of precipitation is greater than 2.5 mm day^{-1}. Global land monsoon precipitation refers to the mean precipitation over land areas within the global monsoon.

A.3.4 It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades, and the latitude where tropical cyclones in the western North Pacific reach their peak intensity has shifted northward; these changes cannot be explained by internal variability alone (*medium confidence*). There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. Event attribution studies and physical understanding indicate that human-induced climate change increases heavy precipitation associated with tropical cyclones (*high confidence*) but data limitations inhibit clear detection of past trends on the global scale. {8.2, 11.7, Box TS.10}

A.3.5 Human influence has *likely* increased the chance of compound extreme events[18] since the 1950s. This includes increases in the frequency of concurrent heatwaves and droughts on the global scale (*high confidence*); fire weather in some regions of all inhabited continents (*medium confidence*); and compound flooding in some locations (*medium confidence*). {11.6, 11.7, 11.8, 12.3, 12.4, TS.2.6, Table TS.5, Box TS.10}

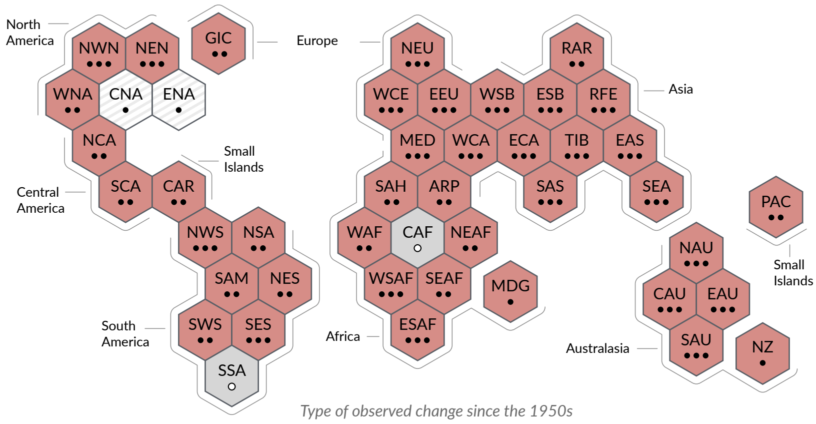
[18] Compound extreme events are the combination of multiple drivers and/or hazards that contribute to societal or environmental risk. Examples are concurrent heatwaves and droughts, compound flooding (e.g., a storm surge in combination with extreme rainfall and/or river flow), compound fire weather conditions (i.e., a combination of hot, dry, and windy conditions), or concurrent extremes at different locations.

Climate change is already affecting every inhabited region across the globe with human influence contributing to many observed changes in weather and climate extremes

a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions

Type of observed change in hot extremes
- Increase (41)
- Decrease (0)
- Low agreement in the type of change (2)
- Limited data and/or literature (2)

Confidence in human contribution to the observed change
- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence

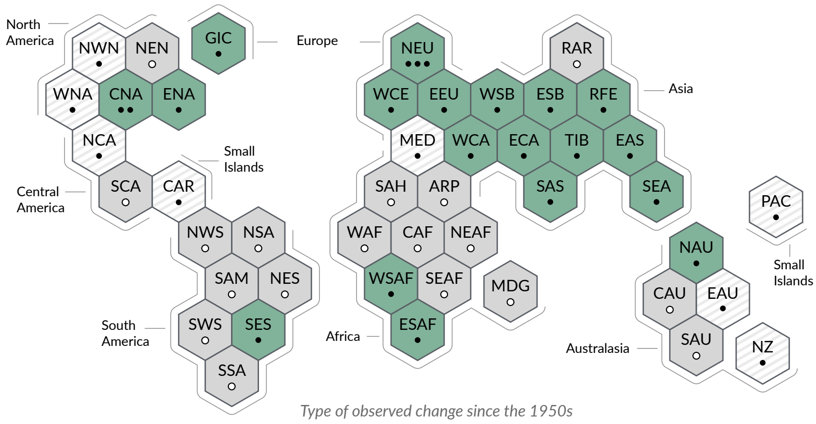


Type of observed change since the 1950s

b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions

Type of observed change in heavy precipitation
- Increase (19)
- Decrease (0)
- Low agreement in the type of change (8)
- Limited data and/or literature (18)

Confidence in human contribution to the observed change
- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence

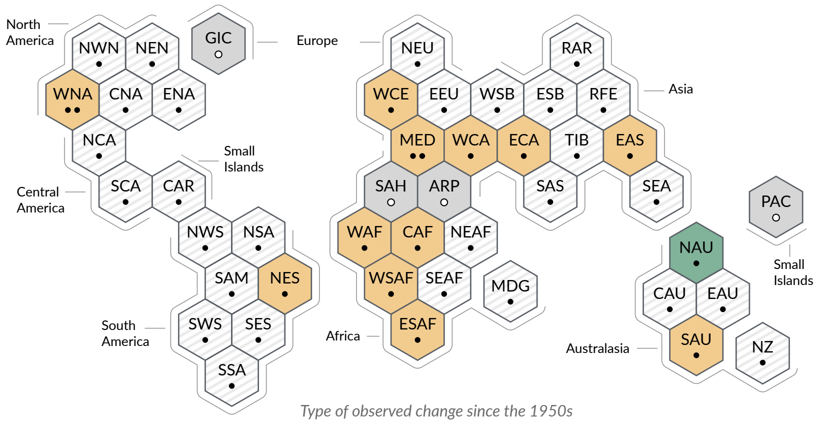


Type of observed change since the 1950s

c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

Type of observed change in agricultural and ecological drought
- Increase (12)
- Decrease (1)
- Low agreement in the type of change (28)
- Limited data and/or literature (4)

Confidence in human contribution to the observed change
- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence



Type of observed change since the 1950s

Each hexagon corresponds to one of the IPCC AR6 WGI reference regions

North-Western North America

IPCC AR6 WGI reference regions: **North America:** ***NWN*** *(North-Western North America,* ***NEN*** *(North-Eastern North America),* ***WNA*** *(Western North America),* ***CNA*** *(Central North America),* ***ENA*** *(Eastern North America),* **Central America:** ***NCA*** *(Northern Central America),* ***SCA*** *(Southern Central America),* ***CAR*** *(Caribbean),* **South America:** ***NWS*** *(North-Western South America),* ***NSA*** *(Northern South America),* ***NES*** *(North-Eastern South America),* ***SAM*** *(South American Monsoon),* ***SWS*** *(South-Western South America),* ***SES*** *(South-Eastern South America),* ***SSA*** *(Southern South America),* **Europe:** ***GIC*** *(Greenland/Iceland),* ***NEU*** *(Northern Europe),* ***WCE*** *(Western and Central Europe),* ***EEU*** *(Eastern Europe),* ***MED*** *(Mediterranean),* **Africa:** ***MED*** *(Mediterranean),* ***SAH*** *(Sahara),* ***WAF*** *(Western Africa),* ***CAF*** *(Central Africa),* ***NEAF*** *(North Eastern Africa),* ***SEAF*** *(South Eastern Africa),* ***WSAF*** *(West Southern Africa),* ***ESAF*** *(East Southern Africa),* ***MDG*** *(Madagascar),* **Asia:** ***RAR*** *(Russian Arctic),* ***WSB*** *(West Siberia),* ***ESB*** *(East Siberia),* ***RFE*** *(Russian Far East),* ***WCA*** *(West Central Asia),* ***ECA*** *(East Central Asia),* ***TIB*** *(Tibetan Plateau),* ***EAS*** *(East Asia),* ***ARP*** *(Arabian Peninsula),* ***SAS*** *(South Asia),* ***SEA*** *(South East Asia),* **Australasia:** ***NAU*** *(Northern Australia),* ***CAU*** *(Central Australia),* ***EAU*** *(Eastern Australia),* ***SAU*** *(Southern Australia),* ***NZ*** *(New Zealand),* **Small Islands:** ***CAR*** *(Caribbean),* ***PAC*** *(Pacific Small Islands)*

Figure SPM.3: Synthesis of assessed observed and attributable regional changes.

The IPCC AR6 WGI inhabited regions are displayed as **hexagons** with identical size in their approximate geographical location (see legend for regional acronyms). All assessments are made for each region as a whole and for the 1950s to the present. Assessments made on different time scales or more local spatial scales might differ from what is shown in the figure. The **colours** in each panel represent the four outcomes of the assessment on observed changes. White and light grey striped hexagons are used where there is *low agreement* in the type of change for the region as a whole, and grey hexagons are used when there is limited data and/or literature that prevents an assessment of the region as a whole. Other colours indicate at least *medium confidence* in the observed change. The **confidence level** for the human influence on these observed changes is based on assessing trend detection and attribution and event attribution literature, and it is indicated by the number of dots: three dots for *high confidence,* two dots for *medium confidence* and one dot for *low confidence* (filled: limited agreement; empty: limited evidence).

Panel a) For hot extremes, the evidence is mostly drawn from changes in metrics based on daily maximum temperatures; regional studies using other indices (heatwave duration, frequency and intensity) are used in addition. Red hexagons indicate regions where there is at least *medium confidence* in an observed increase in hot extremes.

Panel b) For heavy precipitation, the evidence is mostly drawn from changes in indices based on one-day or five-day precipitation amounts using global and regional studies. Green hexagons indicate regions where there is at least *medium confidence* in an observed increase in heavy precipitation.

Panel c) Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand. Yellow hexagons indicate regions where there is at least *medium confidence* in an observed increase in this type of drought and green hexagons indicate regions where there is at least *medium confidence* in an observed decrease in agricultural and ecological drought.

For all regions, table TS.5 shows a broader range of observed changes besides the ones shown in this figure. Note that SSA is the only region that does not display observed changes in the metrics shown in this figure, but is affected by observed increases in mean temperature, decreases in frost, and increases in marine heatwaves.

{11.9, Table TS.5, Box TS.10, Figure 1, Atlas 1.3.3, Figure Atlas.2}

A.4 Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of equilibrium climate sensitivity of 3°C with a narrower range compared to AR5. {2.2, 7.3, 7.4, 7.5, Box 7.2, Cross-Chapter Box 9.1, 9.4, 9.5, 9.6}

A.4.1 Human-caused radiative forcing of 2.72 [1.96 to 3.48] W m^{-2} in 2019 relative to 1750 has warmed the climate system. This warming is mainly due to increased GHG concentrations, partly reduced by cooling due to increased aerosol concentrations. The radiative forcing has increased by 0.43 W m^{-2} (19%) relative to AR5, of which 0.34 W m^{-2} is due to the increase in GHG concentrations since 2011. The remainder is due to improved scientific understanding and changes in the assessment of aerosol forcing, which include decreases in concentration and improvement in its calculation (*high confidence*).
{2.2, 7.3, TS.2.2, TS.3.1}

A.4.2 Human-caused net positive radiative forcing causes an accumulation of additional energy (heating) in the climate system, partly reduced by increased energy loss to space in response to surface warming. The observed average rate of heating of the climate system increased from 0.50 [0.32 to 0.69] W m^{-2} for the period 1971–2006[19], to 0.79 [0.52 to 1.06] W m^{-2} for the period 2006–2018[20] (*high confidence*). Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*).
{7.2, Box 7.2, TS.3.1}

A.4.3 Heating of the climate system has caused global mean sea level rise through ice loss on land and thermal expansion from ocean warming. Thermal expansion explained 50% of sea level rise during 1971–2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%. The rate of ice sheet loss increased by a factor of four between 1992–1999 and 2010–2019. Together, ice sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006-2018. (*high confidence*)
{Cross-Chapter Box 9.1, 9.4, 9.5, 9.6}

A.4.4 The equilibrium climate sensitivity is an important quantity used to estimate how the climate responds to radiative forcing. Based on multiple lines of evidence[21], the *very likely* range of equilibrium climate sensitivity is between 2°C (*high confidence*) and 5°C (*medium confidence*). The AR6 assessed best estimate is 3°C with a *likely* range of 2.5°C to 4°C (*high confidence*), compared to 1.5°C to 4.5°C in AR5, which did not provide a best estimate.
{7.4, 7.5, TS.3.2}

[19] cumulative energy increase of 282 [177 to 387] ZJ over 1971–2006 (1 ZJ = 10^{21} J).

[20] cumulative energy increase of 152 [100 to 205] ZJ over 2006–2018.

[21] Understanding of climate processes, the instrumental record, paleoclimates and model-based emergent constraints (see glossary).

B. Possible Climate Futures

A set of five new illustrative emissions scenarios is considered consistently across this report to explore the climate response to a broader range of greenhouse gas (GHG), land use and air pollutant futures than assessed in AR5. This set of scenarios drives climate model projections of changes in the climate system. These projections account for solar activity and background forcing from volcanoes. Results over the 21st century are provided for the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100) relative to 1850–1900, unless otherwise stated.

Box SPM.1: Scenarios, Climate Models and Projections

Box SPM.1.1: This report assesses the climate response to five illustrative scenarios that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. They start in 2015, and include scenarios[22] with high and very high GHG emissions (SSP3-7.0 and SSP5-8.5) and CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively, scenarios with intermediate GHG emissions (SSP2-4.5) and CO_2 emissions remaining around current levels until the middle of the century, and scenarios with very low and low GHG emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions[23] (SSP1-1.9 and SSP1-2.6) as illustrated in Figure SPM.4. Emissions vary between scenarios depending on socio-economic assumptions, levels of climate change mitigation and, for aerosols and non-methane ozone precursors, air pollution controls. Alternative assumptions may result in similar emissions and climate responses, but the socio-economic assumptions and the feasibility or likelihood of individual scenarios is not part of the assessment.
{TS.1.3, 1.6, Cross-Chapter Box 1.4} **(Figure SPM.4)**

Box SPM.1.2: This report assesses results from climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Programme. These models include new and better representation of physical, chemical and biological processes, as well as higher resolution, compared to climate models considered in previous IPCC assessment reports. This has improved the simulation of the recent mean state of most large-scale indicators of climate change and many other aspects across the climate system. Some differences from observations remain, for example in regional precipitation patterns. The CMIP6 historical simulations assessed in this report have an ensemble mean global surface temperature change within 0.2°C of the observations over most of the historical period, and observed warming is within the *very likely* range of the CMIP6 ensemble. However, some CMIP6 models simulate a warming that is either above or below the assessed *very likely* range of observed warming.
{1.5, Cross-Chapter Box 2.2, 3.3, 3.8, TS.1.2, Cross-Section Box TS.1} (Figure SPM.1 b, Figure SPM.2)

Box SPM.1.3: The CMIP6 models considered in this Report have a wider range of climate sensitivity than in CMIP5 models and the AR6 assessed *very likely* range, which is based on multiple lines of evidence. These CMIP6 models also show a higher average climate sensitivity than CMIP5 and the AR6 assessed best estimate. The higher CMIP6 climate sensitivity values compared to CMIP5 can be traced to an amplifying cloud feedback that is larger in CMIP6 by about 20%.
{Box 7.1, 7.3, 7.4, 7.5, TS.3.2}

Box SPM.1.4: For the first time in an IPCC report, assessed future changes in global surface temperature, ocean warming and sea level are constructed by combining multi-model projections with observational constraints based on past simulated warming, as well as the AR6 assessment of climate sensitivity. For other quantities, such robust methods do not yet exist to constrain the projections. Nevertheless, robust projected

[22] Throughout this report, the five illustrative scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in W m^{-2}) resulting from the scenario in the year 2100. A detailed comparison to scenarios used in earlier IPCC reports is provided in Section TS1.3 and 1.6 and 4.6. The SSPs that underlie the specific forcing scenarios used to drive climate models are not assessed by WGI. Rather, the SSPx-y labelling ensures traceability to the underlying literature in which specific forcing pathways are used as input to the climate models. IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

[23] Net negative CO_2 emissions are reached when anthropogenic removals of CO_2 exceed anthropogenic emissions. {Glossary}

geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached. {1.6, Box 4.1, 4.3, 4.6, 7.5, 9.2, 9.6, Cross-Chapter Box 11.1, Cross-Section Box TS.1}

Future emissions cause future additional warming, with total warming dominated by past and future CO_2 emissions

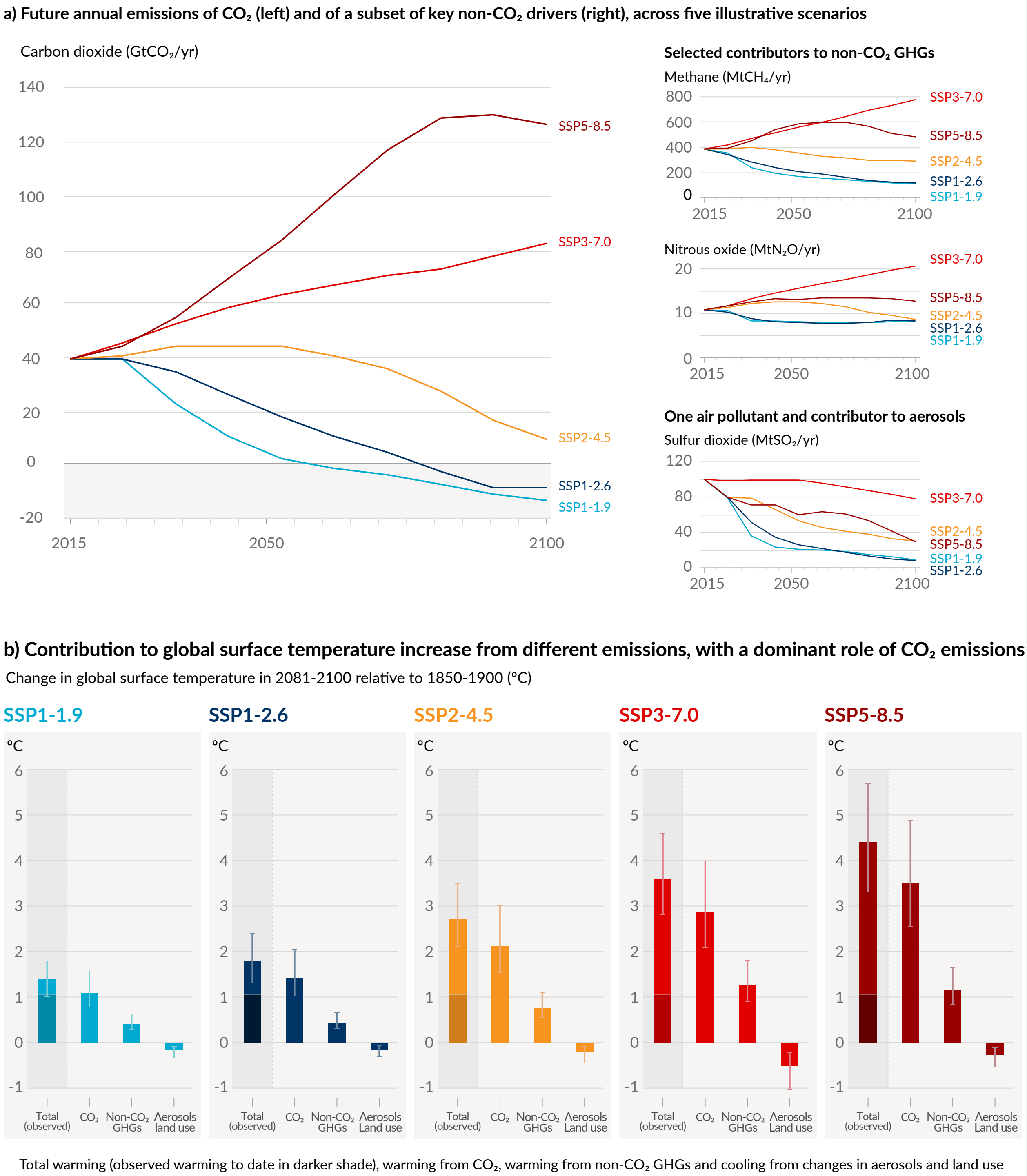


Figure SPM.4: Future anthropogenic emissions of key drivers of climate change and warming contributions by groups of drivers for the five illustrative scenarios used in this report.

The five scenarios are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

Panel a) Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for carbon dioxide (CO_2) from all sectors ($GtCO_2$/yr) (left graph) and for a subset of three key non-CO_2 drivers considered in the scenarios: methane (CH_4, $MtCH_4$/yr, top-right graph), nitrous oxide (N_2O, MtN_2O/yr, middle-right graph) and sulfur dioxide (SO_2, $MtSO_2$/yr, bottom-right graph, contributing to anthropogenic aerosols in panel b).

Panel b) Warming contributions by groups of anthropogenic drivers and by scenario are shown as change in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date. Bars and whiskers represent median values and the *very likely* range, respectively. Within each scenario bar plot, the bars represent total global warming (°C; total bar) (see Table SPM.1) and warming contributions (°C) from changes in CO_2 (CO_2 bar), from non-CO_2 greenhouse gases (non-CO_2 GHGs bar; comprising well-mixed greenhouse gases and ozone) and net cooling from other anthropogenic drivers (aerosols and land-use bar; anthropogenic aerosols, changes in reflectance due to land-use and irrigation changes, and contrails from aviation; see Figure SPM.2, panel c, for the warming contributions to date for individual drivers). The best estimate for observed warming in 2010–2019 relative to 1850–1900 (see Figure SPM.2, panel a) is indicated in the darker column in the total bar. Warming contributions in panel b are calculated as explained in Table SPM.1 for the total bar. For the other bars the contribution by groups of drivers are calculated with a physical climate emulator of global surface temperature which relies on climate sensitivity and radiative forcing assessments.

{Cross-Chapter Box 1.4, 4.6, Figure 4.35, 6.7, Figure 6.18, 6.22 and 6.24, Cross-Chapter Box 7.1, 7.3, Figure 7.7, Box TS.7, Figures TS.4 and TS.15}

B.1 Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.

{2.3, Cross-Chapter Box 2.3, Cross-Chapter Box 2.4, 4.3, 4.4, 4.5} **(Figure SPM.1, Figure SPM.4, Figure SPM.8, Table SPM.1, Box SPM.1)**

B.1.1 Compared to 1850–1900, global surface temperature averaged over 2081–2100 is *very likely* to be higher by 1.0°C to 1.8°C under the very low GHG emissions scenario considered (SSP1-1.9), by 2.1°C to 3.5°C in the intermediate scenario (SSP2-4.5) and by 3.3°C to 5.7°C under the very high GHG emissions scenario (SSP5-8.5)[24]. The last time global surface temperature was sustained at or above 2.5°C higher than 1850–1900 was over 3 million years ago (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 4.3, 4.5, Box TS.2, Box TS.4, Cross-Section Box TS.1} **(Table SPM.1)**

Table SPM.1: Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. This includes the revised assessment of observed historical warming for the AR5 reference period 1986–2005, which in AR6 is higher by 0.08 [–0.01 to 0.12] °C than in the AR5 (see footnote 10). Changes relative to the recent reference period 1995–2014 may be calculated approximately by subtracting 0.85°C, the best estimate of the observed warming from 1850–1900 to 1995–2014. {Cross-Chapter Box 2.3, 4.3, 4.4, Cross-Section Box TS.1}

[24] Changes in global surface temperature are reported as running 20-year averages, unless stated otherwise.

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

B.1.2 Based on the assessment of multiple lines of evidence, global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under the high and very high GHG emissions scenarios considered in this report (SSP3-7.0 and SSP5-8.5, respectively). Global warming of 2°C would *extremely likely* be exceeded in the intermediate scenario (SSP2-4.5). Under the very low and low GHG emissions scenarios, global warming of 2°C is *extremely unlikely* to be exceeded (SSP1-1.9), or *unlikely* to be exceeded (SSP1-2.6)[25]. Crossing the 2°C global warming level in the mid-term period (2041–2060) is *very likely* to occur under the very high GHG emissions scenario (SSP5-8.5), *likely* to occur under the high GHG emissions scenario (SSP3-7.0), and *more likely than not* to occur in the intermediate GHG emissions scenario (SSP2-4.5)[26].
{4.3, Cross-Section Box TS.1} **(Table SPM.1, Figure SPM.4, Box SPM.1)**

B.1.3 Global warming of 1.5°C relative to 1850-1900 would be exceeded during the 21st century under the intermediate, high and very high scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021-2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9)[27]. Furthermore, for the very low GHG emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.
{4.3, Cross-Section Box TS.1} **(Table SPM.1, Figure SPM.4)**

[25] SSP1-1.9 and SSP1-2.6 are scenarios that start in 2015 and have very low and low GHG emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions.

[26] Crossing is defined here as having the assessed global surface temperature change, averaged over a 20-year period, exceed a particular global warming level.

[27] The AR6 assessment of when a given global warming level is first exceeded benefits from the consideration of the illustrative scenarios, the multiple lines of evidence entering the assessment of future global surface temperature response to radiative forcing, and the improved estimate of historical warming. The AR6 assessment is thus not directly comparable to the SR1.5 SPM, which reported likely reaching 1.5°C global warming between 2030 and 2052, from a simple linear extrapolation of warming rates of the recent past. When considering scenarios similar to SSP1-1.9 instead of linear extrapolation, the SR1.5 estimate of when 1.5°C global

B.1.4 Global surface temperature in any single year can vary above or below the long-term human-induced trend, due to substantial natural variability[28]. The occurrence of individual years with global surface temperature change above a certain level, for example 1.5°C or 2ºC, relative to 1850–1900 does not imply that this global warming level has been reached[29].
{Cross-Chapter Box 2.3, 4.3, 4.4, Box 4.1, Cross-Section Box TS.1} **(Table SPM.1, Figure SPM.1, Figure SPM.8)**

B.2 Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, and proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover and permafrost. {4.3, 4.5, 4.6, 7.4, 8.2, 8.4, Box 8.2, 9.3, 9.5, Box 9.2, 11.1, 11.2, 11.3, 11.4, 11.6, 11.7, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11} **(Figure SPM.5, Figure SPM.6, Figure SPM.8)**

B.2.1 It is *virtually certain* that the land surface will continue to warm more than the ocean surface (*likely* 1.4 to 1.7 times more). It is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming.
{2.3, 4.3, 4.5, 4.6, 7.4, 11.1, 11.3, 11.9, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Section Box TS.1, TS.2.6} **(Figure SPM.5)**

B.2.2 With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts[30] in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*).
{8.2, 11.2, 11.3, 11.4, 11.6, 11.9, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1, TS.2.6} **(Figure SPM.5, Figure SPM.6)**

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warming is first exceeded is close to the best estimate reported here.

[28] Natural variability refers to climatic fluctuations that occur without any human influence, that is, internal variability combined with the response to external natural factors such as volcanic eruptions, changes in solar activity and, on longer time scales, orbital effects and plate tectonics.

[29] The internal variability in any single year is estimated to be ± 0.25°C (5–95% range, *high confidence*).

[30] Projected changes in agricultural and ecological droughts are primarily assessed based on total column soil moisture. See footnote 15 for definition and relation to precipitation and evapotranspiration.

B.2.3 Some mid-latitude and semi-arid regions, and the South American Monsoon region, are projected to see the highest increase in the temperature of the hottest days, at about 1.5 to 2 times the rate of global warming (*high confidence*). The Arctic is projected to experience the highest increase in the temperature of the coldest days, at about 3 times the rate of global warming (*high confidence*). With additional global warming, the frequency of marine heatwaves will continue to increase (*high confidence*), particularly in the tropical ocean and the Arctic *(medium confidence).*
{Box 9.2, 11.1, 11.3, 11.9, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1, 12.4, TS.2.4, TS.2.6} **(Figure SPM.6)**

B.2.4 It is *very likely* that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming (*high confidence*). The proportion of intense tropical cyclones (categories 4-5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (*high confidence*).
{8.2, 11.4, 11.7, 11.9, Cross-Chapter Box 11.1, Box TS.6, TS.4.3.1} **(Figure SPM.5, Figure SPM.6)**

B.2.5 Additional warming is projected to further amplify permafrost thawing, and loss of seasonal snow cover, of land ice and of Arctic sea ice (*high confidence*). The Arctic is *likely* to be practically sea ice free in September[31] at least once before 2050 under the five illustrative scenarios considered in this report, with more frequent occurrences for higher warming levels. There is *low confidence* in the projected decrease of Antarctic sea ice.
{4.3, 4.5, 7.4, 8.2, 8.4, Box 8.2, 9.3, 9.5, 12.4, Cross-Chapter Box 12.1, Atlas.5, Atlas.6, Atlas.8, Atlas.9, Atlas.11, TS.2.5} **(Figure SPM.8)**

[31] monthly average sea ice area of less than 1 million km^2 which is about 15% of the average September sea ice area observed in 1979-1988

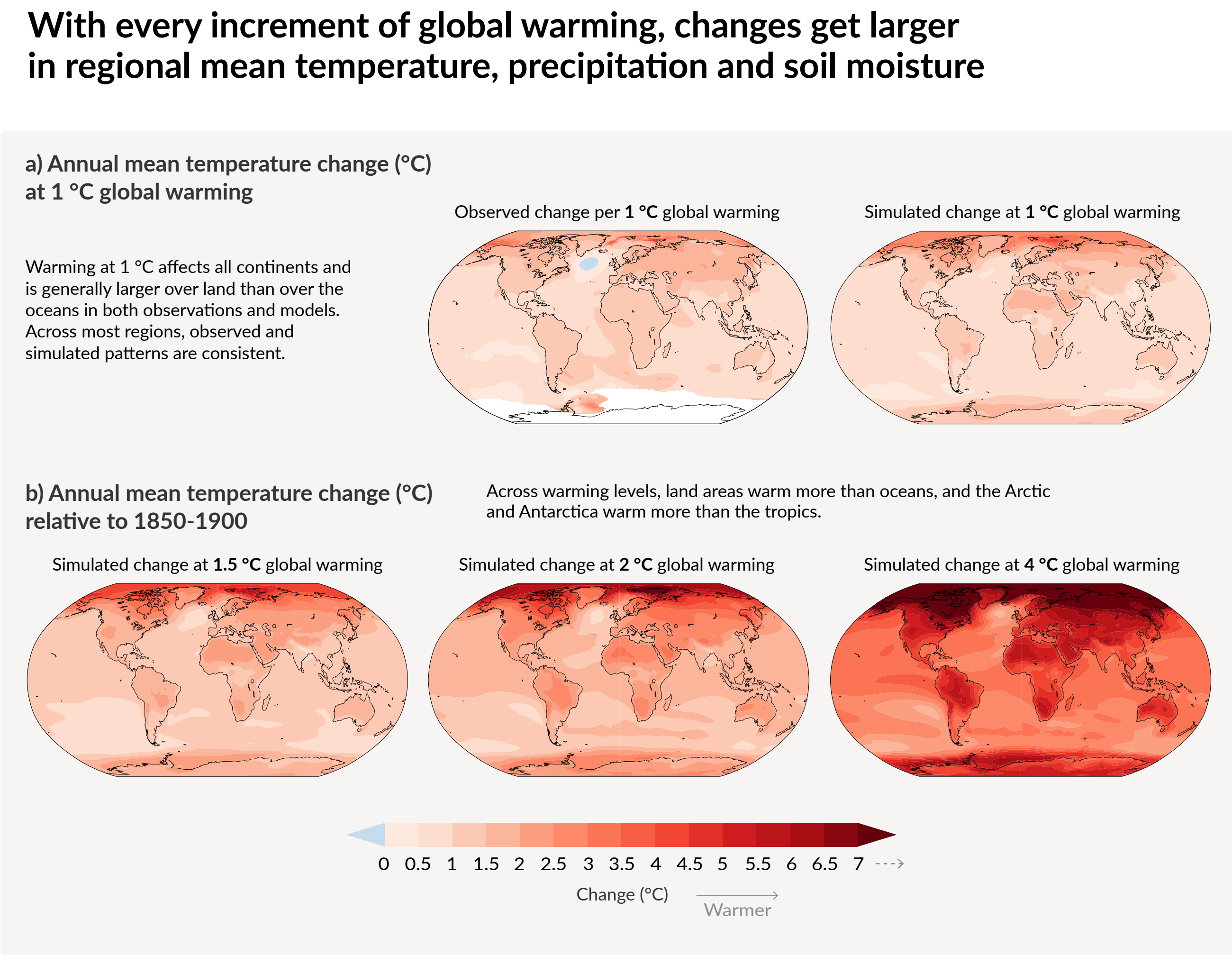
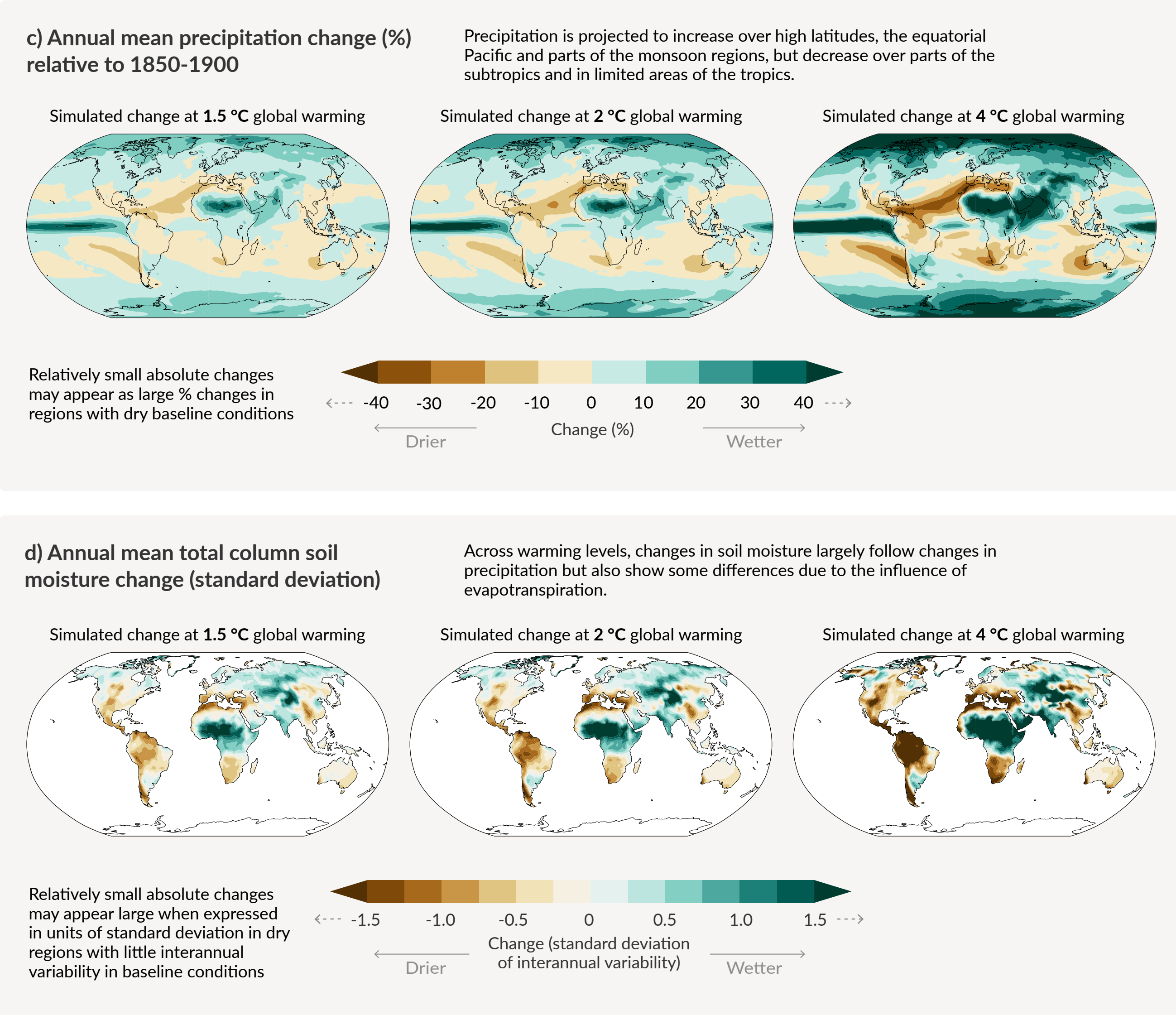


Figure SPM.5: Changes in annual mean surface temperature, precipitation, and soil moisture.

Panel a) Comparison of observed and simulated annual mean surface temperature change. The **left map** shows the observed changes in annual mean surface temperature in the period of 1850–2020 per °C of global warming (°C). The local (i.e., grid point) observed annual mean surface temperature changes are linearly regressed against the global surface temperature in the period 1850–2020. Observed temperature data are from Berkeley Earth, the dataset with the largest coverage and highest horizontal resolution. Linear regression is applied to all years for which data at the corresponding grid point is available. The regression method was used to take into account the complete observational time series and thereby reduce the role of internal variability at the grid point level. White indicates areas where time coverage was 100 years or less and thereby too short to calculate a reliable linear regression. The **right map** is based on model simulations and shows change in annual multi-model mean simulated temperatures at a global warming level of 1°C (20-year mean global surface temperature change relative to 1850–1900). The triangles at each end of the color bar indicate out-of-bound values, that is, values above or below the given limits.

Panel b) Simulated annual mean temperature change (°C), panel c) precipitation change (%), and panel d) total column soil moisture change (standard deviation of interannual variability) at global warming levels of 1.5°C, 2°C and 4°C (20-yr mean global surface temperature change relative to 1850–1900). Simulated changes correspond to CMIP6 multi-model mean change (median change for soil moisture) at the corresponding global warming level, i.e. the same method as for the right map in panel a).



In **panel c),** high positive percentage changes in dry regions may correspond to small absolute changes. In **panel d),** the unit is the standard deviation of interannual variability in soil moisture during 1850–1900. Standard deviation is a widely used metric in characterizing drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850–1900. In panel d), large changes in dry regions with little interannual variability in the baseline conditions can correspond to small absolute change. The triangles at each end of the color bars indicate out-of-bound values, that is, values above or below the given limits. Results from all models reaching the corresponding warming level in any of the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are averaged. Maps of annual mean temperature and precipitation changes at a global warming level of 3°C are available in Figure 4.31 and Figure 4.32 in Section 4.6.

Corresponding maps of panels b), c) and d) including hatching to indicate the level of model agreement at grid-cell level are found in Figures 4.31, 4.32 and 11.19, respectively; as highlighted in CC-box Atlas.1, grid-cell level hatching is not informative for larger spatial scales (e.g., over AR6 reference regions) where the aggregated signals are less affected by small-scale variability leading to an increase in robustness.

{TS.1.3.2, Figure TS.3, Figure TS.5, Figure 1.14, 4.6.1, Cross-Chapter Box 11.1, Cross-Chapter Box Atlas.1}

Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming

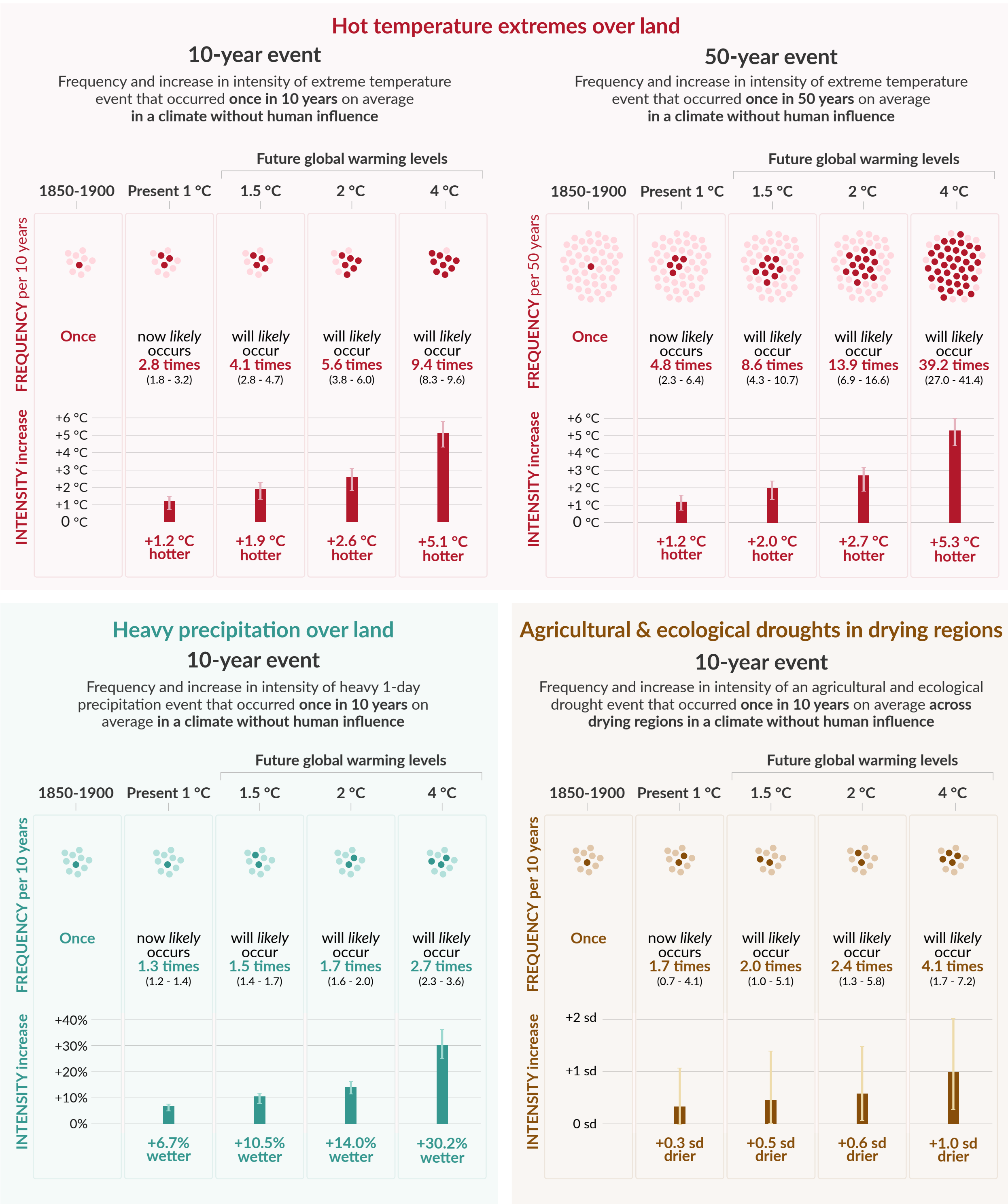


Figure SPM.6: Projected changes in the intensity and frequency of hot temperature extremes over land, extreme precipitation over land, and agricultural and ecological droughts in drying regions.

Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to 1850-1900[9] representing a climate without human influence. The figure depicts frequencies and increases in intensity of 10- or 50-year extreme events from the base period (1850-1900) under different global warming levels.
Hot temperature extremes are defined as the daily maximum temperatures over land that were exceeded on average once in a decade (10-year event) or once in 50 years (50-year event) during the 1850–1900 reference period. **Extreme precipitation events** are defined as the daily precipitation amount over land that was exceeded on average once in a decade during the 1850–1900 reference period. **Agricultural and ecological drought events** are defined as the annual average of total column soil moisture below the 10th percentile of the 1850–1900 base period. These extremes are defined on model grid box scale. For hot temperature extremes and extreme precipitation, results are shown for the global land. For agricultural and ecological drought, results are shown for drying regions only, which correspond to the AR6 regions in which there is at least *medium confidence* in a projected increase in agricultural/ecological drought at the 2°C warming level compared to the 1850–1900 base period in CMIP6. These regions include W. North-America, C. North-America, N. Central-America, S. Central-America, Caribbean, N. South-America, N.E. South-America, South-American-Monsoon, S.W. South-America, S. South-America, West & Central-Europe, Mediterranean, W. Southern-Africa, E. Southern-Africa, Madagascar, E. Australia, S. Australia (Caribbean is not included in the calculation of the figure because of the too small number of full land grid cells). The non-drying regions do not show an overall increase or decrease in drought severity. Projections of changes in agricultural and ecological droughts in the CMIP5 multi-model ensemble differ from those in CMIP6 in some regions, including in part of Africa and Asia. Assessments on projected changes in meteorological and hydrological droughts are provided in Chapter 11. {11.6, 11.9}

In the **'frequency' section,** each year is represented by a dot. The dark dots indicate years in which the extreme threshold is exceeded, while light dots are years when the threshold is not exceeded. Values correspond to the medians (in bold) and their respective 5–95% range based on the multi-model ensemble from simulations of CMIP6 under different SSP scenarios. For consistency, the number of dark dots is based on the rounded-up median. In the **'intensity' section,** medians and their 5–95% range, also based on the multi-model ensemble from simulations of CMIP6, are displayed as dark and light bars, respectively. Changes in the intensity of hot temperature extremes and extreme precipitations are expressed as degree Celsius and percentage. As for agricultural and ecological drought, intensity changes are expressed as fractions of standard deviation of annual soil moisture.

{11.1, 11.3, 11.4, 11.6, Figure 11.12, Figure 11.15, Figure 11.6, Figure 11.7, Figure 11.18}

B.3 Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events.

{4.3, 4.4, 4.5, 4.6, 8.2, 8.3, 8.4, 8.5, Box 8.2, 11.4, 11.6, 11.9, 12.4, Atlas.3} **(Figure SPM.5, Figure SPM.6)**

B.3.1 There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*). The average annual global land precipitation is projected to increase by 0–5% under the very low GHG emissions scenario (SSP1-1.9), 1.5-8% for the intermediate GHG emissions scenario (SSP2-4.5) and 1–13% under the very high GHG emissions scenario (SSP5-8.5) by 2081–2100 relative to 1995-2014 (*likely* ranges). Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (*very likely*). The portion of the global land experiencing detectable increases or decreases in seasonal mean precipitation is projected to increase (*medium confidence*). There is *high confidence* in an earlier onset of spring snowmelt, with higher peak flows at the expense of summer flows in snow-dominated regions globally.
{4.3, 4.5, 4.6, 8.2, 8.4, Atlas.3, TS.2.6, Box TS.6, TS.4.3} **(Figure SPM.5)**

B.3.2 A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (*high confidence*), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. It is *very likely* that rainfall variability related to the El Niño–Southern Oscillation is projected to be amplified by the second half of the 21st century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.
{4.3, 4.5, 4.6, 8.2, 8.4, 8.5, 11.4, 11.6, 11.9, 12.4, TS.2.6, TS.4.2, Box TS.6} **(Figure SPM.5, Figure SPM.6)**

B.3.3 Monsoon precipitation is projected to increase in the mid- to long term at global scale, particularly over South and Southeast Asia, East Asia and West Africa apart from the far west Sahel (*high confidence*). The monsoon season is projected to have a delayed onset over North and South America and West Africa (*high confidence*) and a delayed retreat over West Africa (*medium confidence*).
{4.4, 4.5, 8.2, 8.3, 8.4, Box 8.2, Box TS.13}

B.3.4 A projected southward shift and intensification of Southern Hemisphere summer mid-latitude storm tracks and associated precipitation is *likely* in the long term under high GHG emissions scenarios (SSP3-7.0, SSP5-8.5), but in the near term the effect of stratospheric ozone recovery counteracts these changes (*high confidence*). There is *medium confidence* in a continued poleward shift of storms and their precipitation in the North Pacific, while there is *low confidence* in projected changes in the North Atlantic storm tracks.
{TS.4.2, 4.4, 4.5, 8.4, TS.2.3}

B.4 Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere.

{4.3, 5.2, 5.4, 5.5, 5.6} **(Figure SPM.7)**

B.4.1 While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative CO_2 emissions. This is projected to result in a higher proportion of emitted CO_2 remaining in the atmosphere (*high confidence*).
{5.2, 5.4, Box TS.5} **(Figure SPM.7)**

B.4.2 Based on model projections, under the intermediate scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and oceans are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, land and oceans begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is *very unlikely* that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions[32] (SSP2-4.5, SSP3-7.0, SSP5-8.5).
{4.3, 5.4, 5.5, 5.6, Box TS.5, TS.3.3}

B.4.3 The magnitude of feedbacks between climate change and the carbon cycle becomes larger but also more uncertain in high CO_2 emissions scenarios (*very high confidence*). However, climate model projections show that the uncertainties in atmospheric CO_2 concentrations by 2100 are dominated by the differences between emissions scenarios (*high confidence*). Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).
{5.4, Box TS.5, TS.3.2}

[32] These projected adjustments of carbon sinks to stabilization or decline of atmospheric CO_2 are accounted for in calculations of remaining carbon budgets.

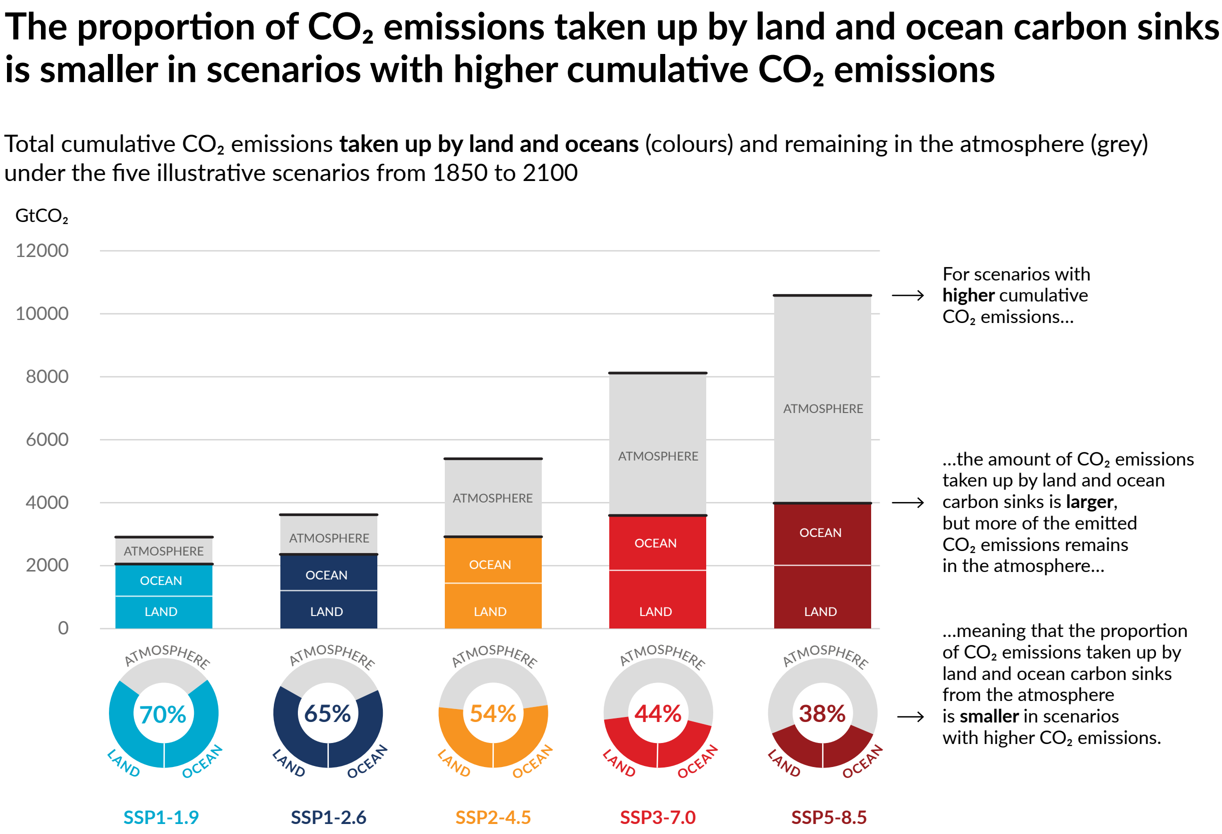


Figure SPM.7: Cumulative anthropogenic CO2 emissions taken up by land and ocean sinks by 2100 under the five illustrative scenarios.

The cumulative anthropogenic (human-caused) carbon dioxide (CO_2) emissions taken up by the land and ocean sinks under the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are simulated from 1850 to 2100 by CMIP6 climate models in the concentration-driven simulations. Land and ocean carbon sinks respond to past, current and future emissions, therefore cumulative sinks from 1850 to 2100 are presented here. During the historical period (1850-2019) the observed land and ocean sink took up 1430 $GtCO_2$ (59% of the emissions).

The **bar chart** illustrates the projected amount of cumulative anthropogenic CO_2 emissions ($GtCO_2$) between 1850 and 2100 remaining in the atmosphere (grey part) and taken up by the land and ocean (coloured part) in the year 2100. The **doughnut chart** illustrates the proportion of the cumulative anthropogenic CO_2 emissions taken up by the land and ocean sinks and remaining in the atmosphere in the year 2100. Values in % indicate the proportion of the cumulative anthropogenic CO_2 emissions taken up by the combined land and ocean sinks in the year 2100. The overall anthropogenic carbon emissions are calculated by adding the net global land use emissions from CMIP6 scenario database to the other sectoral emissions calculated from climate model runs with prescribed CO_2 concentrations[33]. Land and ocean CO_2 uptake since 1850 is calculated from the net biome productivity on land, corrected for CO_2 losses due to land-use change by adding the land-use change emissions, and net ocean CO_2 flux.

{Box TS.5, Box TS.5, Figure 1, 5.2.1, Table 5.1, 5.4.5, Figure 5.25}

[33] The other sectoral emissions are calculated as the residual of the net land and ocean CO_2 uptake and the prescribed atmospheric CO_2 concentration changes in the CMIP6 simulations. These calculated emissions are net emissions and do not separate gross anthropogenic emissions from removals, which are included implicitly.

B.5 Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level. {Cross-Chapter Box 2.4, 2.3, 4.3, 4.5, 4.7, 5.3, 9.2, 9.4, 9.5, 9.6, Box 9.4} **(Figure SPM.8)**

B.5.1 Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Over the rest of the 21st century, *likely* ocean warming ranges from 2–4 (SSP1-2.6) to 4–8 times (SSP5-8.5) the 1971–2018 change. Based on multiple lines of evidence, upper ocean stratification (*virtually certain*), ocean acidification (*virtually certain*) and ocean deoxygenation (*high confidence*) will continue to increase in the 21st century, at rates dependent on future emissions. Changes are irreversible on centennial to millennial time scales in global ocean temperature (*very high confidence*), deep ocean acidification (*very high confidence*) and deoxygenation (*medium confidence*).
{4.3, 4.5, 4.7, 5.3, 9.2, TS.2.4} **(Figure SPM.8)**

B.5.2 Mountain and polar glaciers are committed to continue melting for decades or centuries (*very high confidence*). Loss of permafrost carbon following permafrost thaw is irreversible at centennial timescales (*high confidence*). Continued ice loss over the 21st century is *virtually certain* for the Greenland Ice Sheet and *likely* for the Antarctic Ice Sheet. There is *high confidence* that total ice loss from the Greenland Ice Sheet will increase with cumulative emissions. There is *limited evidence* for low-likelihood, high-impact outcomes (resulting from ice sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios[34]. {4.3, 4.7, 5.4, 9.4, 9.5, Box 9.4, Box TS.1, TS.2.5}

B.5.3 It is *virtually certain* that global mean sea level will continue to rise over the 21st century. Relative to 1995-2014, the *likely* global mean sea level rise by 2100 is 0.28-0.55 m under the very low GHG emissions scenario (SSP1-1.9), 0.32-0.62 m under the low GHG emissions scenario (SSP1-2.6), 0.44-0.76 m under the intermediate GHG emissions scenario (SSP2-4.5), and 0.63-1.01 m under the very high GHG emissions scenario (SSP5-8.5), and by 2150 is 0.37-0.86 m under the very low scenario (SSP1-1.9), 0.46-0.99 m under the low scenario (SSP1-2.6), 0.66-1.33 m under the intermediate scenario (SSP2-4.5), and 0.98-1.88 m under the very high scenario (SSP5-8.5) (*medium confidence*)[35]. Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice sheet processes.
{4.3, 9.6, Box 9.4, Box TS.4} **(Figure SPM.8)**

B.5.4 In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and will remain elevated for thousands of years (*high confidence*). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C, 2 to 6 m if limited to 2°C and 19 to 22 m with 5°C of warming, and it will continue to rise over subsequent millennia (*low confidence*). Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: *likely* 5–10 m higher than today around 125,000 years ago, when global temperatures were *very likely* 0.5°C–1.5°C higher than 1850–1900; and *very likely* 5–25 m higher roughly 3 million years ago, when global temperatures were 2.5°C–4°C higher (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 9.6, Box TS.2, Box TS.4, Box TS.9}

[34] Low-likelihood, high-impact outcomes are those whose probability of occurrence is low or not well known (as in the context of deep uncertainty) but whose potential impacts on society and ecosystems could be high. A tipping point is a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. {Cross-Chapter Box 1.3, 1.4, 4.7}

[35] To compare to the 1986–2005 baseline period used in AR5 and SROCC, add 0.03 m to the global mean sea level rise estimates. To compare to the 1900 baseline period used in Figure SPM.8, add 0.16 m.

Human activities affect all the major climate system components, with some responding over decades and others over centuries

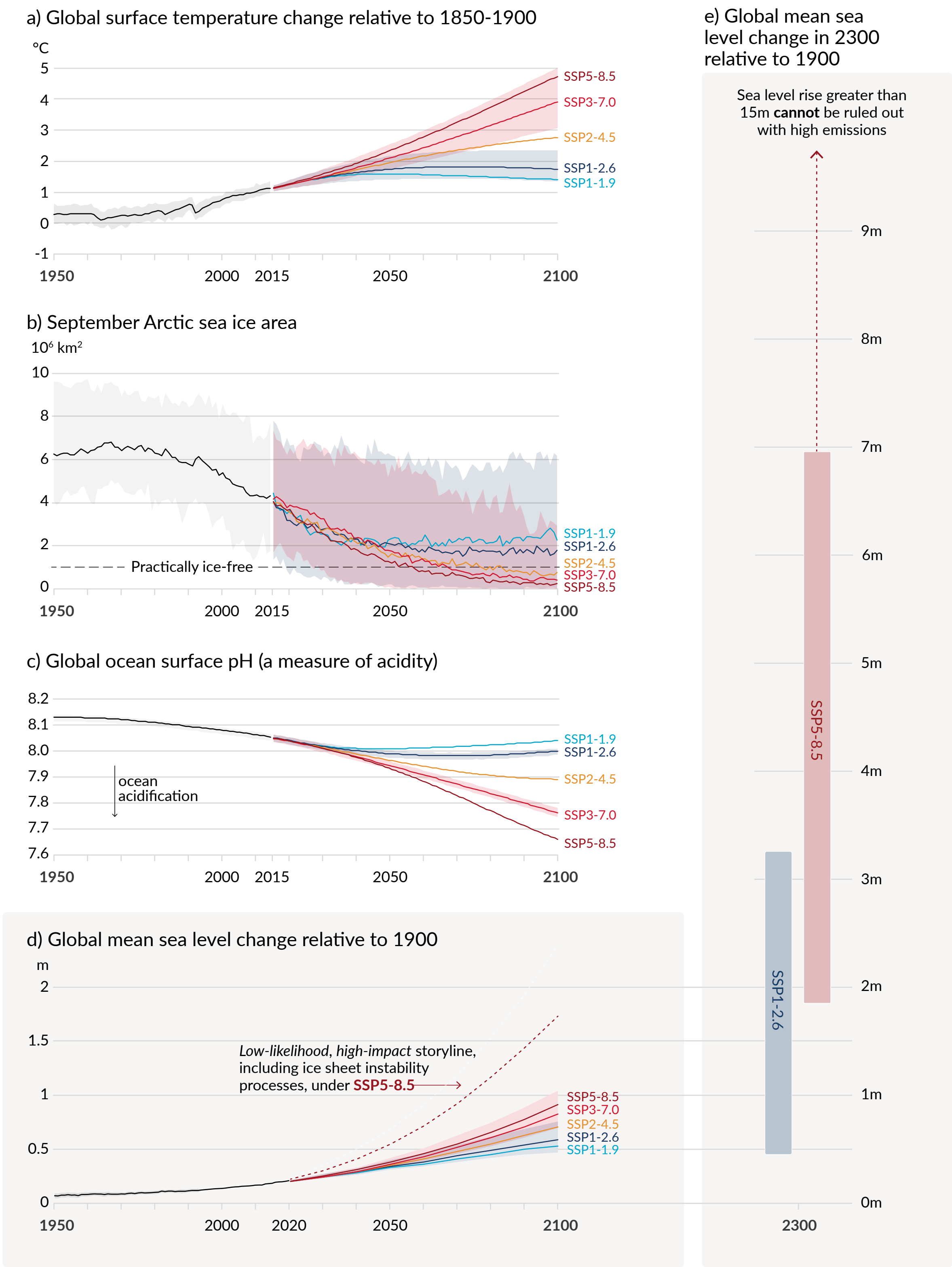


Figure SPM.8: Selected indicators of global climate change under the five illustrative scenarios used in this report.

The projections for each of the five scenarios are shown in colour. Shades represent uncertainty ranges – more detail is provided for each panel below. The black curves represent the historical simulations (panels a, b, c) or the observations (panel d). Historical values are included in all graphs to provide context for the projected future changes.

Panel a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (see Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0.

Panel b) September Arctic sea ice area in 10^6 km^2 based on CMIP6 model simulations. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0. The Arctic is projected to be practically ice-free near mid-century under mid- and high GHG emissions scenarios.

Panel c) Global ocean surface pH (a measure of acidity) based on CMIP6 model simulations. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0.

Panel d) Global mean sea level change in meters relative to 1900. The historical changes are observed (from tide gauges before 1992 and altimeters afterwards), and the future changes are assessed consistently with observational constraints based on emulation of CMIP, ice sheet, and glacier models. *Likely* ranges are shown for SSP1-2.6 and SSP3-7.0. Only *likely* ranges are assessed for sea level changes due to difficulties in estimating the distribution of deeply uncertain processes. The dashed curve indicates the potential impact of these deeply uncertain processes. It shows the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice sheet processes that cannot be ruled out; because of *low confidence* in projections of these processes, this curve does not constitute part of a *likely* range. Changes relative to 1900 are calculated by adding 0.158 m (observed global mean sea level rise from 1900 to 1995–2014) to simulated and observed changes relative to 1995–2014.

Panel e): Global mean sea level change at 2300 in meters relative to 1900. Only SSP1-2.6 and SSP5-8.5 are projected at 2300, as simulations that extend beyond 2100 for the other scenarios are too few for robust results. The 17th–83rd percentile ranges are shaded. The dashed arrow illustrates the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice sheet processes that cannot be ruled out.

Panels b) and c) are based on single simulations from each model, and so include a component of internal variability. Panels a), d) and e) are based on long-term averages, and hence the contributions from internal variability are small.

{Figure TS.8, Figure TS.11, Box TS.4 Figure 1, Box TS.4 Figure 1, 4.3, 9.6, Figure 4.2, Figure 4.8, Figure 4.11, Figure 9.27}

C. Climate Information for Risk Assessment and Regional Adaptation

Physical climate information addresses how the climate system responds to the interplay between human influence, natural drivers and internal variability. Knowledge of the climate response and the range of possible outcomes, including low-likelihood, high impact outcomes, informs climate services – the assessment of climate-related risks and adaptation planning. Physical climate information at global, regional and local scales is developed from multiple lines of evidence, including observational products, climate model outputs and tailored diagnostics.

C.1 Natural drivers and internal variability will modulate human-caused changes, especially at regional scales and in the near term, with little effect on centennial global warming. These modulations are important to consider in planning for the full range of possible changes.

{1.4, 2.2, 3.3, Cross-Chapter Box 3.1, 4.4, 4.6, Cross-Chapter Box 4.1, 4.4, Box 7.2, 8.3, 8.5, 9.2, 10.3, 10.4, 10.6, 11.3, 12.5, Atlas.4, Atlas.5, Atlas.8, Atlas.9, Atlas.10, Cross-Chapter Box Atlas.2, Atlas.11}

C.1.1 The historical global surface temperature record highlights that decadal variability has enhanced and masked underlying human-caused long-term changes, and this variability will continue into the future (*very high confidence*). For example, internal decadal variability and variations in solar and volcanic drivers partially masked human-caused surface global warming during 1998–2012, with pronounced regional and seasonal signatures (*high confidence*). Nonetheless, the heating of the climate system continued during this period, as reflected in both the continued warming of the global ocean (*very high confidence*) and in the continued rise of hot extremes over land (*medium confidence*).
{1.4, 3.3, Cross-Chapter Box 3.1, 4.4, Box 7.2, 9.2, 11.3, Cross-Section Box TS.1} **(Figure SPM.1)**

C.1.2 Projected human caused changes in mean climate and climatic impact-drivers (CIDs)[36], including extremes, will be either amplified or attenuated by internal variability[37] (*high confidence*). Near-term cooling at any particular location with respect to present climate could occur and would be consistent with the global surface temperature increase due to human influence (*high confidence*).
{1.4, 4.4, 4.6, 10.4, 11.3, 12.5, Atlas.5, Atlas.10, Atlas.11, TS.4.2}

C.1.3 Internal variability has largely been responsible for the amplification and attenuation of the observed human-caused decadal-to-multi-decadal mean precipitation changes in many land regions *(high confidence)*. At global and regional scales, near-term changes in monsoons will be dominated by the effects of internal variability (*medium confidence*). In addition to internal variability influence, near-term projected changes in precipitation at global and regional scales are uncertain because of model uncertainty and uncertainty in forcings from natural and anthropogenic aerosols (*medium confidence*).
{1.4, 4.4, 8.3, 8.5, 10.3, 10.4, 10.5, 10.6, Atlas.4, Atlas.8, Atlas.9, Atlas.10, Cross-Chapter Box Atlas.2, Atlas.11, TS.4.2, Box TS.6, Box TS.13}

[36] Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions. CID types include heat and cold, wet and dry, wind, snow and ice, coastal and open ocean.

[37] The main internal variability phenomena include El Niño–Southern Oscillation, Pacific Decadal variability and Atlantic Multi-decadal variability through their regional influence.

C.1.4 Based on paleoclimate and historical evidence, it is *likely* that at least one large explosive volcanic eruption would occur during the 21st century[38]. Such an eruption would reduce global surface temperature and precipitation, especially over land, for one to three years, alter the global monsoon circulation, modify extreme precipitation and change many CIDs (*medium confidence*). If such an eruption occurs, this would therefore temporarily and partially mask human-caused climate change.
{4.4, Cross-Chapter Box 4.1, 2.2, 8.5, TS.2.1}

C.2 With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels.
{8.2, 9.3, 9.5, 9.6, Box 10.3, Box 11.3, Box 11.4, 11.3, 11.4, 11.5, 11.6, 11.7, 11.9, 12.2, 12.3, 12.4, 12.5, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1} **(Table SPM.1, Figure SPM.9)**

C.2.1 All regions[39] are projected to experience further increases in hot climatic impact-drivers (CIDs) and decreases in cold CIDs (*high confidence*). Further decreases are projected in permafrost, snow, glaciers and ice sheets, lake and Arctic sea ice (*medium* to *high confidence*)[40]. These changes would be larger at 2°C global warming or above than at 1.5°C (*high confidence*). For example, extreme heat thresholds relevant to agriculture and health are projected to be exceeded more frequently at higher global warming levels (*high confidence*).
{9.3, 9.5, 11.3, 11.9, 12.3, 12.4, 12.5, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, TS.4.3, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1} **(Table SPM.1, Figure SPM.9)**

C.2.2 At 1.5°C global warming, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia (*high confidence*), North America (*medium* to *high confidence*)[40] and Europe (*medium confidence*). Also**,** more frequent and/or severe agricultural and ecological droughts are projected in a few regions in all continents except Asia compared to 1850–1900 (*medium confidence*); increases in meteorological droughts are also projected in a few regions (*medium confidence*). A small number of regions are projected to experience increases or decreases in mean precipitation (*medium confidence*).
{11.4, 11.5, 11.6, 11.9, Atlas.4, Atlas.5, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, TS.4.3} **(Table SPM.1)**

[38] Based on 2,500 year reconstructions, eruptions more negative than –1 W m^{-2} occur on average twice per century.

[39] Regions here refer to the AR6 WGI reference regions used in this Report to summarize information in sub-continental and oceanic regions. Changes are compared to averages over the last 20–40 years unless otherwise specified. {1.4, 12.4, Atlas.1, Interactive Atlas}.

[40] The specific level of confidence or likelihood depends on the region considered. Details can be found in the Technical Summary and the underlying Report.

C.2.3 At 2°C global warming and above, the level of confidence in and the magnitude of the change in droughts and heavy and mean precipitation increase compared to those at 1.5°C. Heavy precipitation and associated flooding events are projected to become more intense and frequent in the Pacific Islands and across many regions of North America and Europe (*medium* to *high confidence*)[40]. These changes are also seen in some regions in Australasia and Central and South America (*medium confidence*). Several regions in Africa, South America and Europe are projected to experience an increase in frequency and/or severity of agricultural and ecological droughts with *medium* to *high confidence*[40]; increases are also projected in Australasia, Central and North America, and the Caribbean with *medium confidence*. A small number of regions in Africa, Australasia, Europe and North America are also projected to be affected by increases in hydrological droughts, and several regions are projected to be affected by increases or decreases in meteorological droughts with more regions displaying an increase (*medium confidence*). Mean precipitation is projected to increase in all polar, northern European and northern North American regions, most Asian regions and two regions of South America (*high confidence*).
{11.4, 11.6, 11.9, 12.4, 12.5, Atlas.5, Atlas.7, Atlas.8, Atlas.9, Atlas.11, TS.4.3, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1} **(Table SPM.1, Figure SPM.5, Figure SPM.6, Figure SPM.9)**

C.2.4 More CIDs across more regions are projected to change at 2°C and above compared to 1.5°C global warming (*high confidence*). Region-specific changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), increases in river floods (*medium* to *high confidence*)[40], reductions in mean precipitation and increases in aridity (*medium* to *high confidence*)[40], and increases in fire weather (*medium* to *high confidence*)[40]. There is *low confidence* in most regions in potential future changes in other CIDs, such as hail, ice storms, severe storms, dust storms, heavy snowfall, and landslides.
{11.7, 11.9, 12.4, 12.5, Atlas.4, Atlas.6, Atlas.7, Atlas.8, Atlas.10, TS.4.3.1, TS.4.3.2, TS.5, Cross-Chapter Box, 11.1, Cross-Chapter Box 12.1} **(Table SPM.1, Figure SPM.9)**

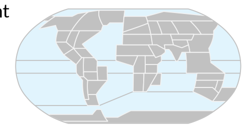
C.2.5 It is *very likely* to *virtually certain*[40] that regional mean relative sea level rise will continue throughout the 21st century, except in a few regions with substantial geologic land uplift rates. Approximately two-thirds of the global coastline has a projected regional relative sea level rise within ±20% of the global mean increase (*medium confidence*). Due to relative sea level rise, extreme sea level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100 (*high confidence*). Relative sea level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts (*high confidence*).
{9.6, 12.4, 12.5, Box TS.4, TS.4.3, Cross-Chapter Box 12.1} **(Figure SPM.9)**

C.2.6 Cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes will increase the severity of heatwaves (*very high confidence*). Urbanization also increases mean and heavy precipitation over and/or downwind of cities (*medium confidence*) and resulting runoff intensity (*high confidence*). In coastal cities, the combination of more frequent extreme sea level events (due to sea level rise and storm surge) and extreme rainfall/riverflow events will make flooding more probable (*high confidence*).
{8.2, Box 10.3, 11.3, 12.4, Box TS.14}

C.2.7 Many regions are projected to experience an increase in the probability of compound events with higher global warming (*high confidence*). In particular, concurrent heatwaves and droughts are *likely* to become more frequent. Concurrent extremes at multiple locations become more frequent, including in crop-producing areas, at 2°C and above compared to 1.5°C global warming (*high confidence*).
{11.8, Box 11.3, Box 11.4, 12.3, 12.4, TS.4.3, Cross-Chapter Box 12.1} **(Table SPM.1)**

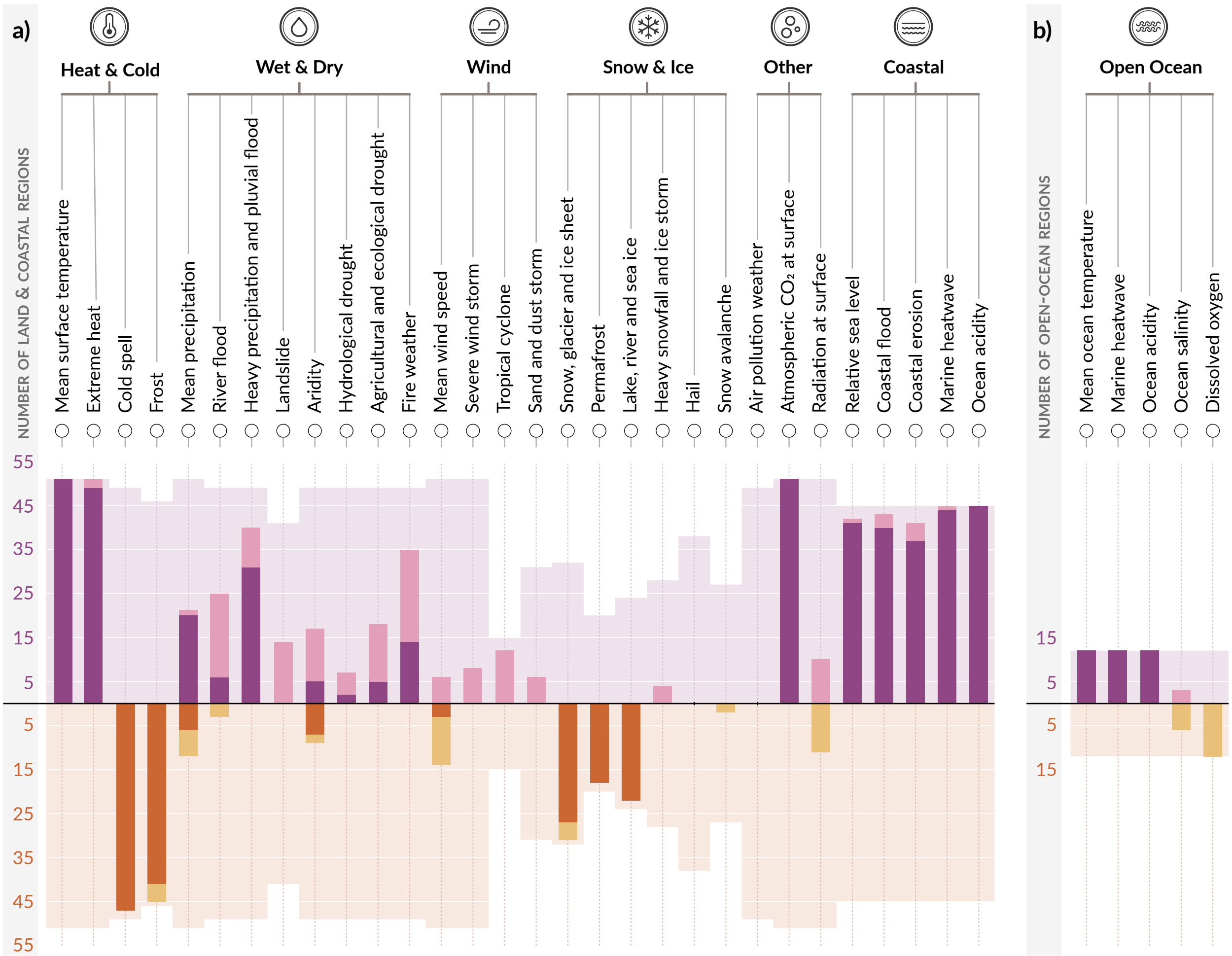
Multiple climatic impact-drivers are projected to change in all regions of the world

Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions. The CIDs are grouped into seven types, which are summarized under the icons in the figure. All regions are projected to experience changes in at least 5 CIDs. Almost all (96%) are projected to experience changes in at least 10 CIDs and half in at least 15 CIDs. For many CIDs there is wide geographical variation in where they change and so each region are projected to experience a specific set of CID changes. Each bar in the chart represents a specific geographical set of changes that can be explored in the WGI Interactive Atlas.



interactive-atlas.ipcc.ch

Number of land & coastal regions (a) and **open-ocean regions** (b) where each **climatic impact-driver** (CID) is projected to increase or decrease with ***high** confidence* (dark shade) or ***medium** confidence* (light shade)



BAR CHART LEGEND

- Regions with ***high** confidence* **increase**
- Regions with ***medium** confidence* **increase**
- Regions with ***high** confidence* **decrease**
- Regions with ***medium** confidence* **decrease**

LIGHTER-SHADED 'ENVELOPE' LEGEND

The height of the lighter shaded 'envelope' behind each bar represents the maximum number of regions for which each CID is relevant. The envelope is symmetrical about the x-axis showing the maximum possible number of relevant regions for CID increase (upper part) or decrease (lower part).

ASSESSED FUTURE CHANGES

Changes refer to a 20–30 year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960-2014 or 1850-1900.

Figure SPM.9: Synthesis of the number of AR6 WGI reference regions where climatic impact-drivers are projected to change.

A total of 35 climatic impact-drivers (CIDs) grouped into seven types are shown: heat and cold, wet and dry, wind, snow and ice, coastal, open ocean and other. For each CID, the bar in the graph below displays the number of AR6 WGI reference regions where it is projected to change. The **colours** represent the direction of change and the level of confidence in the change: purple indicates an increase while brown indicates a decrease; darker and lighter shades refer to *high* and *medium confidence*, respectively. Lighter background colours represent the maximum number of regions for which each CID is broadly relevant.

Panel a) shows the 30 CIDs relevant to the **land and coastal regions** while **panel b)** shows the 5 CIDs relevant to the **open ocean regions.** Marine heatwaves and ocean acidity are assessed for coastal ocean regions in panel a) and for open ocean regions in panel b). Changes refer to a 20–30 year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960-2014, except for hydrological drought and agricultural and ecological drought which is compared to 1850-1900. Definitions of the regions are provided in Atlas.1 and the Interactive Atlas (see *interactive-atlas.ipcc.ch*).

{Table TS.5, Figure TS.22, Figure TS.25, 11.9, 12.2, 12.4, Atlas.1} **(Table SPM.1)**

C.3 Low-likelihood outcomes, such as ice sheet collapse, abrupt ocean circulation changes, some compound extreme events and warming substantially larger than the assessed *very likely* range of future warming cannot be ruled out and are part of risk assessment.

{1.4, Cross-Chapter Box 1.3, Cross-Chapter Box 4.1, 4.3, 4.4, 4.8, 8.6, 9.2, Box 9.4, Box 11.2, 11.8, Cross-Chapter Box 12.1} **(Table SPM.1)**

C.3.1 If global warming exceeds the assessed *very likely* range for a given GHG emissions scenario, including low GHG emissions scenarios, global and regional changes in many aspects of the climate system, such as regional precipitation and other CIDs, would also exceed their assessed *very likely* ranges (*high confidence*). Such low-likelihood high-warming outcomes are associated with potentially very large impacts, such as through more intense and more frequent heatwaves and heavy precipitation, and high risks for human and ecological systems particularly for high GHG emissions scenarios.
{Cross-Chapter Box 1.3, 4.3, 4.4, 4.8, Box 9.4, Box 11.2, Cross-Chapter Box 12.1, TS.1.4, Box TS.3, Box TS.4} **(Table SPM.1)**

C.3.2 Low-likelihood, high-impact outcomes[34] could occur at global and regional scales even for global warming within the *very likely* range for a given GHG emissions scenario. The probability of low-likelihood, high impact outcomes increases with higher global warming levels (*high confidence*). Abrupt responses and tipping points of the climate system, such as strongly increased Antarctic ice sheet melt and forest dieback, cannot be ruled out (*high confidence*).
{1.4, 4.3, 4.4, 4.8, 5.4, 8.6, Box 9.4, Cross-Chapter Box 12.1, TS.1.4, TS.2.5, Box TS.3, Box TS.4, Box TS.9} **(Table SPM.1)**

C.3.3 If global warming increases, some compound extreme events[18] with low likelihood in past and current climate will become more frequent, and there will be a higher likelihood that events with increased intensities, durations and/or spatial extents unprecedented in the observational record will occur (*high confidence*).
{11.8, Box 11.2, Cross-Chapter Box 12.1, Box TS.3, Box TS.9}

C.3.4 The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all emission scenarios. While there is *high confidence* in the 21st century decline, there is only *low confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. If such a collapse were to occur, it would *very likely* cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons, and drying in Europe. {4.3, 8.6, 9.2, TS2.4, Box TS.3}

C.3.5 Unpredictable and rare natural events not related to human influence on climate may lead to low-likelihood, high impact outcomes. For example, a sequence of large explosive volcanic eruptions within decades has occurred in the past, causing substantial global and regional climate perturbations over several decades. Such events cannot be ruled out in the future, but due to their inherent unpredictability they are not included in the illustrative set of scenarios referred to in this Report. {2.2, Cross-Chapter Box 4.1, Box TS.3} **(Box SPM.1)**

D. Limiting Future Climate Change

Since AR5, estimates of remaining carbon budgets have been improved by a new methodology first presented in SR1.5, updated evidence, and the integration of results from multiple lines of evidence. A comprehensive range of possible future air pollution controls in scenarios is used to consistently assess the effects of various assumptions on projections of climate and air pollution. A novel development is the ability to ascertain when climate responses to emissions reductions would become discernible above natural climate variability, including internal variability and responses to natural drivers.

D.1 **From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.**
{3.3, 4.6, 5.1, 5.2, 5.4, 5.5, 5.6, Box 5.2, Cross-Chapter Box 5.1, 6.7, 7.6, 9.6} **(Figure SPM.10, Table SPM.2)**

D.1.1 This Report reaffirms with *high confidence* the AR5 finding that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions and the global warming they cause. Each 1000 $GtCO_2$ of cumulative CO_2 emissions is assessed to *likely* cause a 0.27°C to 0.63°C increase in global surface temperature with a best estimate of 0.45°C[41]. This is a narrower range compared to AR5 and SR1.5. This quantity is referred to as the transient climate response to cumulative CO_2 emissions (TCRE). This relationship implies that reaching net zero[42] anthropogenic CO_2 emissions is a requirement to stabilize human-induced global temperature increase at any level, but that limiting global temperature increase to a specific level would imply limiting cumulative CO_2 emissions to within a carbon budget[43].
{5.4, 5.5, TS.1.3, TS.3.3, Box TS.5} **(Figure SPM.10)**

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[41] In the literature, units of °C per 1000 PgC are used, and the AR6 reports the TCRE *likely* range as 1.0°C to 2.3°C per 1000 PgC in the underlying report, with a best estimate of 1.65°C.

[42] condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period.

[43] The term carbon budget refers to the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic climate forcers. This is referred to as the total carbon budget when expressed starting from the pre-industrial period, and as the remaining carbon budget when expressed from a recent specified date (see Glossary). Historical cumulative CO_2 emissions determine to a large degree warming to date, while future emissions cause future additional warming. The remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below a specific temperature level.

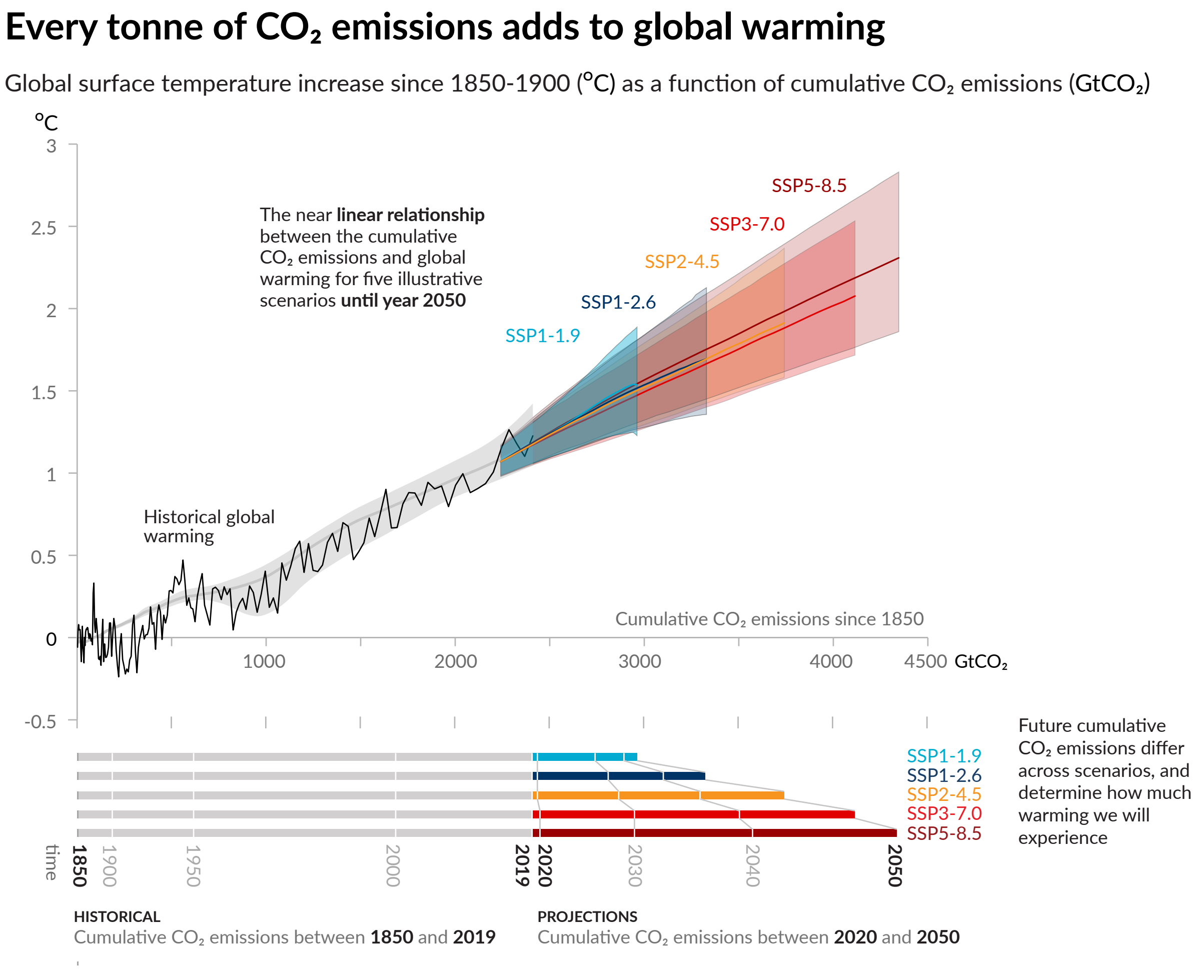

Figure SPM.10: Near-linear relationship between cumulative CO2 emissions and the increase in global surface temperature.

Top panel: Historical data (thin black line) shows observed global surface temperature increase in °C since 1850–1900 as a function of historical cumulative carbon dioxide (CO_2) emissions in $GtCO_2$ from 1850 to 2019. The grey range with its central line shows a corresponding estimate of the historical human-caused surface warming (see Figure SPM.2). Coloured areas show the assessed *very likely* range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO_2 emissions from 2020 until year 2050 for the set of illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, see Figure SPM.4). Projections use the cumulative CO_2 emissions of each respective scenario, and the projected global warming includes the contribution from all anthropogenic forcers. The relationship is illustrated over the domain of cumulative CO_2 emissions for which there is *high confidence* that the transient climate response to cumulative CO_2 emissions (TCRE) remains constant, and for the time period from 1850 to 2050 over which global CO_2 emissions remain net positive under all illustrative scenarios as there is *limited evidence* supporting the quantitative application of TCRE to estimate temperature evolution under net negative CO_2 emissions.

Bottom panel: Historical and projected cumulative CO_2 emissions in $GtCO_2$ for the respective scenarios.

{Figure TS.18, Figure 5.31, Section 5.5}

D.1.2 Over the period 1850–2019, a total of 2390 ± 240 (*likely* range) $GtCO_2$ of anthropogenic CO_2 was emitted. Remaining carbon budgets have been estimated for several global temperature limits and various levels of probability, based on the estimated value of TCRE and its uncertainty, estimates of historical warming, variations in projected warming from non-CO_2 emissions, climate system feedbacks such as emissions from thawing permafrost, and the global surface temperature change after global anthropogenic CO_2 emissions reach net zero.
{5.1, 5.5, Box 5.2, TS.3.3} **(Table SPM.2)**

Table SPM.2: Estimates of historical CO_2 emissions and remaining carbon budgets. Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO_2 emissions are reached. They refer to CO_2 emissions, while accounting for the global warming effect of non-CO_2 emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years. {Table TS.3, Table 3.1, Table 5.1, Table 5.7, Table 5.8, 5.5.1, 5.5.2, Box 5.2}

Global warming between 1850–1900 and 2010–2019 *(°C)*	Historical cumulative CO_2 emissions from 1850 to 2019 *($GtCO_2$)*
1.07 (0.8–1.3; *likely* range)	2390 (± 240; *likely* range)

Approximate global warming relative to 1850–1900 until temperature limit *(°C)**(1)	Additional global warming relative to 2010–2019 until temperature limit *(°C)*	Estimated remaining carbon budgets from the beginning of 2020 *($GtCO_2$)* *Likelihood of limiting global warming to temperature limit*(2)*					Variations in reductions in non-CO_2 emissions*(3)
		17%	*33%*	*50%*	*67%*	*83%*	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

*(1) Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.
*(2) This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks, and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 $GtCO_2$) and non-CO_2 forcing and response (±220 $GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 $GtCO_2$) and the climate response after net zero CO_2 emissions are reached (±420 $GtCO_2$) are separate.
*(3) Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO_2 emissions.

D.1.3 Several factors that determine estimates of the remaining carbon budget have been re-assessed, and updates to these factors since SR1.5 are small. When adjusted for emissions since previous reports, estimates of remaining carbon budgets are therefore of similar magnitude compared to SR1.5 but larger compared to AR5 due to methodological improvements[44].
{5.5, Box 5.2, TS.3.3} **(Table SPM.2)**

D.1.4 Anthropogenic CO_2 removal (CDR) has the potential to remove CO_2 from the atmosphere and durably store it in reservoirs (*high confidence*). CDR aims to compensate for residual emissions to reach net zero CO_2 or net zero GHG emissions or, if implemented at a scale where anthropogenic removals exceed anthropogenic emissions, to lower surface temperature. CDR methods can have potentially wide-ranging effects on biogeochemical cycles and climate, which can either weaken or strengthen the potential of these methods to remove CO_2 and reduce warming, and can also influence water availability and quality, food production and biodiversity[45] (*high confidence*).
{5.6, Cross-Chapter Box 5.1, TS.3.3}

D.1.5 Anthropogenic CO_2 removal (CDR) leading to global net negative emissions would lower the atmospheric CO_2 concentration and reverse surface ocean acidification (*high confidence*). Anthropogenic CO_2 removals and emissions are partially compensated by CO_2 release and uptake respectively, from or to land and ocean carbon pools (*very high confidence*). CDR would lower atmospheric CO_2 by an amount approximately equal to the increase from an anthropogenic emission of the same magnitude (*high confidence*). The atmospheric CO_2 decrease from anthropogenic CO_2 removals could be up to 10% less than the atmospheric CO_2 increase from an equal amount of CO_2 emissions, depending on the total amount of CDR (*medium confidence*). {5.3, 5.6, TS.3.3}

D.1.6 If global net negative CO_2 emissions were to be achieved and be sustained, the global CO_2-induced surface temperature increase would be gradually reversed but other climate changes would continue in their current direction for decades to millennia (*high confidence*). For instance, it would take several centuries to millennia for global mean sea level to reverse course even under large net negative CO_2 emissions (*high confidence*).
{4.6, 9.6, TS.3.3}

D.1.7 In the five illustrative scenarios, simultaneous changes in CH_4, aerosol and ozone precursor emissions, that also contribute to air pollution, lead to a net global surface warming in the near and long-term (*high confidence*). In the long term, this net warming is lower in scenarios assuming air pollution controls combined with strong and sustained CH_4 emission reductions (*high confidence*). In the low and very low GHG emissions scenarios, assumed reductions in anthropogenic aerosol emissions lead to a net warming, while reductions in CH_4 and other ozone precursor emissions lead to a net cooling. Because of the short lifetime of both CH_4 and aerosols, these climate effects partially counterbalance each other and reductions in CH_4 emissions also contribute to improved air quality by reducing global surface ozone (*high confidence*).
{6.7, Box TS.7} **(Figure SPM.2, Box SPM.1)**

[44] Compared to AR5, and when taking into account emissions since AR5, estimates in AR6 are about 300–350 $GtCO_2$ larger for the remaining carbon budget consistent with limiting warming to 1.5°C; for 2°C, the difference is about 400–500 $GtCO_2$.

[45] Potential negative and positive effects of CDR for biodiversity, water and food production are methods-specific, and are often highly dependent on local context, management, prior land use, and scale. IPCC Working Groups II and III assess the CDR potential, and ecological and socio-economic effects of CDR methods in their AR6 contributions.

D.1.8 Achieving global net zero CO_2 emissions is a requirement for stabilizing CO_2-induced global surface temperature increase, with anthropogenic CO_2 emissions balanced by anthropogenic removals of CO_2. This is different from achieving net zero GHG emissions, where metric-weighted anthropogenic GHG emissions equal metric-weighted anthropogenic GHG removals. For a given GHG emission pathway, the pathways of individual greenhouse gases determine the resulting climate response[46], whereas the choice of emissions metric[47] used to calculate aggregated emissions and removals of different GHGs affects what point in time the aggregated greenhouse gases are calculated to be net zero. Emissions pathways that reach and sustain net zero GHG emissions defined by the 100-year global warming potential are projected to result in a decline in surface temperature after an earlier peak (*high confidence*).
{4.6, 7.6, Box 7.3, TS.3.3}

D.2 Scenarios with very low or low GHG emissions (SSP1-1.9 and SSP1-2.6) lead within years to discernible effects on greenhouse gas and aerosol concentrations, and air quality, relative to high and very high GHG emissions scenarios (SSP3-7.0 or SSP5-8.5). Under these contrasting scenarios, discernible differences in trends of global surface temperature would begin to emerge from natural variability within around 20 years, and over longer time periods for many other climatic impact-drivers (*high confidence*).
{4.6, Cross-Chapter Box 6.1, 6.6, 6.7, 9.6, Cross-Chapter Box 11.1, 11.2, 11.4, 11.5, 11.6, 12.4, 12.5} **(Figure SPM.8, Figure SPM.10)**

D.2.1 Emissions reductions in 2020 associated with measures to reduce the spread of COVID-19 led to temporary but detectible effects on air pollution (*high confidence*), and an associated small, temporary increase in total radiative forcing, primarily due to reductions in cooling caused by aerosols arising from human activities (*medium confidence*). Global and regional climate responses to this temporary forcing are, however, undetectable above natural variability (*high confidence*). Atmospheric CO_2 concentrations continued to rise in 2020, with no detectable decrease in the observed CO_2 growth rate (*medium confidence*)[48].
{Cross-Chapter Box 6.1, TS.3.3}

D.2.2 Reductions in GHG emissions also lead to air quality improvements. However, in the near term[49], even in scenarios with strong reduction of GHGs, as in the low and very low GHG emission scenarios (SSP1-2.6 and SSP1-1.9), these improvements are not sufficient in many polluted regions to achieve air quality guidelines specified by the World Health Organization (*high confidence*). Scenarios with targeted reductions of air pollutant emissions lead to more rapid improvements in air quality within years compared to reductions in GHG emissions only, but from 2040, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions with the magnitude of the benefit varying between regions (*high confidence*). {6.6, 6.7, Box TS.7}.

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[46] A general term for how the climate system responds to a radiative forcing (see Glossary).

[47] The choice of emissions metric depends on the purposes for which gases or forcing agents are being compared. This report contains updated emission metric values and assesses new approaches to aggregating gases.

[48] For other GHGs, there was insufficient literature available at the time of the assessment to assess detectable changes in their atmospheric growth rate during 2020.

[49] Near term: (2021–2040)

D.2.3 Scenarios with very low or low GHG emissions (SSP1-1.9 and SSP1-2.6) would have rapid and sustained effects to limit human-caused climate change, compared with scenarios with high or very high GHG emissions (SSP3-7.0 or SSP5-8.5), but early responses of the climate system can be masked by natural variability. For global surface temperature, differences in 20-year trends would *likely* emerge during the near term under a very low GHG emission scenario (SSP1-1.9), relative to a high or very high GHG emission scenario (SSP3-7.0 or SSP5-8.5). The response of many other climate variables would emerge from natural variability at different times later in the 21st century (*high confidence*).
{4.6, Cross-Section Box TS.1} **(Figure SPM.8, Figure SPM.10)**

D.2.4 Scenarios with very low and low GHG emissions (SSP1-1.9 and SSP1-2.6) would lead to substantially smaller changes in a range of CIDs[36] beyond 2040 than under high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5). By the end of the century, scenarios with very low and low GHG emissions would strongly limit the change of several CIDs, such as the increase in the frequency of extreme sea level events, heavy precipitation and pluvial flooding, and exceedance of dangerous heat thresholds, while limiting the number of regions where such exceedances occur, relative to higher GHG emissions scenarios (*high confidence*). Changes would also be smaller in very low compared to low emissions scenarios, as well as for intermediate (SSP2-4.5) compared to high or very high emissions scenarios (*high confidence*). {9.6, Cross-Chapter Box 11.1, 11.2, 11.3, 11.4, 11.5, 11.6, 11.9, 12.4, 12.5, TS.4.3}

EXHIBIT B

2°C: BEYOND THE LIMIT

Extreme climate change has arrived in America

By **Steven Mufson** , **Chris Mooney** , **Juliet Eilperin** and **John Muyskens**
Photography by **Salwan Georges**

AUG. 13, 2019

LAKE HOPATCONG, N.J. — Before climate change thawed the winters of New Jersey, this lake hosted boisterous wintertime carnivals. As many as 15,000 skaters took part, and automobile owners would drive onto the thick ice. Thousands watched as local hockey clubs battled one another and the Skate Sailing Association of America held competitions, including one in 1926 that featured 21 iceboats on blades that sailed over a three-mile course.

In those days before widespread refrigeration, workers flocked here to harvest ice. They would carve blocks as much as two feet thick, float them to giant ice houses, sprinkle them with sawdust and load them onto rail cars bound for ice boxes in New York City and beyond.

New Jersey's average temperatures have risen nearly 2 degrees Celsius since 1895 — double the average for the Lower 48 states.

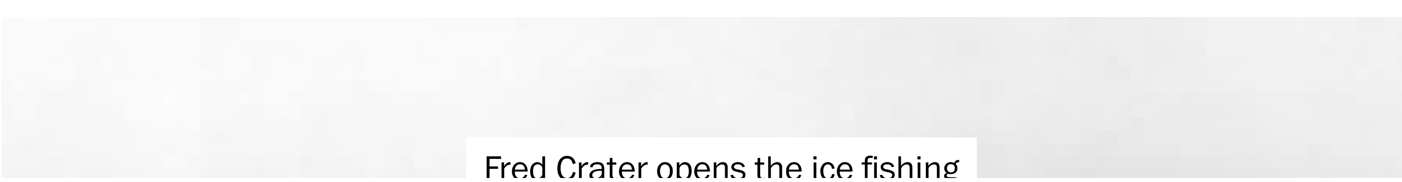
Click here to see your county

"These winters do not exist anymore," says Marty Kane, a lawyer and head of the Lake Hopatcong Foundation.

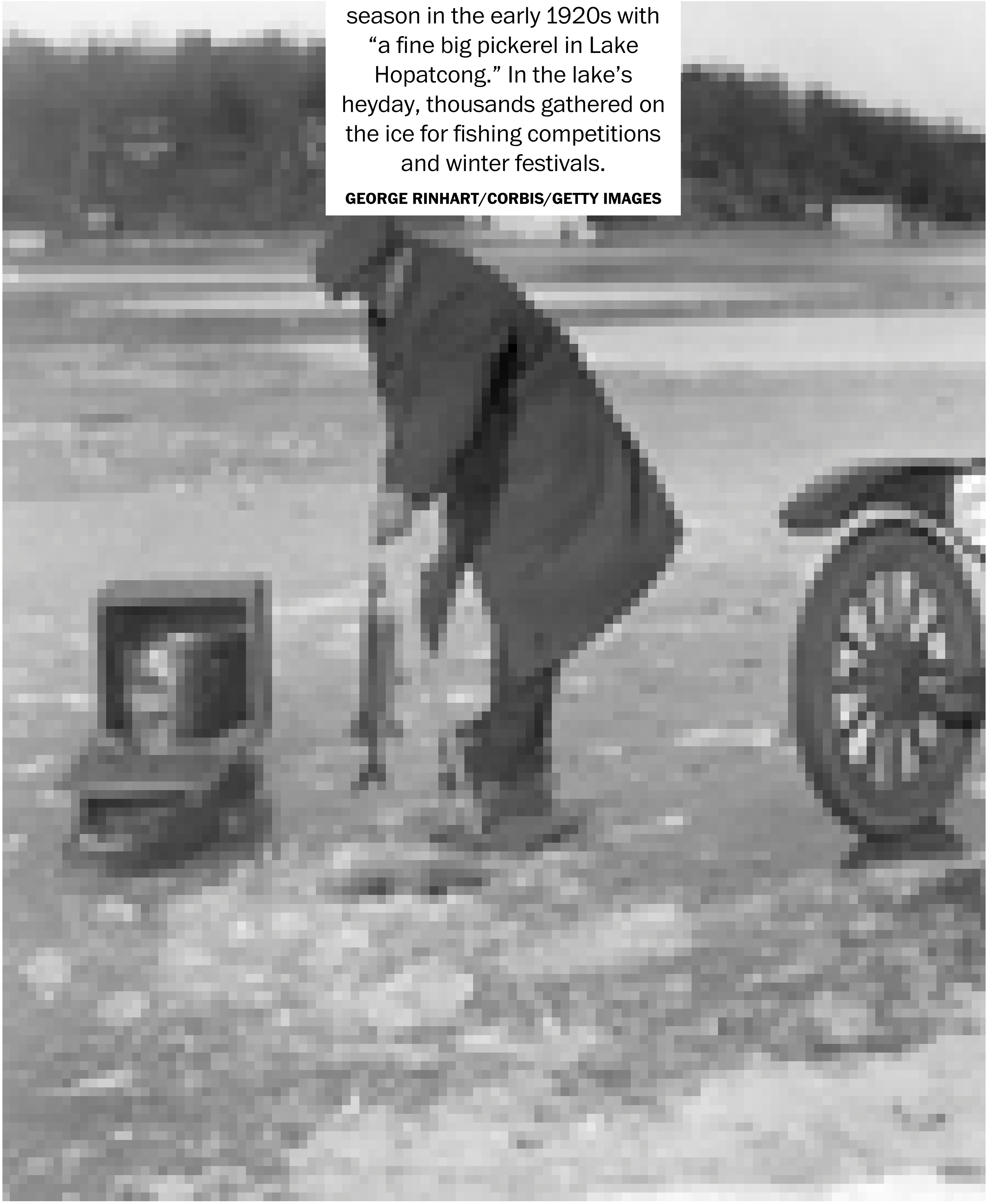
That's because a century of climbing temperatures has changed the character of the Garden State. The massive ice industry and skate sailing association are but black-and-white photographs at the local museum. And even the hardy souls who still try to take part in ice fishing contests here have had to cancel 11 of the past dozen competitions for fear of straying onto perilously thin ice and tumbling into the frigid water.

Click any temperature underlined in the story to convert between Celsius and Fahrenheit

New Jersey may seem an unlikely place to measure climate change, but it is one of the fastest-warming states in the nation. Its average temperature has climbed by close to 2 degrees Celsius since 1895 — double the average for the Lower 48 states.



Fred Crater opens the ice fishing



season in the early 1920s with "a fine big pickerel in Lake Hopatcong." In the lake's heyday, thousands gathered on the ice for fishing competitions and winter festivals.

GEORGE RINHART/CORBIS/GETTY IMAGES

Before the widespread use of

refrigeration, workers harvested ice from Lake Hopatcong, cutting it into blocks for use in shipping or for iceboxes.

LAKE HOPATCONG HISTORICAL MUSEUM

Insulated trains, such as this ice

car from around 1910, brought the ice from New Jersey to New York City.

LAKE HOPATCONG HISTORICAL MUSEUM

Over the past two decades, the 2 degrees Celsius number has emerged as a critical threshold for global warming. In the 2015 Paris accord, international leaders agreed that the world should act urgently to keep the Earth's average temperature increases "well below" 2 degrees Celsius by the year 2100 to avoid a host of catastrophic changes.

The potential consequences are daunting. The United Nations Intergovernmental Panel on Climate Change warns that if Earth heats up by an average of 2 degrees Celsius, virtually all the world's coral reefs will die; retreating ice sheets in Greenland and Antarctica could unleash massive sea level rise; and summertime Arctic sea ice, a shield against further warming, would begin to disappear.

But global warming does not heat the world evenly.

A Washington Post analysis of more than a century of National Oceanic and Atmospheric Administration temperature data across the Lower 48 states and 3,107 counties has found that major areas are nearing or have already crossed the 2-degree Celsius mark.

— Today, more than 1 in 10 Americans — 34 million people — are living in rapidly heating regions, including New York City and Los Angeles. Seventy-one counties have already hit the 2-degree Celsius mark.

— Alaska is the fastest-warming state in the country, but Rhode Island is the first state in the Lower 48 whose average temperature rise has eclipsed 2 degrees Celsius. Other parts of the Northeast — New Jersey, Connecticut, Maine and Massachusetts — trail close behind.

— While many people associate global warming with summer's melting glaciers, forest fires and disastrous flooding, it is higher winter temperatures that have made New Jersey and nearby Rhode Island the fastest warming of the Lower 48 states.

[Five takeaways from The Post's analysis of warming climates in the United States]

The average New Jersey temperature from December through February now exceeds 0 degrees Celsius, the temperature at which water freezes. That threshold, reached over the past three decades, has meant lakes don't freeze as often, snow melts more quickly, and insects and pests don't die as they once did in the harsher cold.

The freezing point "is the most critical threshold among all temperatures," said David A. Robinson, New Jersey state climatologist and professor at Rutgers University's department of geography.

The uneven rise in temperatures across the United States matches what is happening around the world.

Rhode Island is the first state in the Lower 48 whose average temperature rise has eclipsed 2 degrees Celsius.

In the past century, the Earth has warmed 1 degree Celsius. But that's just an average. Some parts of the globe — including the mountains of Romania and the steppes of Mongolia — have registered increases twice as large. It has taken decades or in some cases a century. But for huge swaths of the planet, climate change is a present-tense reality, not one looming ominously in the distant future.

To find the world's 2C hot spots, its fastest-warming places, The Post analyzed temperature databases, including those kept by NASA and NOAA; peer-reviewed scientific studies; and reports by local climatologists. The global data sets draw upon thousands of land-based weather stations and other measurements, such as ocean buoys armed with sensors and ship logs dating as far back as 1850.

In any one geographic location, 2 degrees Celsius may not represent global cataclysmic change, but it can threaten ecosystems, change landscapes and upend livelihoods and cultures.

In Lake Hopatcong, thinning ice let loose waves of aquatic weeds that ordinarily die in the cold. This year, a new blow: Following one of the warmest springs of the past century, harmful bacteria known as blue-green algae bloomed in the lake just as the tourist season was taking off in June.

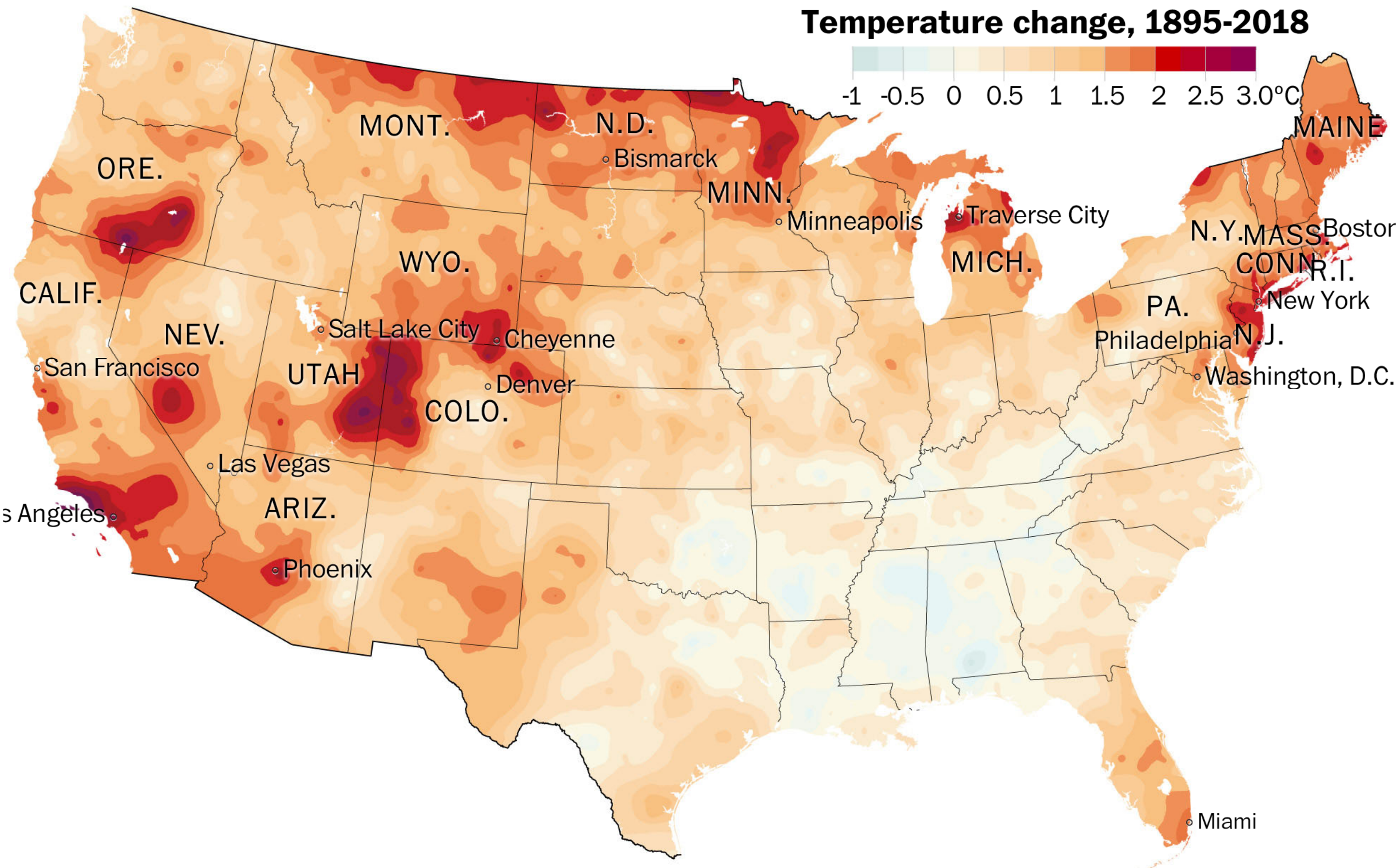
New Jersey closed Lake Hopatcong after the state Department of Environmental Protection detected a toxic bacteria caused in part by one of the warmest springs in the past century.

New Jersey's largest lake was shut down after the state's environmental agency warned against swimming or fishing "for weeks, if not longer."

The nation's hot spots will get worse, absent a global plan to slash emissions of the greenhouse gases fueling climate change. By the time the impacts are fully recognized, the change may be irreversible.

Daniel Pauly, an influential marine scientist at the University of British Columbia, says the 2-degree Celsius hot spots are early warning sirens of a climate shift.

"Basically," he said, "these hot spots are chunks of the future in the present."



Note: NOAA does not provide data for Alaska or Hawaii for this time period.

America's hot spots

Nationwide, trends are clear. Starting in the late 1800s, U.S. temperatures began to rise and continued slowly up through the 1930s. The nation then cooled slightly for several decades. But starting around 1970, temperatures rose steeply.

At the county level, the data reveals isolated 2-degree Celsius clusters: high-altitude deserts in Oregon; stretches of the western Rocky Mountains that feed the Colorado River; a clutch of counties along the northeastern shore of Lake Michigan — home to the famed Sleeping Bear Dunes National Lakeshore near Traverse City.

Along the Canadian border, a string of counties from eastern Montana to

Minnesota are quickly heating up.

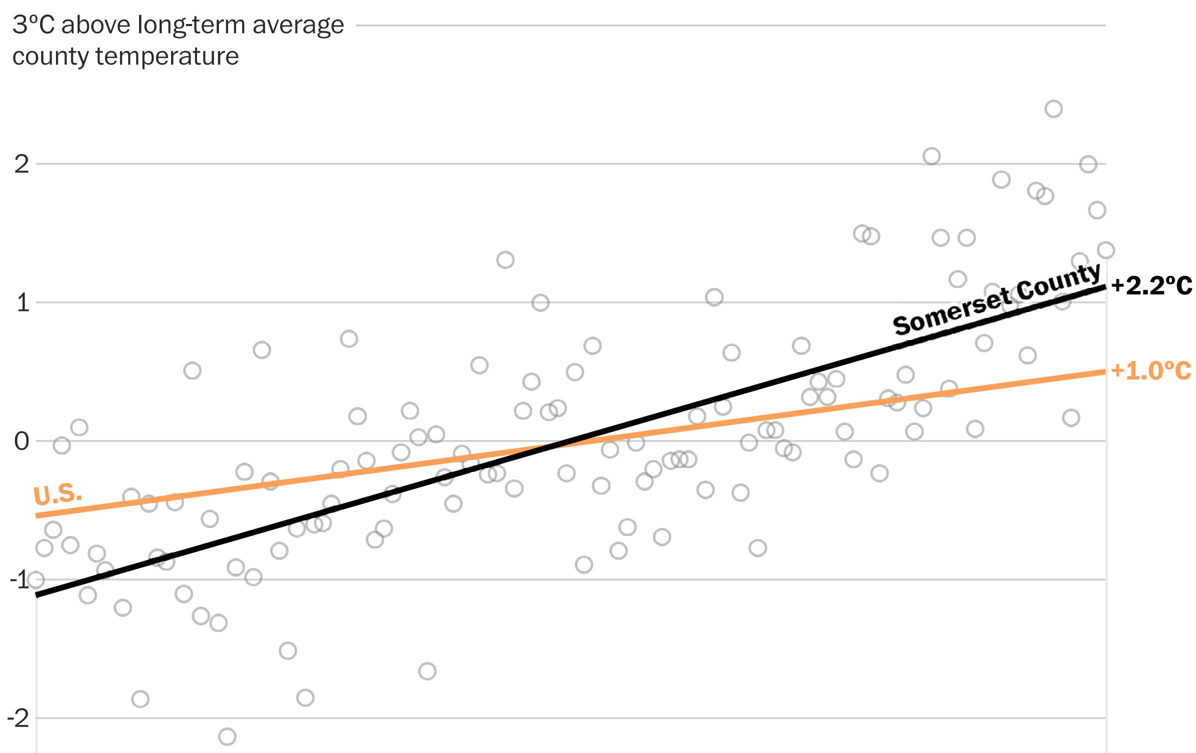
The topography of warming varies. It is intense at some high elevations, such as in Utah and Colorado, and along some highly populated coasts: Temperatures have risen by 2C in Los Angeles and three neighboring counties. New York City is also warming rapidly, and so are the very different areas around it, such as the beach resorts in the Hamptons and leafy Westchester County.

FIND YOUR COUNTY

Somerset County, New Jersey

+2.2° Celsius

Annual temperature change, 1895-2018



The smaller the area, the more difficult it is to pinpoint the cause of warming. Urban heat effects, changing air pollution levels, ocean currents, events like the Dust Bowl, and natural climate wobbles such as El Niño could all be playing some role, experts say.

> The one U.S. region that has not warmed since 1895: the South, where data in some cases even shows a modest cooling.

The only part of the United States that has not warmed significantly since the late 1800s is the South, especially Mississippi and Alabama, where data in some cases shows modest cooling. Scientists have attributed this "warming hole" to atmospheric cycles driven by the Pacific and Atlantic oceans, along with particles of soot from smokestacks and tailpipes, which have damaging health effects but can block some of the sun's intensity. Those types of pollutants were curtailed by environmental policies, while carbon dioxide remained unregulated for decades.

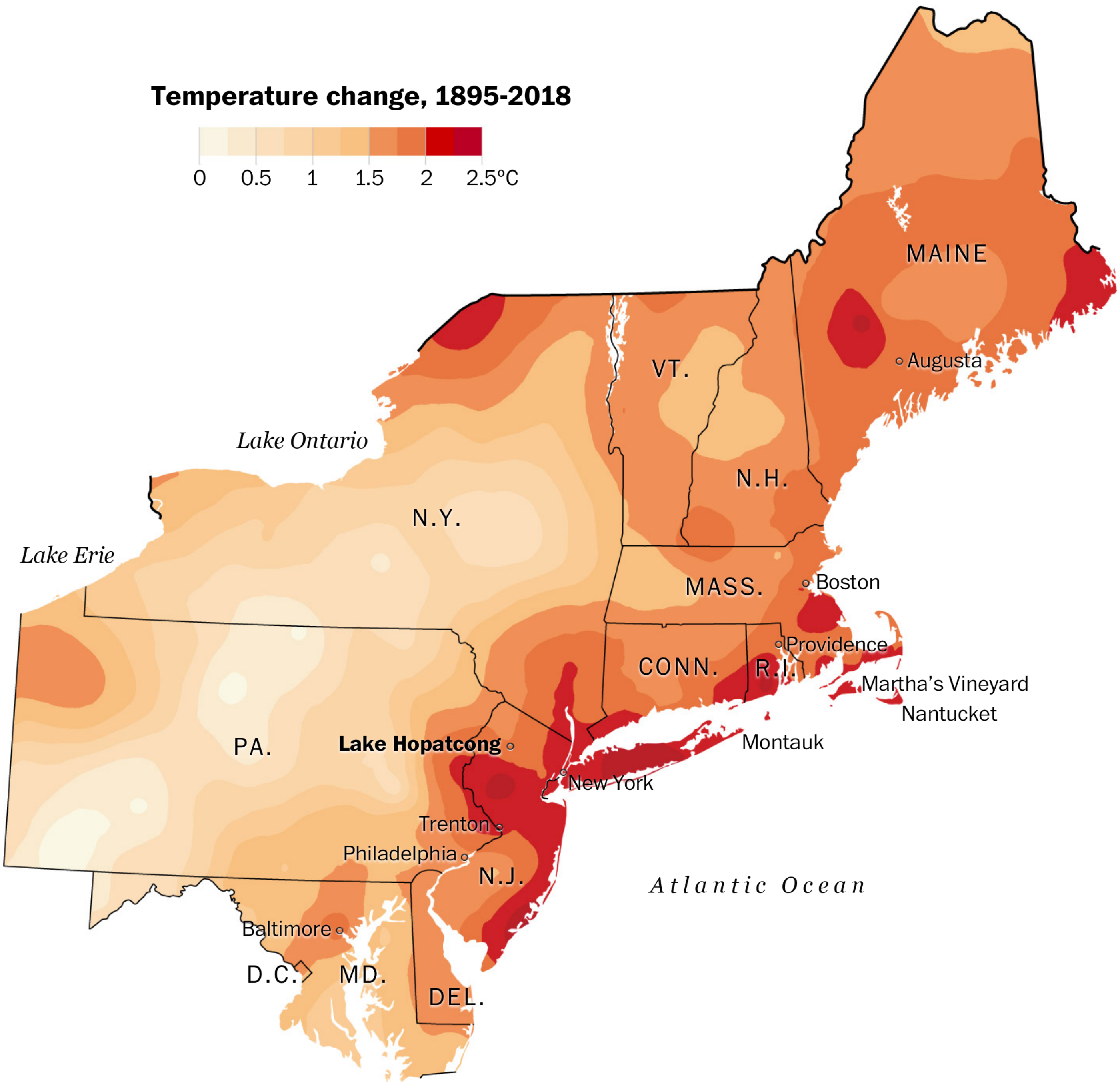
Since the 1960s, however, the region's temperatures have been increasing along with the rest of the country's.

The Northeast is warming especially fast.

Anthony Broccoli, a climate scientist at Rutgers, defines an unusually warm or cold month as ranking among the five most extreme in the record going back to the late 1800s. In the case of New Jersey, he says, "since 2000, we've had 39 months that were unusually warm and zero that were unusually cold."

Scientists do not completely understand the Northeast hot spot. But fading winters and very warm water offshore are the most likely culprits, experts say. That's because climate change is a cycle that feeds on itself.

Warmer winters mean less ice and snow cover. Normally, ice and snow reflect solar radiation back into space, keeping the planet relatively cool. But as the ice and snow retreat, the ground absorbs the solar radiation and warms.



NOAA data shows that in every Northeast state except Pennsylvania, the temperatures of the winter months of December through February have risen by 2 degrees Celsius since 1895-1896. And U.S. Geological Survey data shows that ice breaks up in New England lakes nine to 16 days earlier than in the 19th century.

This doesn't mean the states can't have extreme winters anymore. Polar vortex events, in which frigid Arctic air descends into the heart of the country, can still bring biting cold. But the overall trend remains the same and is set to continue. One recent study found that by the time the entire globe crosses 2 degrees Celsius, the Northeast can expect to have risen by about 3 degrees Celsius, with winter temperatures higher still.

Losing three feet of beach a year

Climate change plays havoc differently in different places.

In Rhode Island, Narragansett Bay has warmed as much as 1.6 degrees Celsius in the past 50 years, and for want of cooler water, the state's lobster catch has plummeted 75 percent in the past two decades.

Along the shoreline, the hotter and higher sea is shuffling the lineup of oceanfront homes.

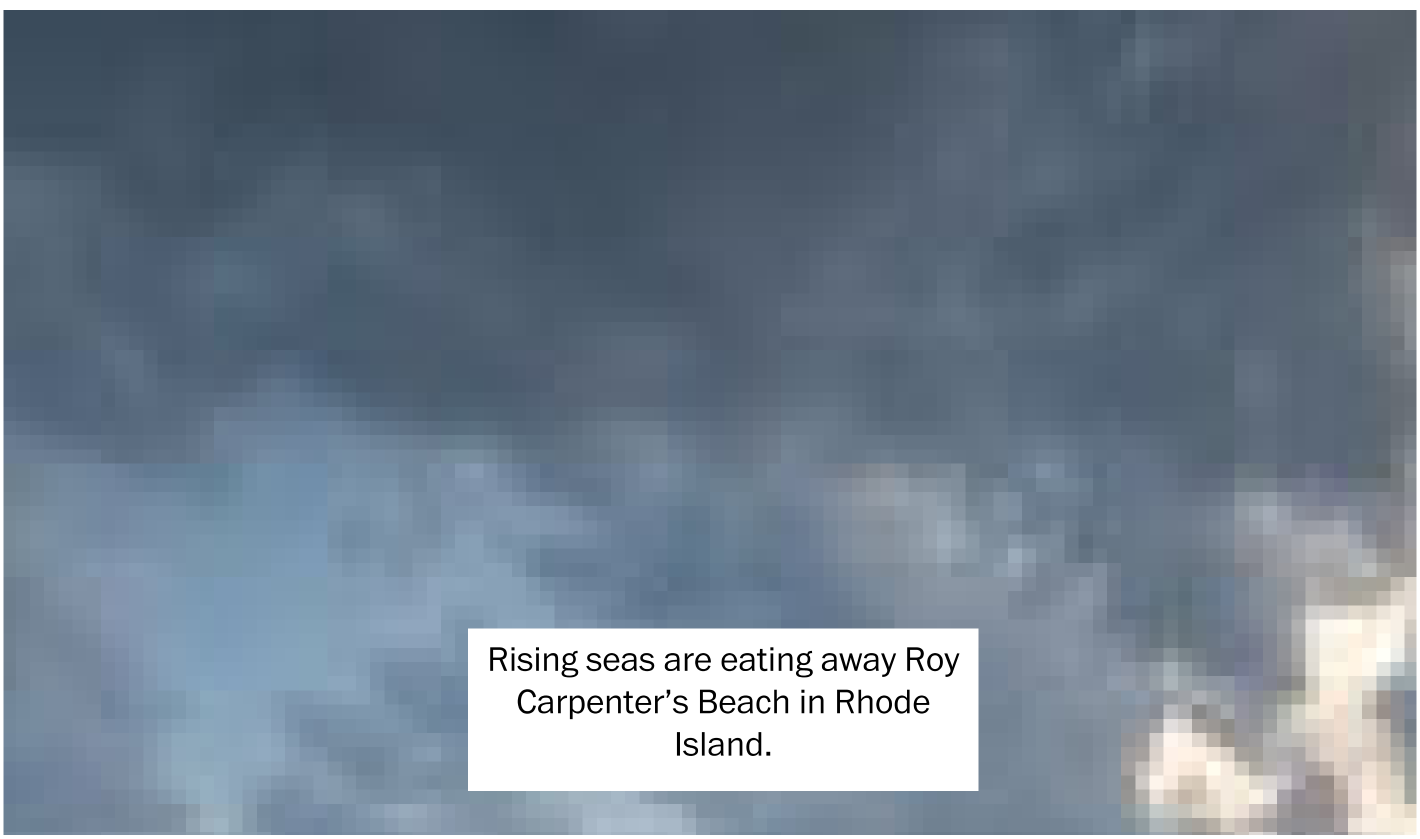
Roy Carpenter's Beach is a collection of summer cottages along a quarter-mile stretch that is eroding faster than any other part of the state — an average of 3.3 feet a year.

Rob Thoresen's great-grandfather bought the property nearly a century ago, and residents living in 377 cottages there now lease the land from the family business.

About a decade ago, the family tried — in vain — to persuade residents to move away from the encroaching ocean. Their reluctance was no surprise; the back of the property features a view of cornfields.

But then the coast took an indirect hit from Hurricane Sandy. It damaged 11 homes in the community's front row, with three of them washing out to sea. The surf laps over the remains of concrete foundations and wooden pylons, knocking over construction fences.

In 2013, 28 families in the first and second rows started moving to the back of the development — roughly 1,000 feet away. The community is planning to move another 20 houses.



Rising seas are eating away Roy Carpenter's Beach in Rhode Island.

Several houses have fallen victim to the encroaching water, forcing their occupants to move farther inland.

Tony Loura bought his cottage nearly 15 years ago. It used to be 1,000 feet from the water. Now, it's only about 150.

It is expensive. Homeowners pay to physically move their cottages or demolish them and rebuild. Matunuck Beach Properties, the management company, must survey the properties and prepare new locations, laying out new roads and sewer pipes.

Tony Loura, who has summered in Roy Carpenter's Beach for 15 years, is philosophical about his predicament. He is on the fourth row, where he has an unobstructed view of the ocean from his rocking chair. He estimates that he used to be 1,000 feet from the water. Now, the ocean is only about 150 feet away.

By 2030, hundreds of buildings on Rhode Island's coast will experience flooding twice a day, a half-dozen times a year.

"I'm hoping that I'm back far enough that I won't have to move to the back," said Loura, 66. "Every time they say there's a storm, I get worried."

With 420 miles of coastline, Rhode Island is particularly vulnerable to the vagaries of the Gulf Stream, a massive warm current that travels up the East Coast from the Gulf of Mexico before making a right turn toward Greenland and Europe.

The Gulf Stream is enormous, encompassing more water than "all of the world's rivers combined," according to NOAA. It is one part of an even larger global "conveyor belt" of currents that transport heat around the world.

A slowing of these currents, which scientists think is caused by the melting of Arctic ice, has pushed the Gulf Stream closer to the East Coast, bringing more warm water and, perhaps, hotter temperatures onshore. Offshore, it has become its own hot spot, helping to boost water temperatures by 2 degrees Celsius or more in some regions.

If the slowing continues, seas could rise farther and faster. That's because when the current slows, water it was driving toward Europe drifts back across the Atlantic to the U.S. coastline. Scientists are trying to determine whether the Gulf Stream is already contributing to rapid sea level rise on the East Coast.

Tidal gauges show sea levels have risen roughly nine inches since 1930, and researchers at the University of Rhode Island have determined that the rate has quickened by about a third in recent years.

The Thoresen family owns the Roy Carpenter's Beach general store, which stands just a few hundred feet from the water.

Nancy Thoresen, Rob's mother, and her family have already had to move their store once because of rising water.

Now, they're moving it once
more, this time far from the
ocean, all the way back to the
18th row of summer cottages.

By 2030, sea level rise will flood 605 buildings six times a year, according to the Rhode Island Coastal Resources Management Council's executive director, Grover Fugate.

Roy Carpenter's Beach is especially vulnerable.

Some residents want the beach's owners to fight off the sea, Loura said.

"They think they should build a sea wall, they should bring in tons of sand," he said. "Last year, they spent a lot of money on sand. Guess what? It's all gone."

Thoresen's family is moving a convenience store and office for the second time in a decade — this time all the way back to the 18th row.

"We moved it back 100 feet, and it only bought us 10 years," Thoresen said. "That's crazy."

That's what people who live in 2-degree Celsius zones are discovering: that climate change seems remote or invisible, until all of a sudden it is inescapable.

'The ice is not safe anymore'

Here at Lake Hopatcong, Tim Clancy, 65, a ruddy-faced fisherman and retiree, has helped run the annual ice fishing contests for years. He has a photo of himself taken in 2015, standing in the middle of the frozen lake, a string of four perch dangling from one hand, his 400-pound all-terrain buggy parked on the ice behind him.

“It was like a tailgate party. Midnight madness. People camped out with their snowmobiles,” he says. “But the ice is not safe anymore.”

At the Lake Hopatcong Foundation offices, director Kane recalls that the lake used to freeze over by Thanksgiving and now rarely does so before January.

According to records kept by the local Knee Deep Club, a fishing group, 26 fishing contests were canceled because of poor ice conditions from 1998 through 2019. Only 19 were held successfully.

Tim Clancy helps run the Knee Deep Club's ice fishing contests at Lake Hopatcong.

The lake used to freeze over by Thanksgiving. Now, it rarely does so before January.

Lake Hopatcong, usually a busy summer destination, was shut down because of toxic bacteria, taking a toll on nearby businesses.

Nine miles long, Lake Hopatcong sits between two counties — Sussex and Morris — in the state's northwest. Both have been warming fast, especially in winter. According to The Post's review of New Jersey data, winter temperatures in Sussex have increased 2.6 degrees Celsius since the winter of 1895-1896. For Morris, the winter increase has been slightly sharper 2.7 degrees Celsius.

Robinson, the state climatologist, found that January temperatures in Sussex County generally need to average around minus-3.9 to minus- 3.3 Celsius for successful ice fishing.

Instead, average winter temperatures are moving closer to the freezing point, with some winters now exceeding 0 degrees Celsius.

It is not just the lake that is being wracked by climate changes.

From the Jersey Shore to the shopping malls of Paramus, from hiking trails in the northwest to the Bayway oil refinery, the state faces exceptionally heavy and unpredictable rainfall — even for New Jersey. Last year, it was inundated by a record 64.77 inches of rainfall statewide, 40 percent above average.

Pests, no longer eradicated by cold winters, are attacking people, crops and landscapes alike.

The ⅛ -inch-long southern pine beetle had been largely confined to southern U.S. forests — hence its name. But the warmer temperatures have spurred the beetle's migration north, where it has damaged more than 20,000 acres of the state's Pine Barrens, a vast coastal forested plain that Congress has defined as a national reserve.

"They are changing the Pinelands," says Matthew Ayres, a Dartmouth researcher who has studied the beetle. "It may not be too long before people are driving through the Pinelands saying, 'Why do they call it the Pinelands?'"

Mosquitoes, once dubbed on postcards as New Jersey's "air force," have longer seasons. The Warren County Mosquito Control Commission, whose records date to 1987, uses fixed-wing aircraft to drop a granular, naturally occurring soil microbe on swamps to kill the mosquito larvae.

But the bugs may be winning the air war. The commission's flights are more frequent, and the past eight years, led by 2018, have had the highest numbers of acres treated annually. Mosquitoes carrying West Nile virus came up from the South 20 years ago. Last year, Warren became the last county in the state to register human cases of the disease.

"Mosquito season used to start on June 1 and end on Sept. 30," said Rutgers professor Dina Fonseca, an expert on insect-borne disease. But unless the air war starts earlier in the spring, "you're not going to address the mosquito problem."

'Completely dead'

On a cool but sunny day in May, Fred Lubnow, director of aquatic programs at Princeton Hydro, and Katie Walston, a senior scientist there, pulled up their anchor in Lake Hopatcong to find it covered with aquatic weeds. The culprit? Fertilizer runoff combined with winters too warm to kill them off.

"The plants start growing earlier and linger around longer, as well," Lubnow said. The thick ice blocked sunlight from nurturing the weeds. But "in some of these shallow areas, as early as February, we're looking through the ice seeing the plants growing."

have been monitoring water temperatures and recording weed growth in Lake Hopatcong.

Fertilizer runoff combined with

warm winters helps aquatic
weeds grow vigorously.

In the summer, the weeds can

become a nuisance to boats and
swimmers alike.

By summer, the weeds become a nuisance, forcing the state government to “harvest” them with large paddles and toss them onto a conveyor belt, then onto barges. Some years, funding has been hard to get, delaying harvesting and angering homeowners.

“If this area is not harvested, you can’t get a boat through it,” Lubnow says. Swimming isn’t possible, either. Fishing becomes difficult.

In late June, disaster struck.

The New Jersey Department of Environmental Protection detected toxic bacteria known as blue-green algae. Aerial photos showed the telltale large streaks of “pea soup” across the lake. The agency urged people to avoid swimming, wading and watersport activities such as jet-skiing, kayaking, windsurfing and paddleboarding.

“It’s almost put us out of business,” says John Clark, co-owner of Little Nicki’s Italian restaurant, which looks out onto the lake. Little Nicki’s does nearly a tenth of its business over the first two weekends in July and is usually jammed the afternoon before July 4. Yet there were only three people there that day. Clark estimated that business was down by half.

"It's completely dead. Everyone was having a banner year. Then you hit a wall."

Little Nicki's Italian restaurant, across the street from Lake Hopatcong, is usually jammed in the summer, but this year, the state warned people to avoid the water, putting a damper on the restaurant's business.

How we analyzed the data

To analyze warming temperatures in the United States, The Washington Post used the National Oceanic and Atmospheric Administration's Climate Divisional Database (nClimDiv), which provides monthly temperature data at the national, state and county level between 1895 and 2018 for the Lower 48 states. NOAA does not provide this data for Hawaii, and its data for Alaska begins in 1925.

We calculated annual mean temperature trends in each state and county in the Lower 48 states using linear regression — analyzing both annual average temperatures and temperatures for the three-month winter season (December, January and February). While not the only approach for analyzing temperature changes over time, this is a widely used method.

County population numbers are the U.S. Census Bureau's estimate of resident total population for July 2018.

Annual temperature averages in the interactive county feature are displayed as departures from the 1895-2018 average temperature for each county. These departures from the average are referred to as "temperature anomalies" by climate scientists.

To make the maps, we applied the same linear regression method for annual average temperatures to NOAA's Gridded 5km GHCN-Daily Temperature and Precipitation Dataset (nClimGrid), which is the basis for nClimDiv. For mapping purposes, the resolution of the data was increased using bilinear interpolation.

The warming of Alaska was treated separately, after consulting with Rick Thoman, an expert on the state's climate at the University of Alaska at Fairbanks. Thoman said that a linear trend does not apply in the case of this state because the warming has been so extreme in the most recent years — something that such a trend would understate. So Thoman used a smoothed curve to plot Alaska's warming trend, calculating about 2.2 degrees Celsius (4 degrees Fahrenheit) just since 1925.

Kenneth Kunkel of the North Carolina Institute for Climate Studies, who developed climate analyses for all 50 U.S. states during the 2013 National Climate Assessment, provided an initial analysis of the Lower 48 states' temperature trends from 1895 through 2018 at The Post's request.

Credits

Project and story editing by Trish Wilson. Graphics editing by Monica Ulmanu. Design and development by Madison Walls. Copy editing by Emily Morman and Brian Malasics. Photo editing and research by Olivier Laurent. Project management by Julie Vitkovskaya. Digital Operations by Sarah Dunton and María Sánchez Díez.

Steven Mufson
Steven Mufson covers the business of climate change. Since joining The Washington Post in 1989, he has covered economic policy, China, diplomacy, energy and the White House. Earlier he worked for The Wall Street Journal in

New York, London and Johannesburg.

Chris Mooney
Chris Mooney covers climate change, energy, and the environment. He has reported from the 2015 Paris climate negotiations, the Northwest Passage, and the Greenland ice sheet, among other locations, and has written four books about science, politics and climate change.

Juliet Eilperin
Juliet Eilperin is The Washington Post's senior national affairs correspondent, covering the transformation of federal environmental policy. She's authored two books, "Demon Fish: Travels Through The Hidden World of Sharks" and "Fight Club Politics: How Partisanship is Poisoning the House of Representatives." and has worked for The Post since 1998.

John Muyskens
John Muyskens is a graphics editor at the Washington Post specializing in data reporting.

Salwan Georges
Salwan Georges is a staff photographer for The Washington Post. He was a photographer on The Post's Murder with Impunity series, which was listed as a finalist for the Pulitzer Prize in Explanatory Reporting in 2019.

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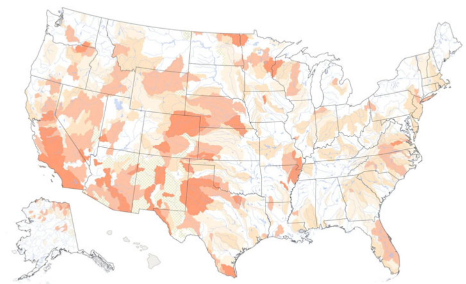
Changing climate imperils global food and water supplies, new U.N. study finds

The world cannot avoid the worst impacts of climate change without overhauling the ways we grow food, raise livestock and manage forests, a major new study says.

Mapping the strain on our water



Pockets in several U.S. states — and across the globe — are draining their limited water supplies.

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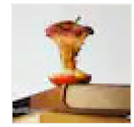

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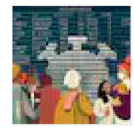

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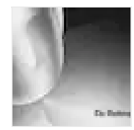

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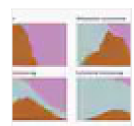

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EXHIBIT C

STATE OF RHODE ISLAND
PUBLIC UTILITIES COMMISSION

IN RE: THE NARRAGANSETT ELECTRIC COMPANY d/b/a NATIONAL GRID - UPDATED ADVANCED METERING FUNCTIONALITY BUSINESS CASE	**:**	**DOCKET NO. 5113**
IN RE: THE NARRAGANSETT ELECTRIC COMPANY d/b/a NATIONAL GRID - GRID MODERNIZATION PLAN	**:**	**DOCKET NO. 5114**

ORDER

In the Amended Settlement approved in Docket No. 4770 (In re: The Narragansett Electric Company d/b/a National Grid – Electric and Gas Distribution Rate Filing), National Grid committed to working with the Power Sector Transformation Working Group to develop a Grid Modernization Plan. The Company also committed to updating its advanced metering functionality (AMF) investment plan business case, with the latter expected in February 1, 2019 and the former expected within six months.[1] In its Order, the Public Utilities Commission (Commission) found that an AMF business case is integral to any Grid Modernization Plan (GMP), and therefore, the parties were encouraged to file the two as close together as possible.[2] Following approval of the Amended Settlement Agreement in August 2018, National Grid sought and was granted extensions of time for these filings.

On January 21, 2021, National Grid filed its proposed Grid Modernization Plan[3] and Updated Advanced Metering Functionality Business Case.[4] On March 15, 2021, the Commission posted an Open Meeting Notice to consider consolidating the two dockets on March 19, 2021. On March 17, 2021, the Division of Public Utilities and Carriers (Division) objected to the

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[1] Docket No. 4770 Amended Settlement at 48-54; http://www.ripuc.ri.gov/eventsactions/docket/4770-4780-NGrid-ComplianceFiling-Book%201%20through%207%20-%20August%2016,%202018.pdf.
[2] Order No. 23823 (May 5, 2020); http://www.ripuc.ri.gov/eventsactions/docket/4770-4780-NGrid-Ord23823%20(5-5-20).pdf.
[3] Docket No. 5114; http://www.ripuc.ri.gov/eventsactions/docket/5114page.html.
[4] Docket No. 5113; http://www.ripuc.ri.gov/eventsactions/docket/5113page.html.

consolidation and further moved to stay consideration of the GMP.[5] On March 18, 2021, PPL Corp. and National Grid announced the sale of The Narragansett Electric Company to PPL. As a result of these events, at the March 19, 2021 Open Meeting, the Commission did not make any decision on consolidation or process. On March 26, 2021, National Grid filed a response and objection to the Division's March 17, 2021 filing.[6]

Considering the announced plans to sell The Narragansett Electric Company to PPL Corp., on May 27, 2021, Commission Counsel issued a memorandum to National Grid and the Division seeking further information so the Commission could determine whether these matters should be considered at this time or held in abeyance pending the outcome of the PPL acquisition.[7] Specifically, Commission Counsel requested the parties[8] to comment on the following:

(1) Is it an accurate statement that the benefit/cost analysis (BCA) contained in the updated AMF business case is based at least in part, on synergies with National Grid's New York operations? If so, will the BCA be materially impacted by the acquisition of The Narragansett Electric Company by PPL?

(2) Are the proposals and pathways in the Grid Modernization Plan based on the services of the National Grid USA Service Company? If so, are the proposals in the Grid Modernization Plan dependent, at least in part, on the functionalities National Grid currently has and intends to deploy? If so, would the proposals and pathways in the Grid Modernization Plan subject to change as a result of the acquisition of The Narragansett Electric Company PPL?

(3) Even if the Commission considered the needs assessment related to metering, would the solutions and benefit cost analysis be dependent upon PPL's current and future functionalities?

(4) If the acquisition of The Narragansett Electric Company would affect the underlying assumptions in the two filings, should the Commission proceed with the assessment of

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[5] Div. Objection; http://www.ripuc.ri.gov/eventsactions/docket/5113-5114-DPUC-Objection%20to%20Consolidate%203-17-21.pdf.

[6] National Grid Response and Objection to Division's Motion to Stay Docket No. 5114; http://www.ripuc.ri.gov/eventsactions/docket/5113-5114-NGrid%20Objection%20to%20Division%20Motion%20(3-26-2021).pdf.

[7] Commission Counsel Mem. to Attorneys Hutchinson and Wold; http://www.ripuc.ri.gov/eventsactions/docket/5113-5114-PUC-Memo%20and%20Data%20Request%20(5-27-21).pdf.

[8] No procedural schedule was set so the only parties to the docket are Petitioner National Grid and the Division, an indispensable party to Commission matters.

these dockets at this time or at a minimum, stay the matters pending the outcome of the Division's acquisition review process to reevaluate the filings? Please support your answer.

On June 3, 2021, the Division, through Counsel, filed a further Motion to Stay and Continued Opposition to Consolidation of the two dockets, incorporating its consultant's responses to the questions.[9] Division consultant Gregory L. Booth, P.E., indicated that the BCA included in the AMF filing is predicated upon the National Grid Service Company providing services to The Narragansett Electric Company. He opined that the synergies associated with this arrangement would be lost and replaced with currently unknown operations, systems, equipment, billing, and other interfaces by PPL.[10] Thus, Mr. Both indicated that the BCA would most probably be materially impacted by the acquisition of The Narragansett Electric Company by PPL. Thus, he contended that virtually nothing within the filing could be relied upon for purposes of a BCA.[11] Addressing the GMP, Mr. Booth responded that the proposals and pathways in the GMP were based on services provided by the National Grid USA Service Company and further, that the proposals are dependent on the functionalities National Grid currently has and intends to deploy. Therefore, these proposals and pathways would be likely to change as a result of the acquisition.[12] Based on these responses, the Division recommended staying the two dockets until a final Order is issued by the Division in the pending matter to review the proposed acquisition (Division Docket D-21-09 - Petition of PPL Corporation, PPL Rhode Island Holdings, LLC, National Grid USA,

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[9] Division's Further Motion to Stay, Continued Opposition to Consolidation, and Responses Commission's Data Requests Contained in the Commission's Memorandum Dated May 27, 2021; http://www.ripuc.ri.gov/eventsactions/docket/5113-5114-DIV%20Motion%20to%20Stay,%20Continued%20Opposition%20to%20Consolidation%20and%20Data%20Responses%20to%20PUC%20Data%20Requests.pdf.

[10] Further Motion at 4. The Commission notes that Mr. Booth has previously been qualified as an expert in numerous matters before the PUC including the Docket No. 4770 rate case and every Infrastructure, Safety, and Reliability filing made by National Grid's electric company.

[11] *Id*.

[12] *Id*. at 5.

and The Narragansett Electric Company for Authority to Transfer Ownership of The Narragansett Electric Company to PPL Rhode Island Holdings, LLC).[13]

On June 10, 2021, National Grid filed its responses to the questions presented. National Grid acknowledged that the BCA in the updated AMF business case was based on synergies with National Grid's affiliates in New York and that in the event of Division approval of the acquisition by PPL, those synergies would not be realized.[14] The Company also agreed that the BCA in the GMP filing was based on National Grid USA Service Company supports, that the proposals are dependent, at least in part, on the functionalities and solution National Grid currently has and intends to deploy, and finally, that those proposals and pathways could change based on an acquisition of The Narragansett Electric Company by PPL.[15] Additionally, National Grid indicated that in the event of an acquisition, the final metering solution and BCA will depend on PPL's preferred solution and assumptions.[16] National Grid did not object to a stay of the dockets pending the outcome of the Division's review of the PPL acquisition of The Narragansett Electric Company.[17]

At an Open Meeting held on June 29, 2021, the Commission stayed these two matters pending further consideration following the issuance of a final Order in Docket No. D-21-09 but did not rule on whether or not to consolidate the matters. The data responses from both National Grid and the Division support a finding that the information contained in these two filings will be materially affected should the Division approve the acquisition of The Narragansett Electric Company. Therefore, it would be inefficient and a waste of resources to move forward with these

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[13] *Id*. at 6. The Division matter can be accessed at: http://www.ripuc.ri.gov/eventsactions/docket/D_21_09.html.
[14] National Grid Response to PUC 1-1; http://www.ripuc.ri.gov/eventsactions/docket/5113-5114-NGrid-DR-PUC1(6-10-21).pdf.
[15] National Grid Response to PUC 1-2.
[16] National Grid Response to PUC 1-3.
[17] National Grid Response to PUC 1-4.

two matters at this time. However, the Commission recognizes that grid modernization will be crucial to meeting the State of Rhode Island's clean energy goals and, therefore, will continue to review grid modernization investments that are included in upcoming filings. Additionally, the Commission will review the status of investments that were included in Docket No. 4770 to enable a modern grid to determine if there are any actions the Commission can take to avoid or mitigate stranded ratepayer costs.

Accordingly, it is hereby

(24089) ORDERED:

1. The Narragansett Electric Company, d/b/a National Grid's Updated Advanced Metering Functionality Business Case, Docket No. 5113, is hereby stayed.
2. The Narragansett Electric Company d/b/a National Grid's Grid Modernization Plan, Docket No. 5114, is hereby stayed.

EFFECTIVE AT WARWICK, RHODE ISLAND PURSUANT TO AN OPEN MEETING DECISION ON JUNE 29, 2021. WRITTEN ORDER ISSUED JULY 14, 2021.

PUBLIC UTILITIES COMMISSION

Ronald T. Gerwatowski, Chairperson

Abigail Anthony, Commissioner

*John C. Revens, Jr., Commissioner

*Commissioner Revens did not participate in the decision.

EXHIBIT D

National Grid USA and The Narragansett Electric Company
GECA 1-1

Request:

Recently enacted RIGL §42-6.2 et seq. creates legally enforceable targets for greenhouse gas emissions reductions beginning in 2030 through 2050. Please share any studies conducted or reports published by National Grid regarding how it or any other utility could achieve mandatory greenhouse gas emissions reductions?

Response:

National Grid USA and The Narragansett Electric Company ("Narragansett") have not conducted or published any studies or reports specific to the greenhouse gas ("GHG") emission reduction targets set forth in R.I. Gen. Laws §42-6.2-1, *et seq*., also known as the 2021 Act on Climate (the "2021 Act"). At this time, the 2021 Act does not require public utilities to comply with any specific rules or requirements. The GHG emission reduction targets established in the 2021 Act are economy-wide targets and specific targets for the utility sector are still to be ascertained. Therefore, it is unknown how future rules and regulations implementing the new targets under the 2021 Act will implicate the utility sector. Please also see National Grid USA and Narragansett's response to Data Request AG 1-30 for additional information regarding the implications of the 2021 Act on Narragansett's business plan.

Notwithstanding the above, National Grid USA is committed to helping its customers, state and federal agencies, and other stakeholders achieve their clean energy goals, and has conducted a number of studies and reports regarding how it could help achieve mandatory GHG emissions reductions. For example, the Resilient Rhode Island Act of 2014 ("2014 Act"), which the 2021 Act amended, was one of the drivers for Narragansett's grid modernization strategy as outlined in its Grid Modernization Plan ("GMP"), which was filed with the Rhode Island Public Utilities Commission ("PUC") in January 2021 in Docket No. 5114.[1] The GMP includes a "High Distributed Energy Resource" scenario that was developed based on meeting the GHG emissions reduction targets established by the 2014 Act (i.e., 45 percent below 1990 levels by 2035 and 80 percent below 1990 levels by 2050).[2] A complete copy of the GMP Business Case and Implementation Plan is available at the following link:

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[1] The PUC stayed the GMP proceeding pending the outcome of the Rhode Island Division of Public Utilities and Carriers' review in this proceeding. *See* Order No. 24089, PUC Docket No. 5114 (July 14, 2021).

[2] The grid modernization investments outlined in the GMP will help Rhode Island meet its clean energy goals by enabling greater customer energy savings and distributed energy resources ("DER") adoption (i.e., renewable distributed generation, demand response, electric vehicles, electric heat pumps). Enabling DER adoption, in particular, is a key driver for meeting the State's clean energy needs because it will enable customers to reduce their overall carbon footprint, including reducing transportation-related emissions that make up 40 percent of the State's

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GECA 1-13

Request:

Recently enacted RIGL §42-6.2 *et seq.* creates legally enforceable targets for greenhouse gas emissions reductions beginning in 2030 through 2050. Has PPL, (or National Grid) or any of its related companies, ever taken a position, e.g. made public statements, hired lobbyist, and/or engaged in a trade association campaign, in opposition to greenhouse gas emissions reductions by any government entity?

Response:

PPL and its affiliates engage with policymakers on a number of policy, regulatory and legislative energy-related proposals, and provide input in the best interest of their customers and shareowners.

PPL believes that to be the most effective in producing lasting carbon reductions, legislation mandating greenhouse gas emissions reductions should be economy-wide, market-based and provide for regional flexibility. PPL supports a federal carbon rule that is based on "inside the fence" or unit-specific reductions that are demonstrated to be achievable. PPL's Kentucky subsidiary, LG&E and KU Energy LLC, opposed the Obama Administration's final Clean Power Plan ("CPP") as it was inconsistent with this view and subsequently joined in a lawsuit requesting reconsideration of the rule based on flaws in EPA's methodology, analyses, and assumptions. LG&E and KU Energy LLC have also filed comments and joined in comments by trade associations identifying deficiencies or concerns with various other proposed rules including EPA's Greenhouse Gas New Source Performance Standards, CPP Federal Plan, and Model Trading Rules.

After a reasonable investigation, it is believed that the CPP is the only greenhouse gas emissions reduction regulation where PPL participated directly in a legal challenge in opposition to the rule. PPL has not identified any instances where it took a general position in opposition to greenhouse gas reductions in general, as opposed to identifying substantive or procedural deficiencies in specific proposed or final rules.

National Grid is not aware of having opposed any federal government efforts to reduce greenhouse gas emissions, generally. National Grid has joined in comments by trade associations identifying potential deficiencies and concerns with various proposed rules or policy constructs addressing greenhouse gas emission reductions. National Grid has also expressed concerns about potential implementation paths for greenhouse gas emission reductions as part of public comment processes or open public meetings

Prepared by or under the supervision of: Christine Martin http://www.ripuc.ri.gov/eventsactions/docket/5114page.html

In addition, National Grid USA has commissioned Narragansett-sponsored or Narragansett-affiliated studies in the U.S. and the U.K. related to the decarbonization of natural gas and/or the gas network to better understand how it or any other utilities could help achieve mandatory GHG emissions reductions. A description of these studies, together with redacted copies of the studies are included in Narragansett's response to Data Request PUC 1-1 in PUC Docket No. 5079,[3] a copy of which is provided as Attachment NG-GECA 1-1.

carbon dioxide emissions. Grid modernization investments will help reduce the costs and other barriers to interconnect new DERs in Rhode Island, which will drive more DER adoption and investment in the State.

[3] National Grid's Tariff Advice Filing to Amend RIPUC NG-GAS-No. 101; Response to PUC's First Set of Data Requests issued November 5, 2020.

OER 1-3

Request:

Please describe PPL Rhode Island's planned approach to managing:

(a) Residential energy efficiency programs

(b) Income-Eligible energy efficiency programs

(c) Commercial and Industrial energy efficiency programs

(d) Demand response programs across all customer groups

(e) Provision of energy efficiency services and incentives to customers utilizing delivered fuels (propane, heating oil) for water and/or space heating

Response:

PPL Rhode Island plans to continue The Narragansett Electric Company's ("Narragansett") existing energy efficiency programs on Day 1 in the same manner that the programs are operated and managed today. PPL Rhode Island will evaluate Narragansett's energy efficiency programs after the transaction closes to determine whether any changes or enhancements are appropriate. This evaluation will rely on PPL's experience in designing and managing energy efficiency programs in Pennsylvania and Kentucky as described in PPL's response to OER 1-1. PPL Rhode Island will seek all applicable regulatory approvals in accordance with the Least Cost Procurement statute, R.I. Gen. Laws § 39-1-27.7, to the extent that it determines that it wants to make changes to existing Narragansett energy efficiency programs.

PPL and PPL Rhode Island are working collaboratively with National Grid on Day 1 planning, which is still underway, and, based on the outcome of that planning process, knowledge transfer for Rhode Island energy efficiency programs will happen by way of transfer of employees to PPL on Day 1 or under the Transition Services Agreement. PPL Rhode Island anticipates hiring existing National Grid employees with knowledge of and experience with Narragansett's Rhode Island energy efficiency programs.

Prepared by or under the supervision of: David J. Bonenberger

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GECA 1-11

Request:

Please provide a breakdown of the fuel mix for electricity in each electric distribution territory served by PPL. Please distinguish between coal, oil, natural gas, solar, wind, nuclear, hydropower, biomass, and other renewables or other non-renewables. Please also indicate the required minimum percentage of electricity that must be renewable in each territory, what statute, order, or other regulation requires such a percentage, and whether the company exceeds that requirement.

Response:

PPL Electric Utilities Corporation ("PPL Electric") does not have specific fuel mix figures for the electricity delivered to end-use customers in its service territory. PPL Electric operates in a deregulated energy market, therefore it has no information on Electric Generation Supplier product offerings or the generation supply used to support those customer offerings. Further, PPL Electric's default service energy supply is primarily met through fixed price load following full requirements, which do not require suppliers to communicate on the generation mix used to meet their supply obligations.

PPL Electric operates within the PJM ISO, who reports generation mix annually. The PJM report entitled "State of the Market Report" for 2020, states that the generation mix was as follows:

- Coal - 19.3%
- Nuclear – 34.2%
- Natural Gas – 39.8%
- Hydroelectric – 2.0%
- Wind – 3.3%
- Waste Fuel – 0.5%
- Oil – 0.3%
- Solar – 0.5%
- Battery – 0.0%
- Biofuel – 0.1%

Source: https://www.pjm.com/-/media/committees-groups/committees/mc/2021/20210329-special/20210329-state-of-the-market-report-for-pjm-2020.ashx

Further, Pennsylvania has implemented an Alternative Energy Portfolio Standards Act ("AEPS Act") which requires Pennsylvania load serving entities to obtain AECs in an amount equal to certain percentages of electric energy sold to retail customers in this Commonwealth. See 52 Pa.

§ Code 54.182. Currently under the AEPS Act, PPL Electric is obligated to procure 18% of its electricity from alternative energy sources. As required by the PA AEPS Act, PPL Electric has always met its alternative energy supply obligations through the purchase of alternative energy credits. PPL Electric is only responsible for meeting the PA AEPS Act for default service customers and does not have information on Electric Generation Supplier's or their compliance with the AEPS Act.

Louisville Gas & Electric Company and Kentucky Utilities Company's generation mix can be found at page 12 of PPL Corporation's Form 10-K which can be found at the following link:

https://app.quotemedia.com/data/downloadFiling?webmasterId=101533&ref=115648011&type=HTML&formType=10-K&dateFiled=2021-02-18&cik=0000922224&CK=922224&symbol=0000922224&companyName=PPL+Corp

Kentucky does not have a required minimum percentage of electricity that must be renewable.

GECA 1-9

Request:

Rhode Island continues to be on the forefront of the development of offshore wind generation, which is expected to be a critical component to meeting the increasing Renewable Energy Standard and the Long-term Contracting Standard (RIGL §39-26.1). What experience does PPL have in conducting or engaging with an RFP for offshore wind?

Response:

PPL does not presently have its own experience in conducting or engaging with offshore wind RFPs in its current utilities in Pennsylvania and Kentucky. PPL and PPL RI will ensure that Narragansett has the necessary experience post-closing in conducting RFPs for offshore wind by: (1) working with National Grid USA Service Company, Inc. ("National Grid Service Company") and Narragansett personnel with experience in this area during the transition period, (2) hiring National Grid Service Company personnel with experience in this area to continue providing service to Narragansett under PPL RI ownership, and (3) bringing additional resources with this expertise on-board into the PPL organization.

Prepared by or under the supervision of: David J. Bonenberger

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National Grid USA and The Narragansett Electric Company
GECA 1-4

Request:

As part of Docket 4780, National Grid described the economies of scale available to it with respect to investment in electric transportation programs due to its position in Massachusetts, Rhode Island, and New York. Based on those studies, what additional costs are likely to be incurred by an entity implementing these programs in Rhode Island only?

Response:

National Grid USA and The Narragansett Electric Company ("Narragansett") have not studied the types of tasks or magnitude of costs that are likely to be incurred by an entity implementing electric transportation programs in Rhode Island only.

Much of Narragansett's testimony in Rhode Island Public Utilities Commission ("PUC") Docket No. 4780 pertaining to the availability of economies of scale due to its position in Massachusetts, Rhode Island, and New York related to Advanced Metering Functionality ("AMF"), such as the ability to conduct multi-jurisdiction request for proposals ("RFP") events in the procurement of meters; however, National Grid USA's electric transportation strategy does not include multi-jurisdiction RFP events at this time. For example, National Grid USA does not currently have plans to purchase large quantities of charging stations across all its jurisdictions. In addition, a transportation education and outreach campaign proposed in Narragansett's general rate case in PUC Docket Nos. 4770 and 4780 and in its Massachusetts affiliates' electric transportation filing was not approved in Rhode Island or Massachusetts, respectively; therefore, opportunities to launch a joint program to allow for regional communication channels to be used with unified messaging did not proceed.

Prepared by or under the supervision of: Mark Siegal

Division 7-49

Request:

Provide the study (or studies) that supported the AMI deployment as it exists today on the PPL system. State whether AMI is fully deployed on all PPL systems.

Response:

Please see Attachment PPL-DIV 7-49-1 Analysis of Metering Alternatives.

PPL Electric Utilities Corporation's ("PPL Electric") Smart Meter Technology Procurement and Installation Plan can be found at the following link:

https://www.puc.pa.gov/pcdocs/1296056.pdf

PPL Electric has effectively fully deployed AMI meters to its entire system. There remain approximately 20 meters that need to be exchanged but which are the subject of pending PUC formal complaints preventing the exchange of those meters.

LGE KU has effectively deployed about 27,000 AMI meters primarily to opt-in program participants. There remain approximately 1.3 million meters and gas indices which the exchanges are planned to commence mid 2022 and continue until 2026.

Prepared by or under the supervision of: David J. Bonenberger and Lonnie E. Bellar