JFAR

The Science of Climate Change

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Joint Forum on Actuarial Regulation

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Image Credit: NASA

Earthrise: Apollo 8, the first manned mission to the moon, entered lunar orbit on 24 December 1968. That evening, the astronauts – Commander Frank Borman, Command Module Pilot Jim Lovell, and Lunar Module Pilot William Anders – held a live broadcast from lunar orbit, in which they showed pictures of the Earth and moon as seen from their spacecraft.

Said Lovell,

"The vast loneliness is awe-inspiring and it makes you realise just what you have back there on Earth." [1]

BANK OF ENGLAND PRUDENTIAL REGULATION AUTHORITY

FCA FINANCIAL CONDUCT AUTHORITY

FRC Financial Reporting Council

Institute and Faculty of Actuaries

The Pensions Regulator

[1] https://www.nasa.gov/multimedia/imagegallery/image_feature_1249.html

Climate Change Deep Dive: The Science of Climate Change

Introduction

In June 2021 the Joint Forum on Actuarial Regulation (JFAR) committed to a:

> **Climate Change Deep Dive focusing on bringing to life the 'science' of climate change. Our conjecture is that actuaries are well-aware that something is happening to the climate but are less familiar with the specifics of the science. The deep dive should build on work already done by actuaries and others and take the form of a meta-analysis of such work.**

The JFAR Risk Perspective 2021 stated: "Climate change risk affects all actuaries in all disciplines. It is imperative that all actuaries have some level of climate change risk knowledge to inform needed judgement."[2] This Climate Change Deep Dive is written with the aim to elevate the confidence of actuaries.

In August 2021 the Intergovernmental Panel on Climate Change (IPCC) released the first of three reports: *Climate Change 2021: The Physical Science Basis* (also known as AR6).[3] This deep dive draws on this report, but also supplements with many other sources. This deep dive has tightly focused on bringing to life the 'science' of climate change. Naturally the science of climate change sits in the broader context of JFAR member regulators' actions and their applicability to actuaries and the work performed by actuaries. We have not attempted to connect these, but extensive resources on this topic can be found in Section 10 (especially within the IFoA's Sustainability Board practical guides[4] and recent Risk Alert[5]).

The JFAR Climate Change Deep Dive working group consisted of Richard Hartigan (FRC), Caroline Winchester (IFoA), Alex Darsley (TPR), and David Berenbaum (FCA). The JFAR particularly thank Nick Spencer and Aled Jones for their thoughtful contributions to the final draft.

2 https://www.frc.org.uk/actuaries/actuarial-policy/jfar/jfar-risk-perspective-2021, p37

3 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf (delineated into a 41 page Summary for Policymakers (SPM), a 151 page Technical Summary (TS), and a 3,756 page main report including Supplementary Materials (SM) and Annexes). Note: AR6 sometimes refers to this report, produced by Working Group I (WG I), but AR6 is more-correctly used to refer (collectively) to reports produced by WG I (August 2021), WG II (February 2022, in final draft), and WG III (April 2022, in final draft). All three reports have been considered in this deep dive.

4 https://actuaries.org.uk/about-us/sustainability-hub/sustainability-practice-area-practical-guides/

5 https://www.actuaries.org.uk/system/files/field/document/2022%20Climate%20change%20and%20sustainability%20Risk%20Alert%20final.pdf

Although designed for actuaries, this deep dive will likely find broad interest among professionals wanting to increase their basic knowledge of climate change.

Section 1 defines climate change and **Section 2** explains the various greenhouse gases and the greenhouse effect. **Section 3** introduces the modelling aspects of climate science and related concepts such as Shared Socioeconomic Pathways. **Section 4** examines the impacts of climate change on the Earth system. **Section 5** links biodiversity to climate change, explaining that each has an impact on the other. **Section 6** documents tipping points – an abrupt and irreversible system reorganisation – a topic which may be of particular interest to actuaries designing Stress Tests. **Section 7** briefly addresses climate change mitigation and introduces the concepts of the 'carbon budget' and 'net zero'. **Section 8** is an acronym key and **Section 9** is a glossary. **Section 10** draws together this deep dive with the broader context of actuarial work.

Note: readers should not assume that the content of this deep dive represents the views of any particular JFAR member regulator.

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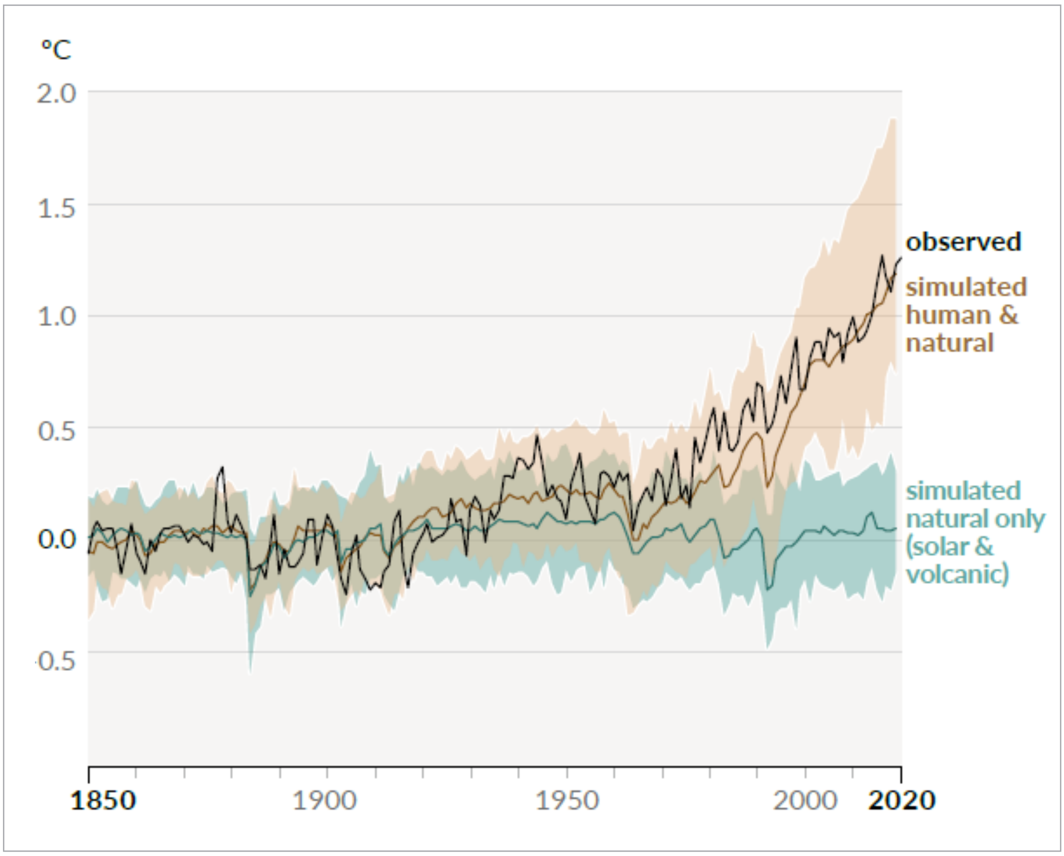
1 What is Climate Change (CC)?

"Climate change refers to long-term shifts in temperatures and weather patterns. These shifts may be natural, such as through variations in the solar cycle. But since the [mid-]1800s, human activities have been the main driver of climate change …"[6]



Change in global surface temperature (annual average) as observed and simulated using ***human & natural*** *and* ***only natural*** *factors (both 1850-2020)*[7]

Often the term 'anthropogenic climate change' will be used; this simply means that the climate change originates with, or is caused by, human activity.

Climate change results in more energy in the Earth system (one manifestation of which will be higher average temperatures). Per the IPCC: "the last time global surface temperature was sustained at or above 2.5°C higher than 1850-1900 was over 3 million years ago".[8]

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6 https://www.un.org/en/climatechange/what-is-climate-change
7 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, SPM-7 (PDF page 8)
8 Ibid., SPM-17 (PDF page 18) (with *medium confidence*)

2 Greenhouse Gases (GHGs)

2.1 The Greenhouse Effect

When sunlight hits the Earth, part of that energy is radiated back into space as infrared radiation. This lower wavelength radiation (unlike visible light) is absorbed by certain gases in the atmosphere, called greenhouse gases. The higher the concentration of GHGs in the atmosphere, the more infrared radiation (energy) is absorbed. Because more energy is then trapped on the Earth rather than being radiated back into space, the temperature of the Earth's atmosphere rises until it radiates enough heat to bring the energy flows into balance. This is the greenhouse effect.[9]

The vast majority of the Earth's atmosphere is made up of nitrogen (78%) and oxygen (21%)[10] which are not greenhouse gases (they are transparent to infrared radiation). Greenhouse gases only occur in trace amounts (0.1%), but have a dramatic effect. Without the greenhouse effect the average temperature of the Earth's surface would only be -18°C, rather than the actual 15°C.[11]

2.2 Main Greenhouse Gases

Some greenhouse gases occur naturally. However the primary focus of climate science is on those produced by human activity, or anthropogenic sources. Seven types of greenhouse gas are recognised in the Kyoto Protocol:[12]

- carbon dioxide (CO_2)
- methane (CH_4)
- nitrous oxide (N_2O)
- hydrofluorocarbons (HFCs)
- perfluorocarbons (PFCs)
- sulphur hexafluoride (SF_6)
- nitrogen trifluoride (NF_3)

(hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride: Fluorinated or F-gases)

Water vapour is also a powerful greenhouse gas, but human activity does not directly affect water vapour concentrations on a global scale.[13]

The impact of each greenhouse gas on global warming is determined by three factors:

- Amount emitted
- Lifetime in the atmosphere, known as the 'residence time'
- Efficiency in absorbing heat

9 https://www.britannica.com/science/greenhouse-effect
10 https://www.nationalgeographic.org/encyclopedia/atmosphere/
11 https://web.archive.org/web/20050112211604/http:/www.giss.nasa.gov/research/briefs/ma_01/
12 https://unfccc.int/kyoto_protocol; nitrogen trifluoride (NF_3) was added in the 2013 amendment: https://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf
13 https://en.wikipedia.org/wiki/Greenhouse_gas#Gases_in_Earth's_atmosphere

Combining the last two points (lifetime and efficiency) gives the Global Warming Potential (GWP). This is defined for a given time horizon and relative to the same mass of CO_2, which is defined to have a GWP = 1 over all time horizons. As an example, methane's (CH_4) initial impact is about 100 times greater than CO_2. However, it has a shorter lifetime in the atmosphere, so its GWP decreases as the time period increases. Conversely, sulphur hexafluoride (SF_6) has a longer lifetime than CO_2, so its GWP increases with time.

The following table summarises these properties for selected greenhouse gases.[14]

Greenhouse Gas	Lifetime (years)	Radiative Efficiency[15]	Global Warming Potential (GWP) for given time horizon		
			20-yr	100-yr	500-yr
carbon dioxide (CO_2)	*	1.33×10^{-5}	1	1	1
methane (CH_4)	12	3.88×10^{-4}	81	28	8
nitrous oxide (N_2O)	109	3.2×10^{-3}	273	273	130
sulphur hexafluoride (SF_6)	3,200	0.567	18,300	25,200	34,100
nitrogen trifluoride (NF_3)	569	0.204	13,400	17,400	18,200

* No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes. For other gases, a meaningful lifetime is easier to calculate because one process dominates their removal from the atmosphere. If one is forced to simplify reality into a single number then several hundred years is a sensible number.[16]

Despite the extremely high GWP figures above for sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) these gases are emitted in miniscule quantities; so, it is carbon dioxide (followed by methane, CH_4) that has the dominant effect on global warming.[17]

2.3 Which human activity produces Greenhouse Gases?

Annex I Parties[18] — Total GHG emissions with LULUCF[19] — Unit: CO_2 equivalent[20]

	% Total (2019)	Human Activities
CO_2	77.2%	power generation, transportation, industrial sources, chemical production, petroleum production, and agricultural practices
CH_4	13.0%	landfills, oil and natural gas systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes
N_2O	6.9%	agriculture, energy use, industrial processes, and waste management
HFCs	2.7%	refrigeration and air-conditioning, aerosols
PFCs	0.1%	aluminium production, semiconductor manufacturing
SF_6	0.1%	transmission and distribution of electricity
NF_3	0.0%	manufacturing of flat-panel displays, photovoltaics, LEDs, and other microelectronics

14 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 7SM-24 & 7SM-29 (PDF pages 1842 & 1847)
15 $W{\cdot}m^{-2}{\cdot}ppb^{-1}$, molar basis
16 https://blogs.edf.org/climate411/2008/02/26/ghg_lifetimes/
17 https://www.pbl.nl/sites/default/files/downloads/pbl-2020-trends-in-global-co2-and-total-greenhouse-gas-emissions-2019-report_4068.pdf, p4 (excluding GHG emissions from land-use change)
18 Annex I Parties include the industrialised countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties)
19 LULUCF = land use, land-use change and forestry (activities)
20 https://di.unfccc.int/comparison_by_gas

It is important to differentiate between GHG emissions and GHG atmospheric concentration. GHGs remain in the atmosphere for an extended period of time (see Page 8). GHG emissions measure CO_2 emissions at a given point-in-time (e.g. 2019). GHG atmospheric concentration measures the cumulative effect of GHG emissions.

2.4 Other drivers of global temperatures

The following table briefly summarises some other factors that influence global temperatures.[21]

Factor	Net effect	Notes
Mainly natural causes		
Water vapour	Warming (significant)	• Largest contributor to greenhouse effect • Human activity doesn't directly impact global concentrations • Warmer air can hold more water vapour, so there is a feedback effect which amplifies other drivers
Solar radiation	Either way (small)	• The Sun has a natural cycle of emitting more or less radiation; small effect compared to other factors • Changes in the Earth's orbit have a larger effect over very long timescales (tens of thousands of years), influencing ice ages and interglacial periods
Mainly human causes		
Ozone (O_3)	Warming	• Produced indirectly by reacting with other man-made chemicals
Aerosols	Cooling (net)	• Aerosols are any suspension of very small particles in the air. Produced naturally (e.g. volcanoes) and artificially (e.g. burning coal) • Different aerosols can serve to reflect sunlight (cooling effect) or absorb sunlight (warming) • Can also encourage cloud formation which leads to more reflection of sunlight (cooling effect)
Reflectance of the Earth's surface ('surface albedo')	Unclear	• Clearance of forests means more sunlight is reflected, giving a cooling effect • Blackening of ice by soot falling on it absorbs more sunlight, giving a warming effect
Aircraft contrails[22]	Warming (net, small)	• Can trap heat in the atmosphere (warming effect) and cause more reflection of sunlight (cooling)

2.5 Attribution of global warming to anthropogenic GHG emissions

Climate science is a highly complex, specialised field and cannot be fully covered on these pages. Many factors affect global temperatures including offsetting positive and negative effects, amplifications, and feedback loops.

However, we can unequivocally say that the combined impact of all types of human activity is having a significant global warming effect. The largest factor is the emission of greenhouse gases, and in turn the largest component of greenhouse gas emissions is carbon dioxide. As such, the high profile of carbon dioxide (and corresponding language like 'decarbonisation', 'carbon neutral', etc.) is reasonable. Nonetheless, all GHGs are equally important (after adjusting for GWP) i.e. CO_2 equivalent.

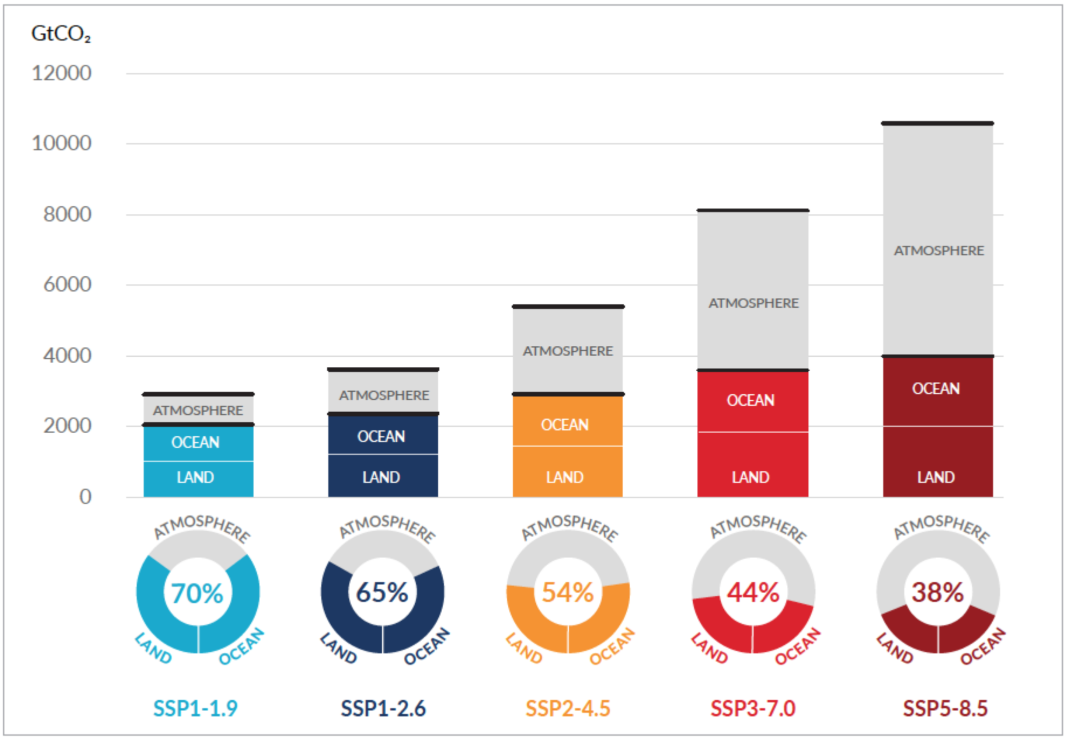
[21] https://sdgacademylibrary.mediaspace.kaltura.com/media/The%20Greenhouse%20Gases%20and%20Feedbacks/1_u867ijl2/123651041 (from 11:20 to 19:58 in this video)
[22] https://earthdata.nasa.gov/learn/sensing-our-planet/on-the-trail-of-contrails

"Human influence on the climate system is now an established fact: The Fourth Assessment Report (AR4) stated in 2007 that 'warming of the climate system is unequivocal', and the AR5 stated in 2013 that 'human influence on the climate system is clear'. Combined evidence from across the climate system strengthens this finding. It is unequivocal that the increase of CO_2, methane (CH_4), and nitrous oxide (N_2O) in the atmosphere over the industrial era is the result of human activities and that human influence is the principal driver of many changes observed across the atmosphere, ocean, cryosphere, and biosphere."[23]

The IPCC AR6 WG II report (February 2022, in final draft) went further: "The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all."[24]

2.6 Carbon sinks

Historically, natural carbon sinks on land (vegetation and soils) and in the ocean have absorbed about half of the CO_2 emitted by human activities. This has served to slow down the increase of CO_2 in the atmosphere and so dampen the impact on global warming.[25] However, as more CO_2 is released, the *proportion* absorbed by land and ocean sinks reduces, leading to a gearing effect on the proportion remaining in the atmosphere, as shown in the figure below. This effect must be considered when setting future emissions targets.



Total cumulative CO_2 emissions taken up by land and oceans (colours) and remaining in the atmosphere (grey) under the five illustrative scenarios from 1850 to 2100 [26]
(See Section 3.3, below, for a discussion on Shared Socioeconomic Pathways (SSPs))

23 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-8 (PDF page 51)
24 https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf, SPM-35 (PDF page 36)
25 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 5-116 (PDF page 1268) (FAQ 5.1)
26 Ibid., SPM-27 (PDF page 28)

3 Climate modelling and scenarios

3.1 Coupled Model Intercomparison Project (CMIP)

Climate science is a highly complex, specialised field. Climate scientists develop and use climate change models to assess the effect of climate change on various aspects of the Earth system (e.g. temperature). At the forefront of this effort is the Coupled Model Intercomparison Project (CMIP).

At its simplest the CMIP compares multiple climate change models under various fixed experimental criteria to allow comparisons between the models, and better understand model performance. "This understanding includes assessments of model performance during the historical period and quantifications of the causes of the spread in future projections."[27]

The CMIP recognises the significant uncertainty in climate change modelling and additionally the significant uncertainty in predicting future human behaviour, and through formal knowledge-sharing seeks to continually refine existing models to reduce that uncertainty.

For a good introductory guide to climate change modelling Dr Tamsin Edwards of King's College London (from 3:20 to 26:40 in this video[28]) speaks at some length on how climate change modellers deal with significant uncertainty.

3.2 Representative Concentration Pathway (RCP)

Representative Concentration Pathways (RCPs) are trajectories for greenhouse gas atmospheric concentrations. RCPs are measured in watts per square metre ($W \cdot m^{-2}$).

RCPs provide for a pathway from the current GHG atmospheric concentration to some future GHG atmospheric concentration (the year 2100 is commonly quoted). RCPs measure GHG atmospheric concentration, not GHG emissions.

3.3 Shared Socioeconomic Pathway (SSP)

Shared Socioeconomic Pathways (SSPs) are five narrative-based deterministic scenarios describing alternative socioeconomic developments. They may be thought of as successors to RCPs.

"Shared Socioeconomic Pathways look at five different ways in which the world might evolve in the absence of climate policy and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with the SSPs."[29]

27 https://www.wcrp-climate.org/wgcm-cmip
28 https://www.youtube.com/watch?v=h2P_pkRQnKs
29 https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

SSP1: Sustainability – Taking the Green Road (low challenges to mitigation and adaptation)

SSP2: Middle of the Road (medium challenges to mitigation and adaptation)

SSP3: Regional Rivalry – A Rocky Road (high challenges to mitigation and adaptation)

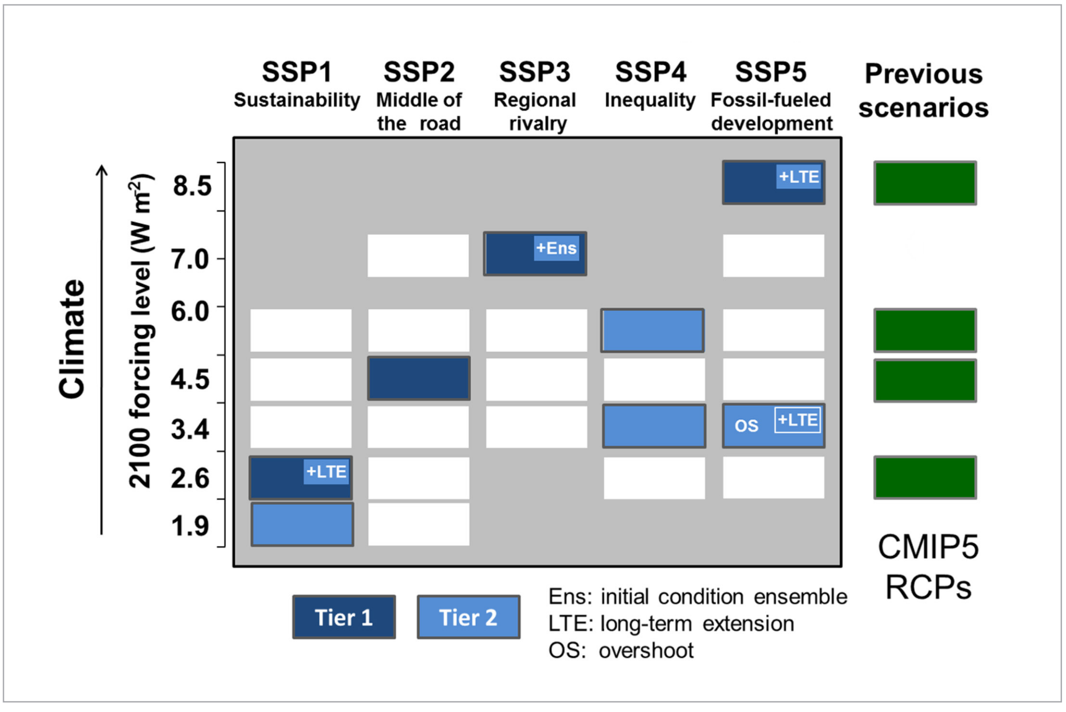
SSP4: Inequality – A Road Divided (low challenges to mitigation, high challenges to adaptation)

SSP5: Fossil-fuelled Development – Taking the Highway (high challenges to mitigation, low challenges to adaptation)[30]

Often rather than just citing (for example) SSP3, one will see SSP3-7.0. The 7.0 refers to "the approximate target level of radiative forcing (in watts per square metre, $W{\cdot}m^{-2}$) resulting from the scenario in the year 2100."[31]

"Projections of future climate change play a fundamental role in improving understanding of the climate system as well as characterising societal risks and response options."[32] The activities described in the video referenced in Section 3.1, above, use SSPs and RCPs as a 'base', permitting "multi-model climate projections based on alternative scenarios of future emissions and land use changes produced with integrated assessment models."[33]

A summary of the most-commonly modelled SSP-RCP combinations follows:

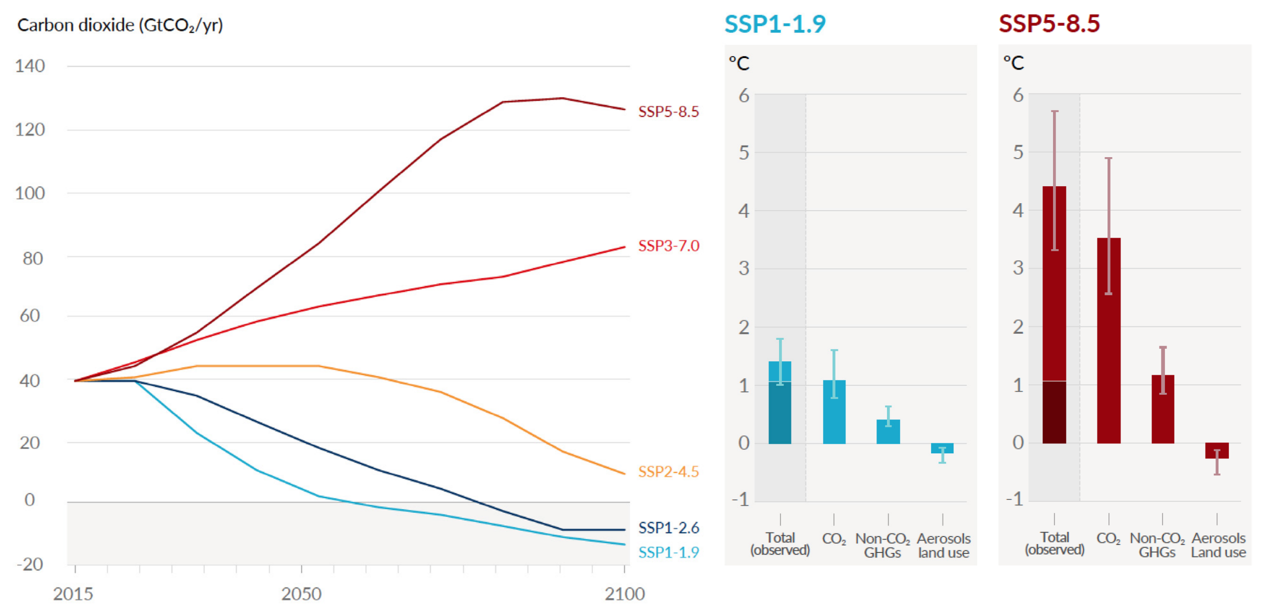


SSP-RCP scenario matrix illustrating CMIP6 simulations[34]*: **Tier 1** is the priority*

[30] Ibid.
[31] https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-22 (PDF page 65)
[32] https://gmd.copernicus.org/articles/9/3461/2016/gmd-9-3461-2016.pdf, p3461 (PDF page 1)
[33] Ibid.
[34] Ibid., p3470 (PDF page 10)

There is a strong link between SSPs, the resultant GHG atmospheric concentration in the year 2100 from a given narrative of human behaviour, and the resultant rise in global temperatures from a given GHG atmospheric concentration in the year 2100. Due to time lags in reaching equilibrium, global temperatures will still be higher in 2100 than 2022, even in the RCP1.9 scenario (as shown in the second graph, below).

A radiative forcing reading (in the year 2100) of 1.9 $W{\cdot}m^{-2}$ would be considered 'very low' and 8.5 $W{\cdot}m^{-2}$ would be considered 'very high'. The current (2019) reading is 2.72 $W{\cdot}m^{-2}$.[35]



Note (1): the y-axis on the left-hand side of the first graph represents CO_2 emissions, whereas the figures on the right-hand side of the first graph (8.5, 7.0, 4.5, 2.6, 1.9) represent radiative forcing in 2100. The darker shading in the second and third graphs is 'to date', relative to 1850-1900.

Note (2): observe that from approximately 2050 that CO_2 emissions under the SSP1 pathway turn negative: this is due to enhancing carbon sinks.

[36]

3.4 Other modelling scenarios

The IPCC's modelling scenarios are widely-used, but many other modelling scenarios have also been developed, often for specific and targeted purposes.

For example, the Bank of England's Climate Biennial Exploratory Scenario (CBES)[37] exercise referred to early / late / no additional policy action scenarios. The Network for Greening the Financial System (NGFS) scenarios[38] are described as orderly / disorderly / hot house world / too little, too late. All approaches essentially try to capture the same circumstances.

35 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-35 (PDF page 78)
36 Ibid., SPM-16 (PDF page 17)
37 https://www.bankofengland.co.uk/paper/2019/biennial-exploratory-scenario-climate-change-discussion-paper
38 https://www.ngfs.net/ngfs-scenarios-portal/

4 Impacts on the Earth system

4.1 Global temperatures

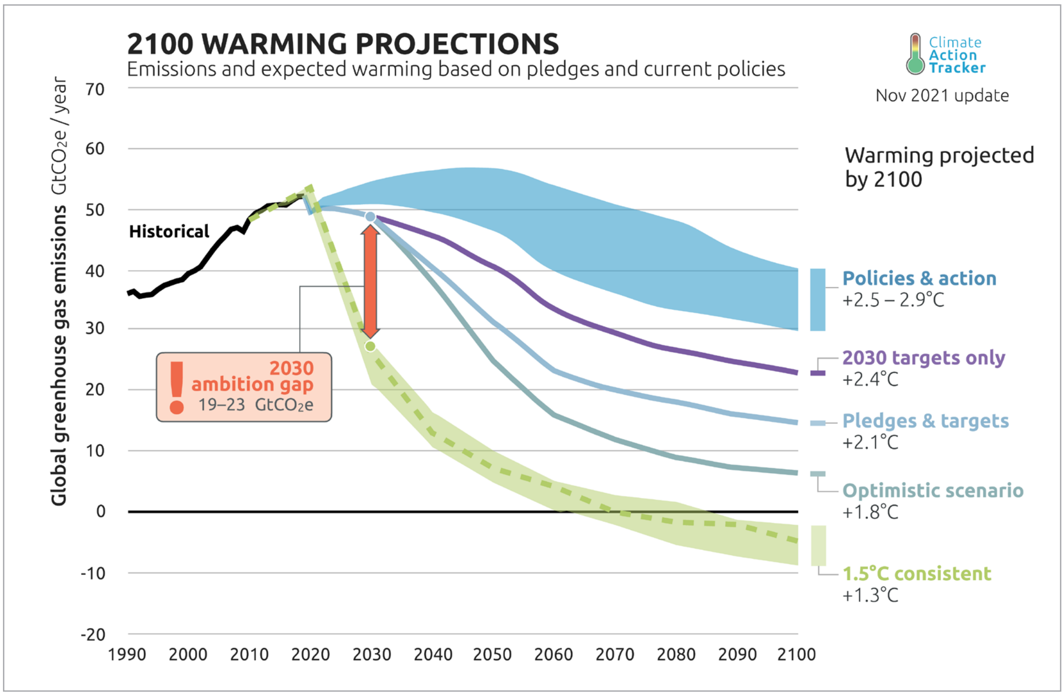
Spencer Glendon of Probable Futures[39] gives a fantastic summary of climate change impacts on land temperatures (from 12:12 to 33:00 in this video[40]).

> "Civilisation *only* exists under a stable climate.
> In climate instability people become nomadic." [this is at 27:00 in the video]

Principle among climate change impacts on land temperatures is likely massive human migration, as "climate change could bring near-unliveable conditions for 3 billion people. Each degree [°C] of warming above present levels corresponds to roughly 1 billion people falling outside of the 'climate niche'."[41]

"… the majority of humans live in a very narrow mean annual temperature band of 11°C-15°C (52°F-59°F). Researchers noted that despite all innovations and migrations, people had mostly lived in these climate conditions for several thousand years. "This strikingly constant climate niche[42] likely represents fundamental constraints on what humans need to survive and thrive," said Professor Marten Scheffer of Wageningen University."

Climate Action Tracker[43] calculates 2100 Warming Projections based on various adjustments of human behaviour and co-ordinated global efforts in response to climate change.



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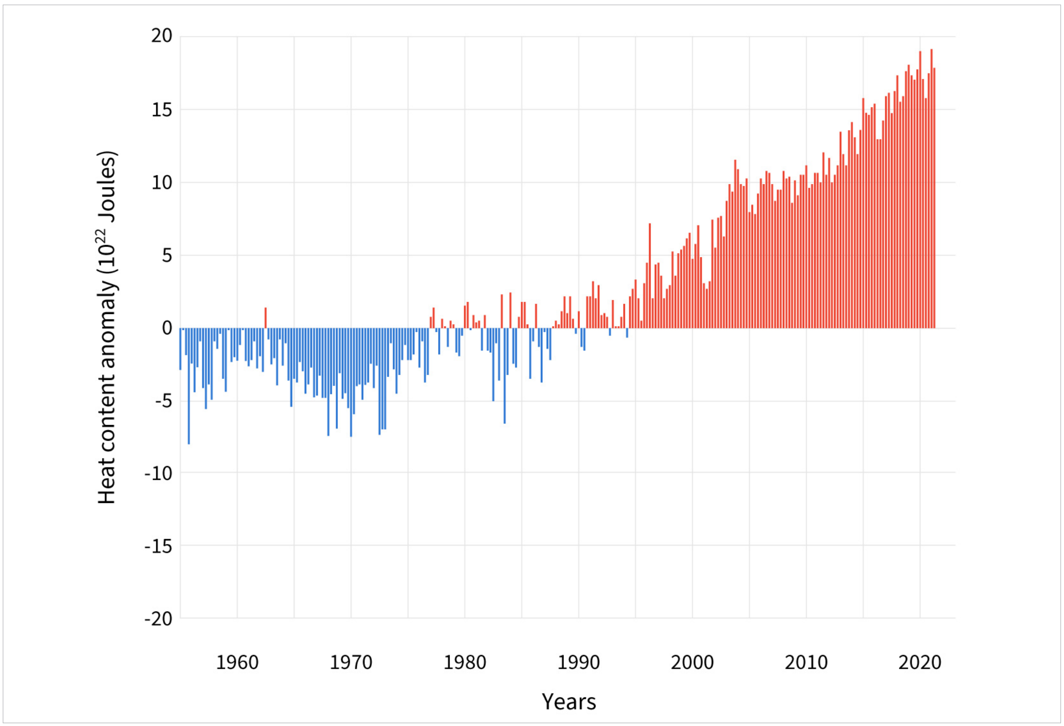
[39] https://probablefutures.org/
[40] https://players.brightcove.net/5716634434001/YaL1J8g8di_default/index.html?videoId=6260857412001
[41] https://www.ft.com/content/072b5c87-7330-459b-a947-be6767a1099d
[42] https://www.pnas.org/content/117/21/11350
[43] https://climateactiontracker.org/global/temperatures/
[44] https://climateactiontracker.org/media/images/CAT-2100WarmingProjectionsGraph-PNG-2021.11.original.png

4.2 Impact on the oceans

More than 90 percent of the excess heat trapped in the Earth system due to human-caused global warming has been absorbed by the oceans.[45]



Ocean heat compared to average [46]

The rate of ocean heat content has doubled over the past few decades and over a third of this accumulated heat is stored below 700m. This excess energy means "the deep ocean is expected to continue to warm and expand for centuries to millennia to come, leading to long-term sea level rise – even if atmospheric greenhouse gas levels were to decline."[47]

Warmer water holds less soluble oxygen and leads to greater stratification of the ocean. The reduction in circulation between upper and lower waters impacts the oxygen exchange between the atmosphere and the sea, increasing the stress on marine life. This is compounded by eutrophication (increased nutrient run-off from land and sewage pollution) and nitrogen deposition. The outcome is that "global [oceanic] oxygen inventory has decreased by ~2% over the period 1960 to 2010".[48]

Increased ocean temperature is the leading cause of coral bleaching. Coral reefs are home to a quarter of all marine species and hundreds of millions of people around the world depend on them for food, jobs, and protection from storms and erosion. When they get stressed, corals expel the algae (zooxanthellae) living in their tissues, causing them to turn completely white. Corals can survive a bleaching event, but it leaves them weakened. The *Status of Coral Reefs of the World: 2020*[49] report "documents the loss of approximately 14 per cent of the world's coral since 2009."[50]

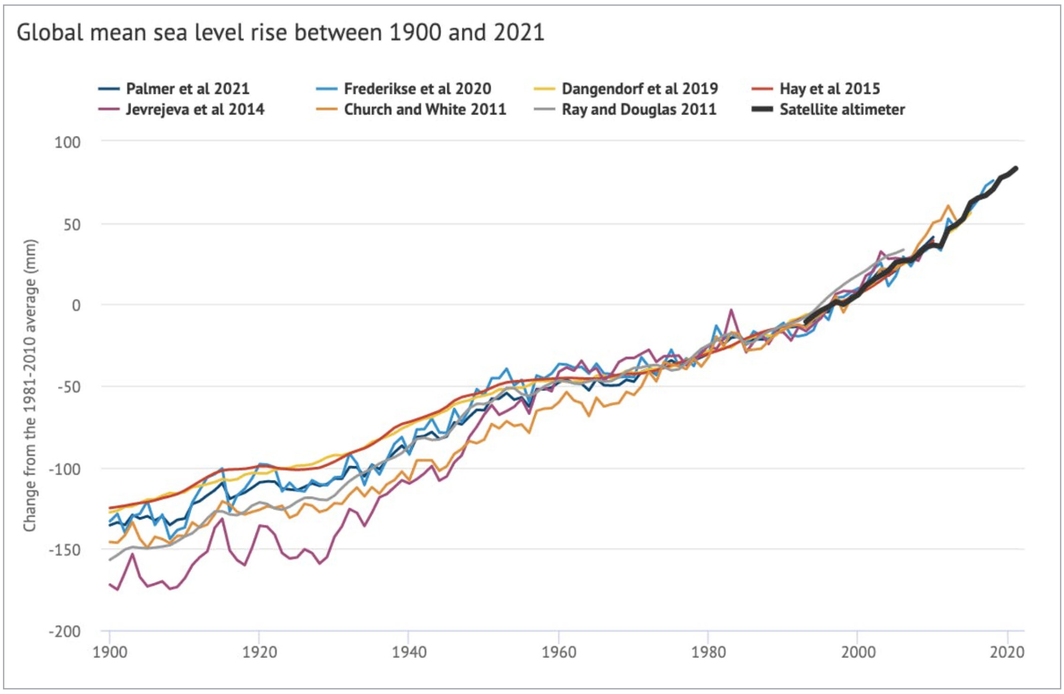
45 https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content
46 https://www.climate.gov/media/13603
47 https://www.metoffice.gov.uk/weather/climate-change/organisations-and-reports/earths-energy-budget-and-climate-sensitivity
48 https://portals.iucn.org/library/node/48892, p25 (PDF page 49)
49 https://www.unep.org/resources/status-coral-reefs-world-2020
50 https://www.unep.org/news-and-stories/press-release/rising-sea-surface-temperatures-driving-loss-14-percent-corals-2009

Since about 1950 many marine species have undergone shifts in geographical range and seasonal activities in response to ocean warming, sea ice change, and biogeochemical changes to their habitats. The IPCC predicts that throughout the 21st century fish stocks will continue to decline and their composition and range change under all emission scenarios.[51]

4.3 Sea levels

"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%."[52]

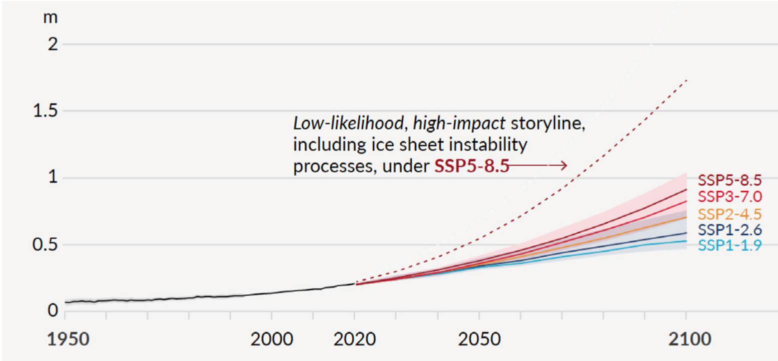
Thermal expansion, melting glaciers and ice sheets, and changes in land water storage have already led to a sea level rise of "around 0.2m (200mm) since 1900".[53] Observed annual global mean sea level (GMSL) rise has accelerated to 3.69mm per year during the period 2006-2018.[54]



55

The IPCC expects global mean sea level to rise a further 0.32-0.62m this century under the low GHG emissions scenario (SSP1-2.6), and 0.63-1.01m under the very high GHG emissions scenario (SSP5-8.5).[56] The sea level rise at a particular location will depend on a number of factors, including the degree of land uplift or fall.

51 https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf, p22
52 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, SPM-14 (PDF page 15)
53 https://www.carbonbrief.org/state-of-the-climate-how-the-world-warmed-in-2021
54 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 9-98 (PDF page 2248)
55 https://www.eco-business.com/news/state-of-the-climate-how-the-world-warmed-in-2021/
56 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, SPM-28 (PDF page 29) (relative to 1995-2014)



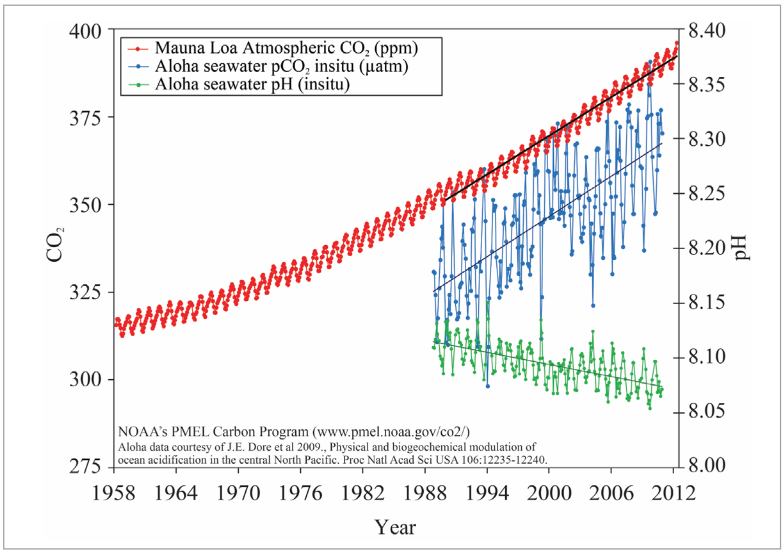
Global mean sea level change relative to 1900 [57]

These estimates do not include earlier-than-projected disintegration of marine ice sheets or the Greenland Ice Sheet. Such low-likelihood, high-impact processes could, in combination, add more than a metre of sea level rise by 2100. Beyond 2100, global sea levels will continue to rise for centuries to millennia due to continuing deep ocean heat uptake and mass loss from ice sheets. The IPCC indicates a "committed long-term GMSL [global mean sea level] rise over 10,000 years, reaching about 8-13m for sustained peak global warming of 2°C and to 28-37m for 5°C".[58]

Extreme sea level events that, until recently, were once-in-a-century occurrences are projected to occur at least once per year at many locations by 2050 in all scenarios, especially in tropical regions. Carbon Brief estimates that coastal flooding in Europe alone could cost up to €1 trillion per year by 2100.[59]

4.4 Ocean acidification

The ocean currently absorbs about 30% of the carbon dioxide that is released in the atmosphere. Water and carbon dioxide combine to form carbonic acid, acidifying the oceans. Over the past 200 years, "the pH of surface ocean waters has fallen by 0.1 pH units … this change represents approximately a 30 percent increase in acidity." [60]



CO_2 Time Series in the North Pacific [61]

57 Ibid., SPM-29 (PDF page 30)
58 Ibid., TS-14 (PDF page 57)
59 https://www.carbonbrief.org/coastal-flooding-in-europe-could-cost-up-to-one-trillion-euros-per-year-by-2100
60 https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification
61 https://pmel.noaa.gov/co2/file/CO2+time+series

The absorption of CO_2 results in fewer carbonate ions available for calcifying organisms to build and maintain their shells, skeletons, and other calcium carbonate structures. If the pH gets too low, shells and skeletons can begin to dissolve.

4.5 Regional variation

The impact of the various trends outlined elsewhere in this deep dive will have significantly different impacts by regions, due to the nature of the changes. Therefore, climate change is likely to have a far more significant impact for particular areas across the world depending on which factors those regions exhibit. Some of the key regional variations are highlighted in this section.

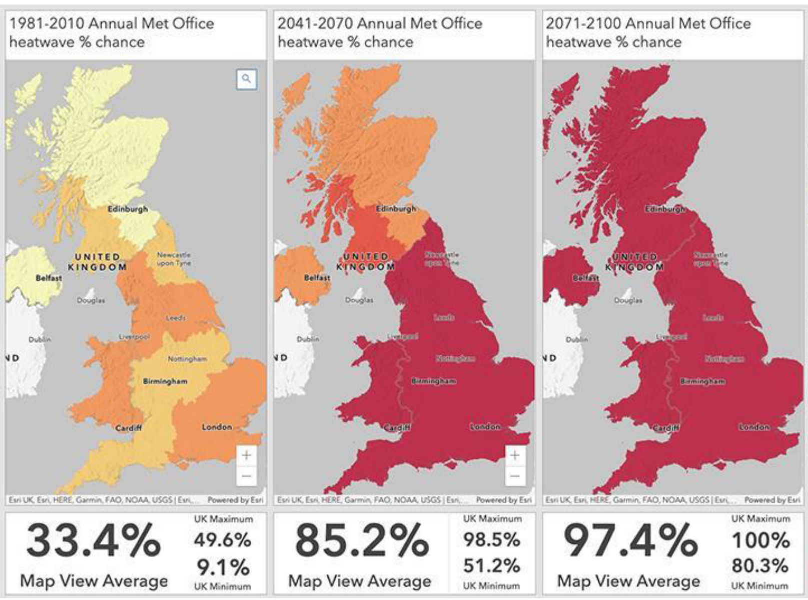
- **Ocean versus continental** – oceans warm more slowly than land. Consequently, the middles of continents are expected to warm more than coastal areas.
- **Latitude** – higher latitudes (i.e. those areas closer to the Arctic) see their temperatures warming more than near the equator. This is also likely to see a greater increase in precipitation levels at higher latitudes, over-and-above the average 3-5% global increase predicted this century.
- **Polar and Arctic regions** – there are complex issues seen at the two Poles which have been warming twice as quickly as the rest of the world. This trend will continue with melting glaciers a key feature. Sea ice has been reducing quite rapidly in recent years and may disappear in summertime by end of the century. In addition, permafrost provides solid ground for building and roads (e.g. in Siberia, Canada) but this could thaw and could release methane (CH_4), which adds to greenhouse gas emissions. Offsetting these trends, to a certain extent, is the likelihood of increasing snowfall so the net outcome is somewhat unclear. This issue is covered in more detail in Section 4.6 below.
- **Equatorial regions** – regions near the Equator, being at lower latitudes, expect to experience decreasing precipitation. The impact in Africa alone could leave up to 250 million people vulnerable to drought by end of this century. Reduced precipitation is likely to lead to a lack of clean fresh water, which is expected to become a particular issue in Asia leading to an increase in illnesses due to unclean water.
- **Urbanised areas** – the increase in rainfall is likely to come with heavy downpours interspersed with longer drier spells, which will be more pronounced where land use has changed and where greater urbanisation and deforestation has taken place. This in turn is expected to adversely impact local agriculture and ecosystems.
- **Low-lying areas** – low-lying areas, particularly those in low-latitude and mid-latitude regions are expected to suffer more-frequent and deeper droughts. Alongside that, there is also an associated risk of wildfires in these regions. A further implication will be the risk of saltwater coming into inland estuaries, harming ecosystems. Low-lying coastal regions are therefore at risk from rising sea levels, though this will depend on the topology of the land.

It is anticipated that large areas of nations such as Bangladesh, Netherlands, many Pacific Islands, and parts of the southern USA are at great risk due to only being a few feet above sea level. In extreme cases, there are concerns that entire Pacific nations could disappear early in the next century. This issue is considered in more detail in Section 4.3 above.

- **High-altitude areas** – glaciers are retreating and melting, and this is expected to impact those communities which are largely reliant on glacial waters for drinking and agriculture (e.g. in the Himalayan and Andean regions). The reduction in available water supplies will affect ecosystems, threaten species that live at high-altitude, and are likely to lead to increased levels of disease from unclean water. In areas at lower levels, faster rates of snow melting could lead to more flooding, for example in South Asia.
- **Hurricane and storm regions** – areas already prone to hurricanes and monsoons will see risks increase, impacted by higher temperatures at sea, from where hurricanes derive their energy. Reductions in extreme weather (e.g. monsoons in India) may also negatively impact agriculture. There is also likely to be a higher risk of more rain with hurricanes in a warmer global climate (warmer weather means hurricanes can carry more water vapour). There are six main hurricane regions around the world, and each may be affected differently due to location and storm patterns. Storms may move into higher-latitude areas, and into areas where they haven't previously been, as oceans warm. Cyclical phenomena such as El Niño and monsoons in South Asia may also change in nature, with potential effects further afield.

Impact on the UK and Europe

Europe (and especially the UK) is likely to be less impacted by many of the trends identified above than many other parts of the world. Some lesser-known tipping points (not discussed elsewhere in this deep dive) may result in Europe getting much colder.



Annual likelihood of reaching maximum temperature above region-specific thresholds (25°C-28°C) for at least 3 consecutive days [62]

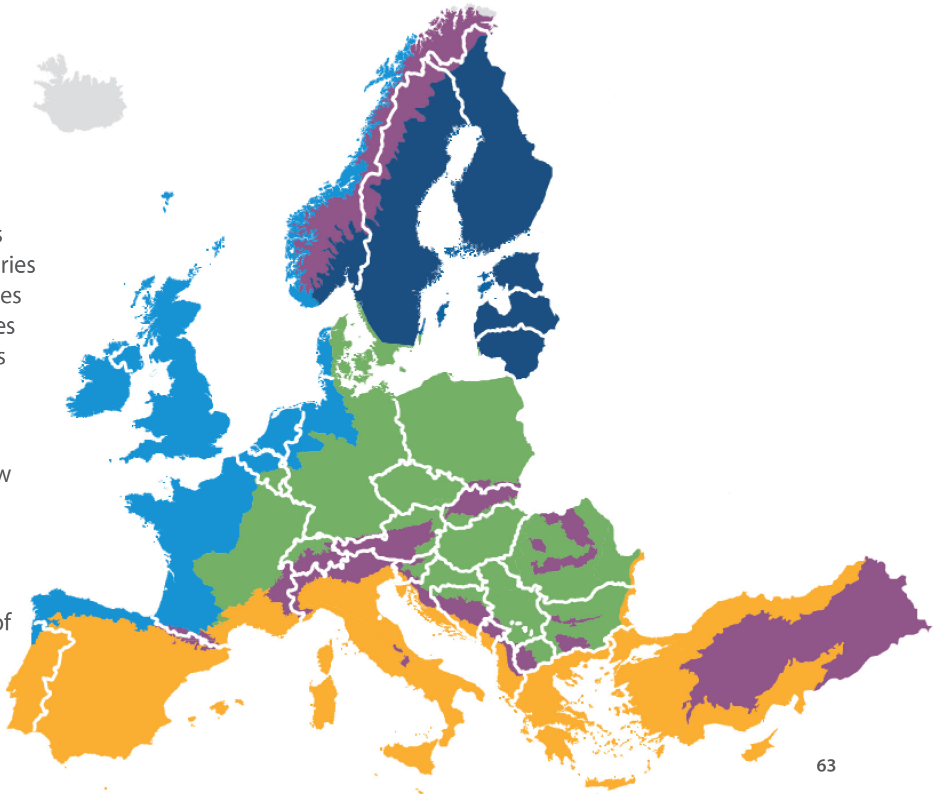
On a global scale the physical impacts of climate change in the UK are modest. One likely development in the UK will be an increase in the regularity of heatwaves as shown, left. Temperatures close to 40°C have already been recorded during recent summers. This in turn is starting to result in an increase in wildfires.

[62] https://www.sec-ed.co.uk/resources-products/cop26-climate-change-resources-met-office-esri-uk-geography-1/

Winter storms and flooding are getting worse and happening more often, as experienced by the spate of storms in February 2022. These have been causing increasing levels of damage to property and leading to some risks being seen as uninsurable.

More storms, plus sea level rises, are gradually eroding coastlines around the UK. Norfolk is one part of the UK that is facing sea level rise and erosion, and storms have led to the collapse of coastal railway lines in areas such as Devon and Cornwall. These changes are starting to impact various animal and plant species which are increasingly facing loss of habitat.

Across Europe there will be a variety of trends that are likely to develop, as shown below.



[63]

Coastal zones and regional seas

- Sea level rise
- Increase in sea surface temperatures
- Increase in ocean acidity
- Northward migration of marine species
- Risks and some opportunities for fisheries
- Changes in phytoplankton communities
- Increasing number of marine dead zones
- Increasing risk of water-borne diseases

Mediterranean region

- Large increase in heat extremes
- Decrease in precipitation and river flow
- Increasing risk of forest fires
- Increased competition between different water users
- Increase in mortality from heatwaves
- High vulnerability to spillover effects of climate change from outside Europe

[note: this list has been trimmed: see footnote 63 for the full list]

Atlantic region

- Increase in heavy precipitation events
- Increase in river flow
- Increasing risk of river and coastal flooding
- Increasing damage risk from winter storms
- Decrease in energy demand for heating
- Increase in multiple climatic hazards

Continental region

- Increase in heat extremes
- Decrease in summer precipitation
- Increasing risk of river floods
- Increasing risk of forest fires
- Decrease in economic value of forests
- Increase in energy demand for cooling

Boreal region

- Increase in heavy precipitation events
- Decrease in snow, lake, and river ice cover
- Increase in precipitation and river flows
- Increasing potential for forest growth and increasing risk of forest pests
- Increasing damage risk from winter storms
- Increase in crop yields
- Decrease in energy demand for heating
- Increase in hydropower potential
- Increase in summer tourism

Mountain regions

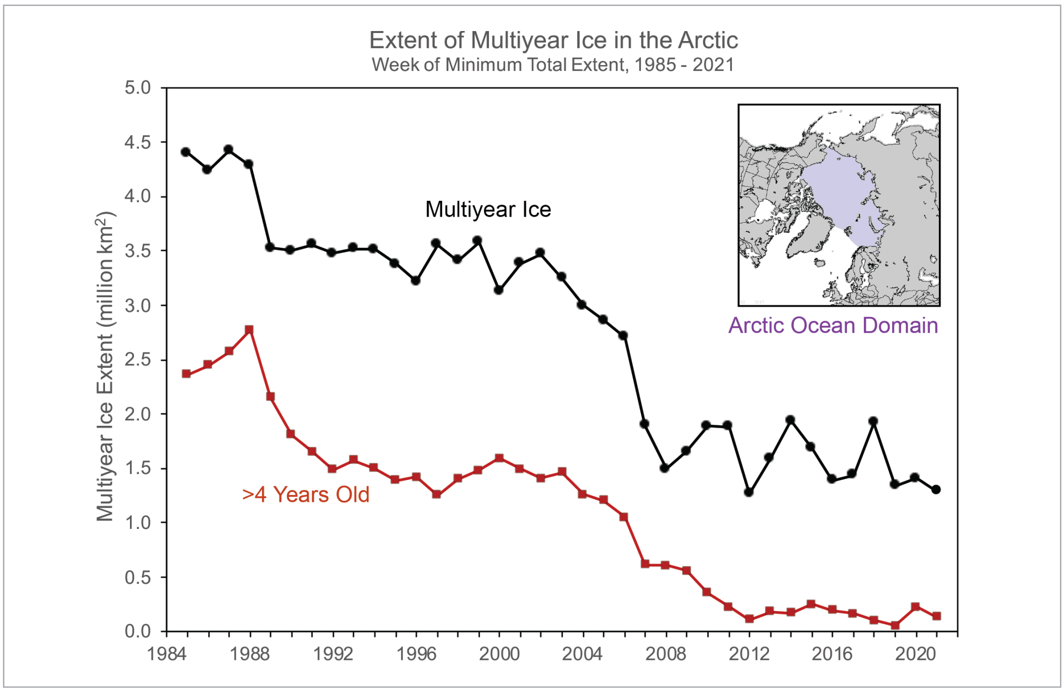
- Temperature rise larger than European average
- Decrease in glacier extent and volume
- Upward shift of plant and animal species
- High risk of species extinctions
- Increasing risk of forest pests
- Increasing risk from rock falls and landslides
- Changes in hydropower potential
- Decrease in ski tourism

[63] https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016, p25

4.6 Polar ice

Arctic sea ice in the summer is now smaller than any time in the last 1000 years. The "summer Arctic sea ice area has reduced by approximately 40% since 1979."[64] The "average thickness near the end of the melt season … decreased by 2.0m or some 66% over six decades".[65]

"The Arctic is likely to be practically sea ice free in September at least once before 2050"[66] and in the winter will be "thinner and more fragile than it used to be".[67] If global warming continues and we reach 3°C or 4°C, it would be ice-free most summers, if not all.



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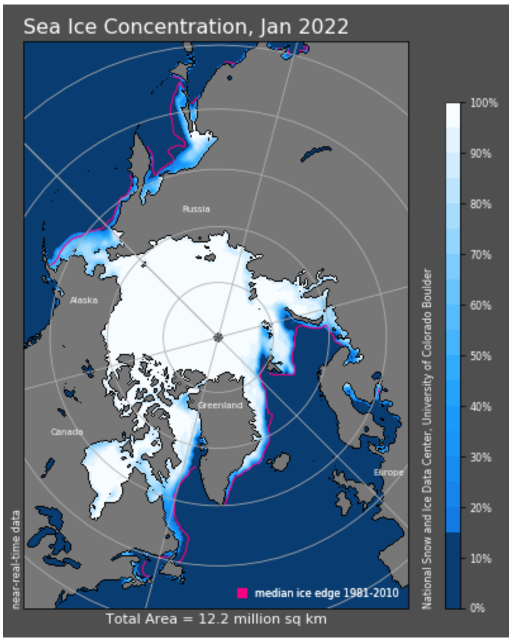
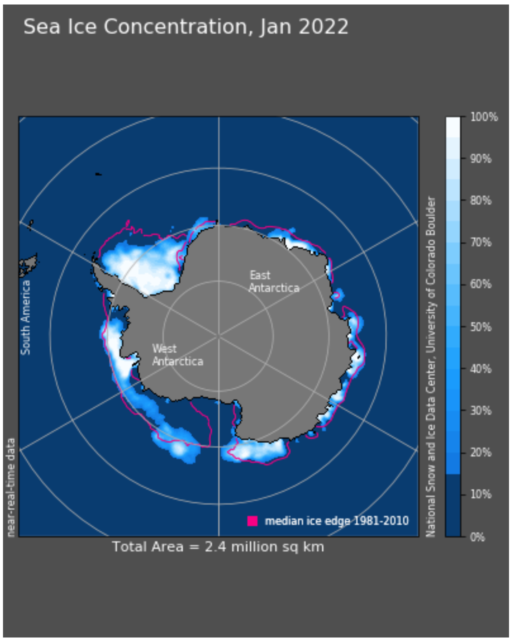
The loss of sea ice amplifies global warming by losing the reflective cover over the polar north. As sea ice melts in the summer it exposes the dark ocean surface. Instead of reflecting 80% of the sunlight, the ocean absorbs 90% of the sunlight, heating it up. "The Arctic is currently warming on average more than twice the global mean, with some regions experiencing even higher rates."[69]

Warmer meltwater impacts the ocean's thermohaline circulation[70] which draws dissolved gases such as carbon dioxide and oxygen into the deep ocean. Warm water is less dense than cold water and fresh water is less dense than salty, so the circulation slows, leading to increased areas of low oxygen. Less carbon dioxide is drawn down and stored in the deep ocean,[71] resulting in increased carbon dioxide in our surface waters and acidification. As the ocean absorbs less CO_2, more is left in the atmosphere.

64 https://www.eumetsat.int/state-arctic-and-antarctic-sea-ice-2021
65 https://iopscience.iop.org/article/10.1088/1748-9326/aae3ec
66 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, SPM-20 (PDF page 21)
67 https://www.climate.gov/news-features/understanding-climate/climate-change-arctic-sea-ice-summer-minimum
68 https://arctic.noaa.gov/Report-Card/Report-Card-2021/ArtMID/8022/ArticleID/945/Sea-Ice
69 https://www.researchgate.net/publication/343298299_Past_perspectives_on_the_present_era_of_abrupt_Arctic_climate_change
70 https://oceanservice.noaa.gov/education/tutorial_currents/05conveyor1.html#:~:text=Thermohaline%20circulation%20
71 https://www.floridamuseum.ufl.edu/earth-systems/blog/climate-change-is-weakening-the-oceans-currents-heres-why-that-matters/

Without the cooling effect of polar ice caps, latent heat would expand "into the higher latitude, increasing the extent of storms."[72] In the Arctic, the ocean energy being released causes a weakening of the polar vortex winds, which normally keep cold air centred over the polar region, allowing them to slip through the jet stream. A growing body of research shows a correlation between Arctic sea ice loss and more-frequent "polar vortex disruptions that result in severe winter weather in mid-latitude regions."[73] A stratospheric polar vortex disruption was linked to the February 2021 North American cold wave.





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Melting land-based ice causes sea levels to rise. "Over the period 1992-2020, Greenland likely lost 4890 ± 460 gigatonnes of ice, contributing 13.5 ± 1.3mm to global mean sea level rise."[74] The rate of ice loss is accelerating. Thriving ecosystems, which have been supported by the upwelling of nutrients at the edge of glaciers, are at risk as glaciers retreat inland. The IPCC notes that "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".[75]

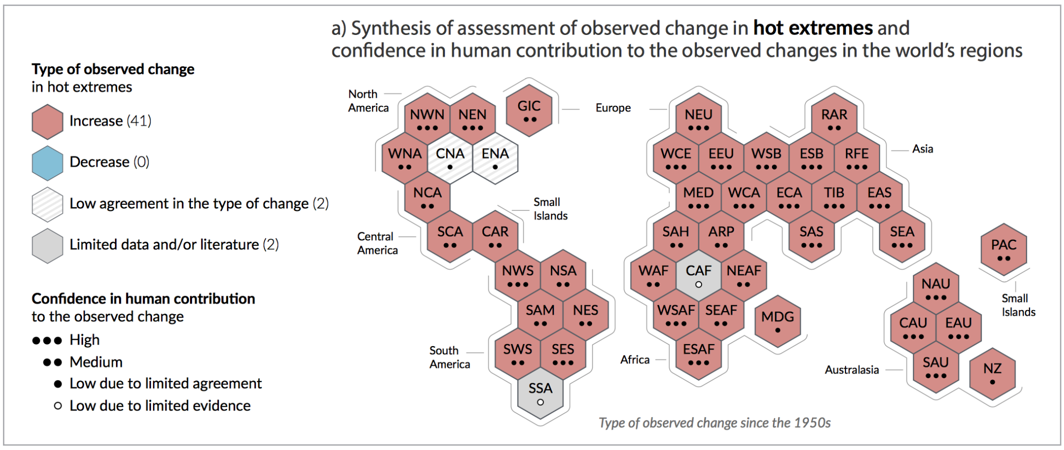
Unlike the Arctic, Antarctica has not shown a clear declining trend in sea ice area. This is because of regionally opposing trends and large internal variability. The "Antarctic Ice Sheet has lost 2670 ± 530 gigatonnes, contributing 7.4 ± 1.5mm to global mean sea level rise over 1992-2020".[77] But while the West Antarctic Ice Sheet and parts of the East Antarctic Ice Sheet have lost ice mass, "snowfall has likely increased over the western Antarctic Peninsula and eastern West Antarctica, with large spatial and interannual variability over the rest of Antarctica."[78]

The IPCC notes there "is only limited evidence, with medium agreement, of anthropogenic forcing of the observed Antarctic mass loss since 1992."[79] However, the IPCC predicts "increasing mass loss from ice shelves [mainly induced by ice shelf basal melt] and inland discharge will likely continue to outpace increasing snowfall over the 21st century".[80] In late-February 2022 the Antarctica Sea Ice Extent dropped to its lowest level since satellite monitoring began.[81]

72 Ibid.
73 https://www.climatesignals.org/events/polar-vortex-breakdown-and-central-us-winter-storms-february-2021#/more
74 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-43 (PDF page 86)
75 Ibid., SPM-9 (PDF page 10)
76 https://nsidc.org/data/seaice_index
77 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-44 (PDF page 87)
78 Ibid.
79 Ibid.
80 Ibid.
81 https://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/

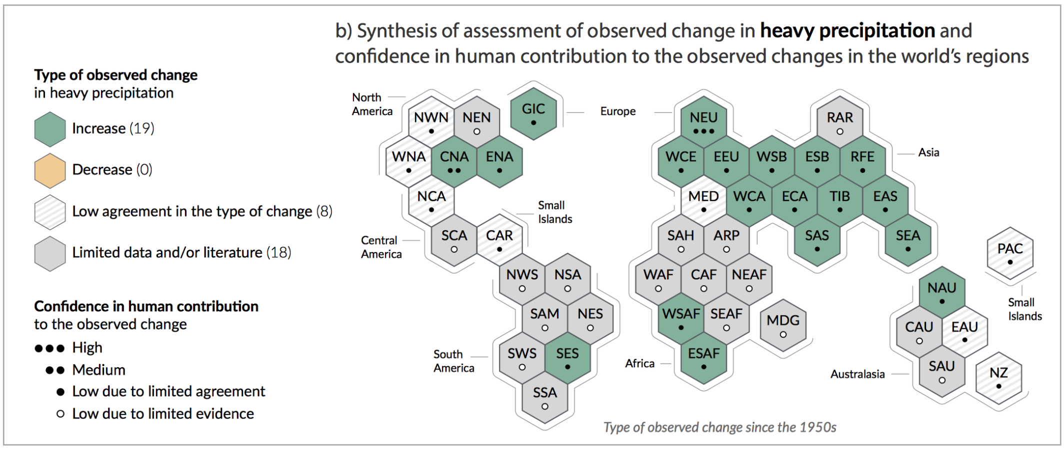
4.7 Extreme weather (hot extremes, heavy precipitation, drought)

Since the 1950s there has been a near-global observed increase in hot extremes, almost all attributed to human contribution with a high level of confidence.



82

Since the 1950s there has been an observed increase in heavy precipitation, attributed to human contribution with a low-medium level of confidence.



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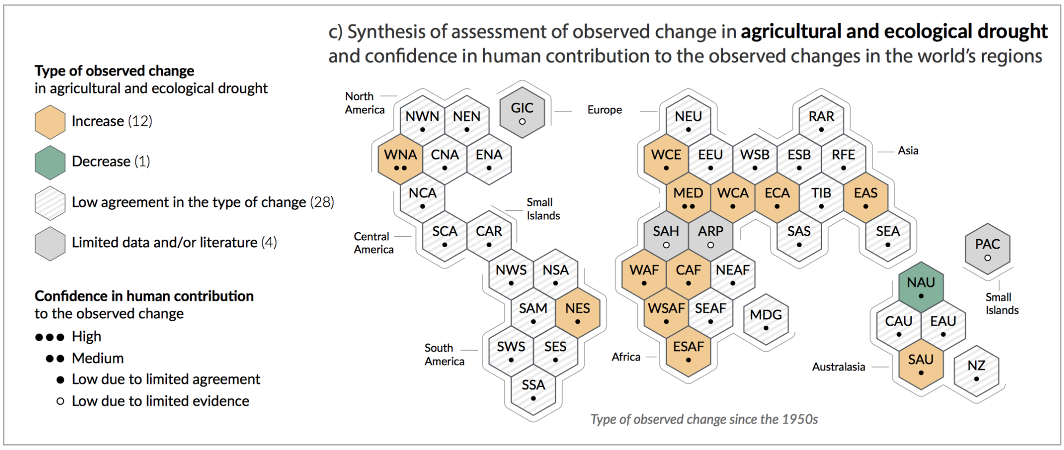
Since the 1950s there has been an observed increase in agricultural and ecological droughts,[84] attributed to human contribution with a low-medium level of confidence.



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82 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, SPM-12 (PDF page 13)
83 Ibid.
84 Ibid., SPM-10 (PDF page 11)
85 Ibid., SPM-12 (PDF page 13)

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

4.8 Food security / production

The central place in human existence of food security and food production is explicitly recognised by the Paris Agreement (PA).[86] This recognised the particular vulnerabilities of food production systems to the adverse impacts of climate change. Climate change poses various challenges to farmers, and to the larger communities that depend on them for food. Some of these challenges are already being experienced:

- More extreme weather harming livestock, soil, and crops (e.g. storms and winds).
- Water scarcity making it more difficult to sustain crops and livestock.
- Changes to seasons, with growing seasons starting earlier and getting hotter.
- Increases in wildfires can decimate land and hay stocks, for example.
- Warmer weather can adversely affect food supply, safety, and quality.
- Heat induced agricultural labour productivity reduction.
- Contamination of seafood from harmful algae and chemicals.
- Changes in weather and temperatures altering which crops are most efficient in a certain location (and difficulty in substituting to new more-efficient crops, especially due to supply chain constraints).

[86] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, recitals and Article 2 1.(b)

Climate-related risk to food security can arise from potential climate change impacts and responses to climate change and can be exacerbated by other stressors. The impact is complex as some adverse factors which lead to reducing yields (e.g. drought, temperature extremes, humidity) could be moderated to some extent by factors which may help to increase yields (e.g. increased CO_2 fertilisation). There is also the potential for indirect climate-related impacts (e.g. pest outbreaks triggered by ecosystem responses to weather patterns).

The overall impact will be dependent on the exposure of people (e.g. how many people depend on a particular crop) and vulnerability or adaptability (how able affected people are to substitute other sources of food, which may in turn be related to financial access and markets).

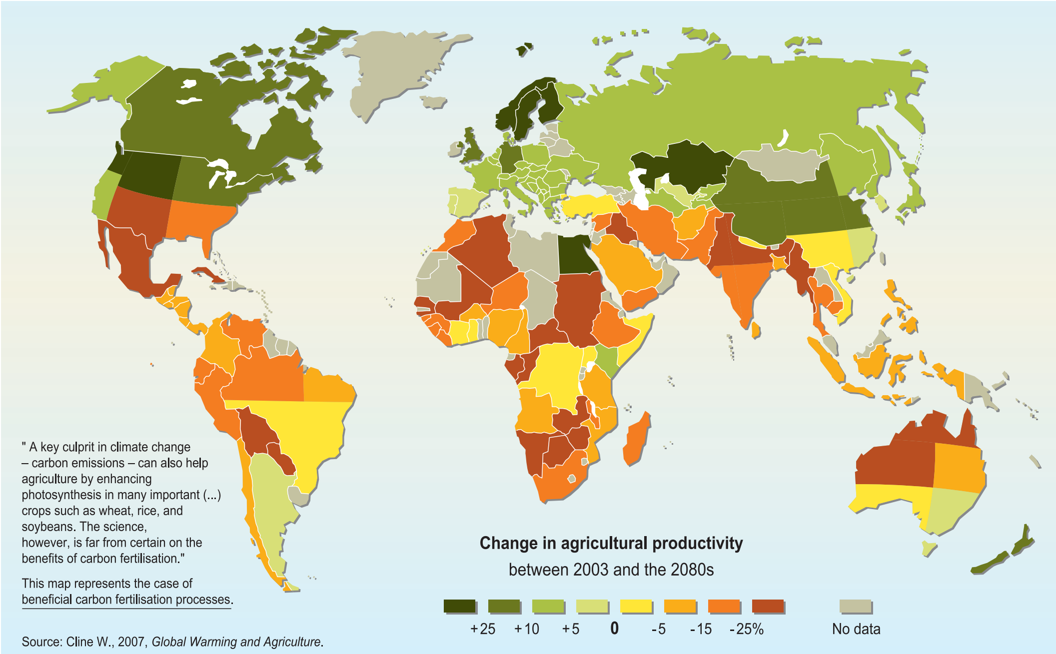
The Special Report on Climate Change and Land (SRCCL) observed that climate change "has already affected food security due to warming, changing precipitation patterns, and greater frequency of some extreme events".[87] Some of the key findings:

- Changing precipitation patterns, and greater frequency of some extreme events.
- Yields of some crops (e.g. maize and wheat) in many lower-latitude regions have been affected negatively by observed climate changes.
- However, in many higher-latitude regions, yields of some crops (e.g. maize, wheat, and sugar beets) have been affected positively over recent decades.
- Climate change has resulted in lower animal growth rates and productivity in pastoral systems in Africa.
- There is strong evidence that agricultural pests and diseases have already responded to climate change resulting in both increases and decreases of infestations.
- Climate change is affecting food security in drylands, particularly those in Africa, and high mountain regions of Asia and South America.

The IPCC notes that these trends have accelerated. It noted that, by the middle of the century, climate change "will increasingly put pressure on food production and access, especially in vulnerable regions", and "concentrated in sub-Saharan Africa, South Asia, Central and South America, and Small Islands."[88]

The impact on agricultural yields in Africa will be particularly acute. On the current emissions trajectory substantial maize and bean growing areas will go out of production. This will mean that certain parts of Africa will become uninhabitable. The impact on agricultural yields will vary by region, as illustrated below.

87 https://www.ipcc.ch/site/assets/uploads/sites/4/2021/07/210714-IPCCJ7230-SRCCL-Complete-BOOK-HRES.pdf, p8
88 https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf, SPM-14 (PDF page 15)



Projected impact of climate change on agricultural yields [89]

4.9 Human health / mortality

The impact of climate change on human health can be considered as applying in three distinct ways. The impact will be direct on death rates but also on wider health impacts, leading to increased burdens on health systems:

(a) The impact of extreme events

This arises from the impact of extreme events such as heatwaves, droughts, and storms. Evidence to date already shows that the number of heatwave-related deaths in some regions has been starting to rise in the past decade. More people are starting to be affected by the hazards arising from hurricanes, flooding, wildfires, and similar extreme climate events. Over time, the greater frequency of drought, as covered in Section 4.7 above, is likely to see malnutrition rates in lower-latitude areas rise, and this trend has already started to be seen.

For some regions there may be some health benefits that do arise from climate change; for instance, fewer cold-related deaths may occur, and there may be an increase in the growth of crops in higher-latitude areas. However, on a global basis, any such positive impacts on health that may arise are likely to be outweighed by negative impacts on health.

Environmental degradation could also lead to forced migration which in turn could also lead to civil conflict (see Section 4.1 above), with secondary impacts on mental health for those affected.

(b) The impact of disease from transmission

This arises from the increase in prevalence of diseases such as malaria and dengue fever which only thrive in certain conditions (e.g. higher rainfall, see Section 4.7 above), and which are expected to increase with climate change.

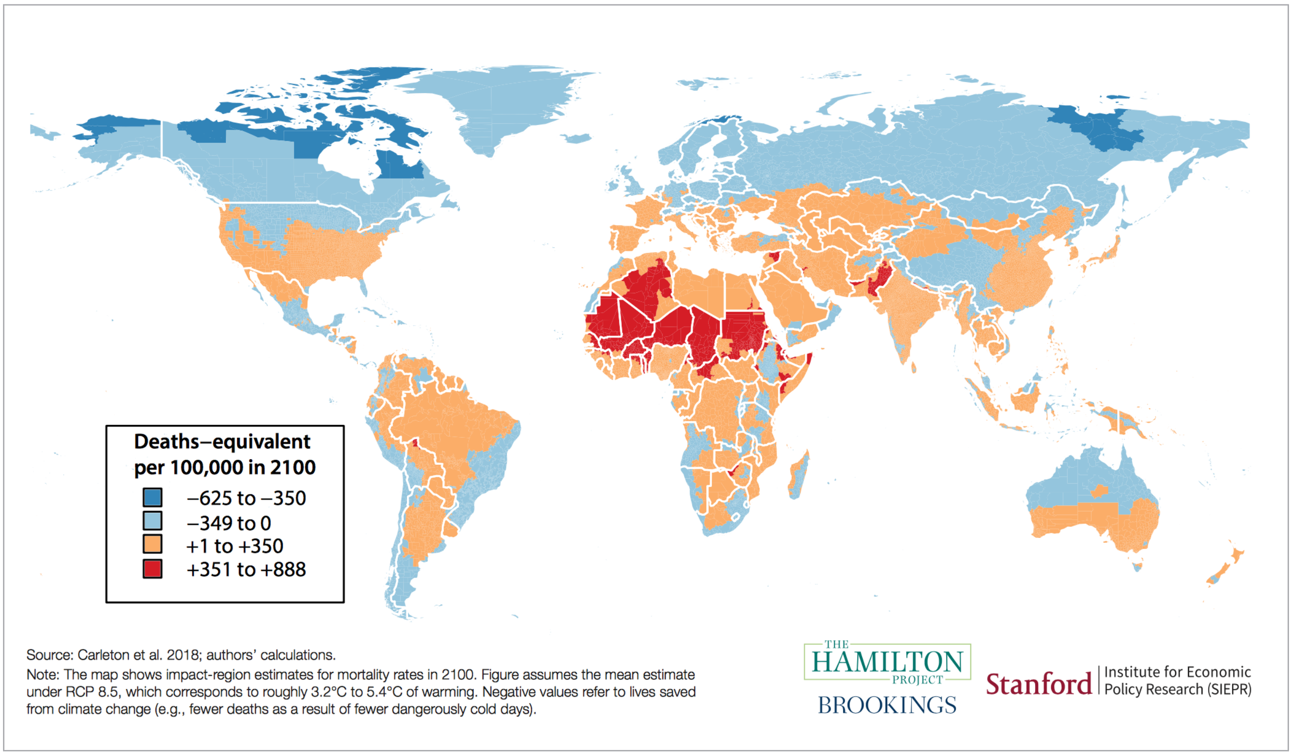
[89] https://www.eea.europa.eu/data-and-maps/figures/projected-impact-of-climate-change

There is already some evidence that climate change is having an impact in this respect; for instance, there is evidence that certain insects carrying disease are now being found in areas that were previously considered too cold for those insects to survive in, such as in Andean regions.

(c) The impact of water-related illnesses

Reduced water supply will arise from increased occurrences of flooding and drought, as well as changes to the patterns of melting of glaciers and snow, and rising sea levels. This will in turn lead to greater dependence, for both consumption and cleaning, on unclean water supplies. This will in turn also have an impact on food supply with resultant health issues (malnutrition, etc.).

The expected mortality impact by region can be seen from the following chart:



[89]

Mortality impacts from climate change in 2100 by region

[90] https://www.brookings.edu/research/ten-facts-about-the-economics-of-climate-change-and-climate-policy/

5 Biodiversity

Biodiversity loss is a major global challenge distinct from climate change – but the two are inextricably linked.

Biodiversity is defined – from the Convention for Biological Diversity[91] – as the diversity of species, variation of genes and different ecosystems. "All societies depend on biodiversity for their very survival, but the biosphere is declining faster than at any time in human history (IPBES, 2019). In the last 50 years, global wildlife populations have declined by 60%, leading to a global environmental crisis which is often referred to as the 6th mass extinction."[92] "Current extinction rates of species in various orders are estimated to have risen to 100-1,000 times the average extinction rate over the past tens of millions of years".[93]

Climate change is one of the factors leading to this decline in biodiversity (but not the only factor or even the main one – other drivers include changes in land use, pollution, and invasive species). However, "climate change may become the major driver of biodiversity loss in the coming decades."[94]

How climate change contributes to biodiversity loss

- Temperature increases – species must migrate if they are not adapted to the changing temperatures
- Change in precipitation patterns
- Increased frequency of natural disasters (e.g. wildfires, drought, flooding) – physically damaging or destroying ecosystems
- Increased CO_2 concentrations leading to ocean acidification – damaging coral reef ecosystems (see Section 4.4 above)
- Any combination of the above causing an ecosystem to cross a 'tipping point' – e.g. the Amazon shifting from rainforest to savannah (see Section 6 below)

How biodiversity loss contributes to climate change

This issue is the more critical because the causal link also works in the other direction – biodiversity loss itself contributes to climate change. This includes direct CO_2 emissions due to deforestation – the "Amazon rainforest, for example, contains an amount of carbon equivalent to a decade of global human emissions".[95] Marine and terrestrial ecosystems act as sinks for carbon dioxide, sequestering 60% of global anthropogenic emissions.[96] The loss of biodiversity also reduces the capacity of ecosystems for this sequestration, so hindering one of our options for managing CO_2 emissions.

91 https://www.cbd.int/
92 https://wwfeu.awsassets.panda.org/downloads/nature_is_too_big_to_fail_en_web.pdf, p7
93 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/962785/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf, p104
94 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882222/The_Economics_of_Biodiversity_The_Dasgupta_Review_Interim_Report.pdf, p2
95 Ibid., p10
96 https://wwfeu.awsassets.panda.org/downloads/nature_is_too_big_to_fail_en_web.pdf, p10

The two-way relationship between these twin challenges leads to the risk of a positive feedback spiral, accelerating changes in both areas, but also means that well-designed nature-based mitigation options can deliver complementary benefits.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), established in 2012, builds on the IPCC model of a science-policy interface and assessment.[97]

Readers wishing to explore this topic further can find further resources on the Institute and Faculty of Actuaries' biodiversity curated library.[98]

97 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 1-28 (PDF page 222)
98 https://www.actuaries.org.uk/learn-and-develop/lifelong-learning/sustainability-and-lifelong-learning/biodiversity

6 Nonlinearity and tipping points

A tipping point[99] is a critical threshold beyond which a system reorganises abruptly and irreversibly. This can take several years up to millennia, depending on the response times of the system. Natural fluctuations can be the final nudge for a tipping point pushed to the brink by anthropogenic (human-induced) climate change.

Researchers use ancient geological and observational data along with climate modelling to project tipping points. Large uncertainties in future projections still remain, with knowledge gaps in atmospheric (Greenland) and oceanic (Antarctic) forcing. Future emissions pathways are uncertain and climate models, although relatively complex, inevitably simplify processes. The climate system is chaotic, with exceptionally warm or exceptionally cold years compared to the background trend. Nevertheless, observational data shows we are now closer to tipping points than previously thought, with more than half of the climate tipping points identified a decade ago now 'active'.[100]

Tipping Element	Threshold temperature, °C[101]
Arctic Winter Sea Ice	6.3 (4.5-8.7) **
Greenland Ice Sheets	1.6 (0.8-3.2) **
West Antarctic Ice Sheet	1.5 (1.0-3.0) **
East Antarctic sub-glacial basins	3.0 (2.0-6.0) *
East Antarctic land-based Ice Sheet	7.0 (5.0-10.0) *
Arctic Permafrost Thaw	4.0 (3.0-6.0) *
Atlantic Meridional Overturning Circulation	5.0 (3.0-8.0)
Warm-water coral reefs	1.5 (1.0-2.0) **
Boreal Forest Dieback	3.5 (3.0-5.0)
Amazon Forest Dieback	4.0 (2.0-6.2) *

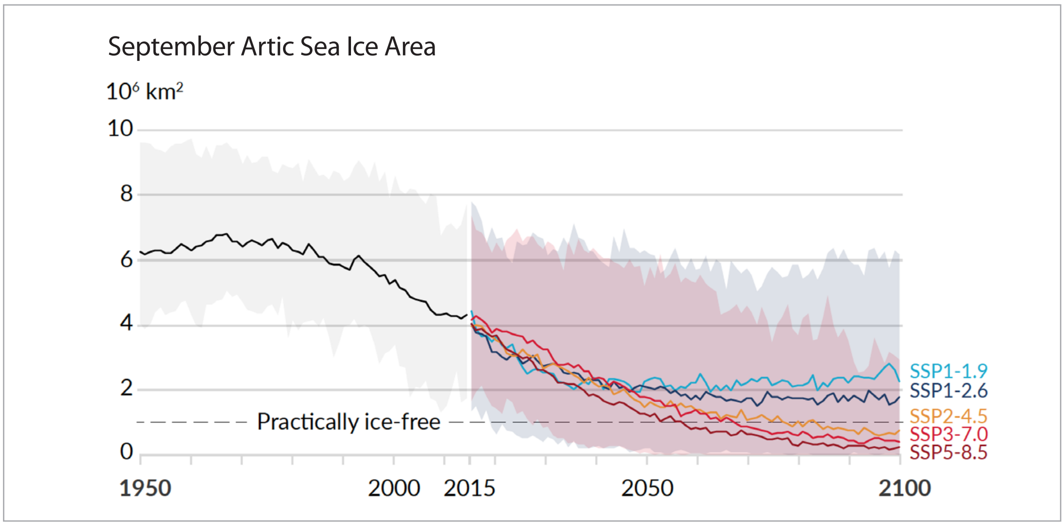
Confidence: ** = high, * = medium, none = low

The IPCC expects "a near-linear dependence of global temperature on cumulative GHG emissions" in the next century.[102] However, the IPCC now includes low-likelihood, high-impact projections, as it believes these "cannot be excluded, especially at global warming levels above 4°C."[103] Interacting tipping elements could lead to a domino effect with non-linear cascades that amplify climate change.

99 https://www.nature.com/articles/d41586-019-03595-0
100 https://www.sciencedaily.com/releases/2019/11/191127161418.htm
101 https://presentations.copernicus.org/EGU2020/EGU2020-17889_presentation.pdf, Slide 10, and https://www.researchgate.net/publication/357287728_Updated_assessment_suggests_15C_global_warming_could_trigger_multiple_climate_tipping_points, pp71&73
102 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 1-66 (PDF page 260)
103 Ibid., 11-10 (PDF page 2780)

Arctic sea ice

Arctic summer sea ice has been declining rapidly since the 1970s and at a faster pace than previously thought.[104] There is high confidence that occasional ice-free Septembers will occur above 1.7°C (1.3°C-2.0°C).[105] However, models suggest this summer ice loss is gradual,[106] and the IPCC does not view this as a tipping point: "Arctic summer sea ice varies approximately linearly with global surface temperature, implying that there is no tipping point and observed / projected losses are potentially reversible".[107]



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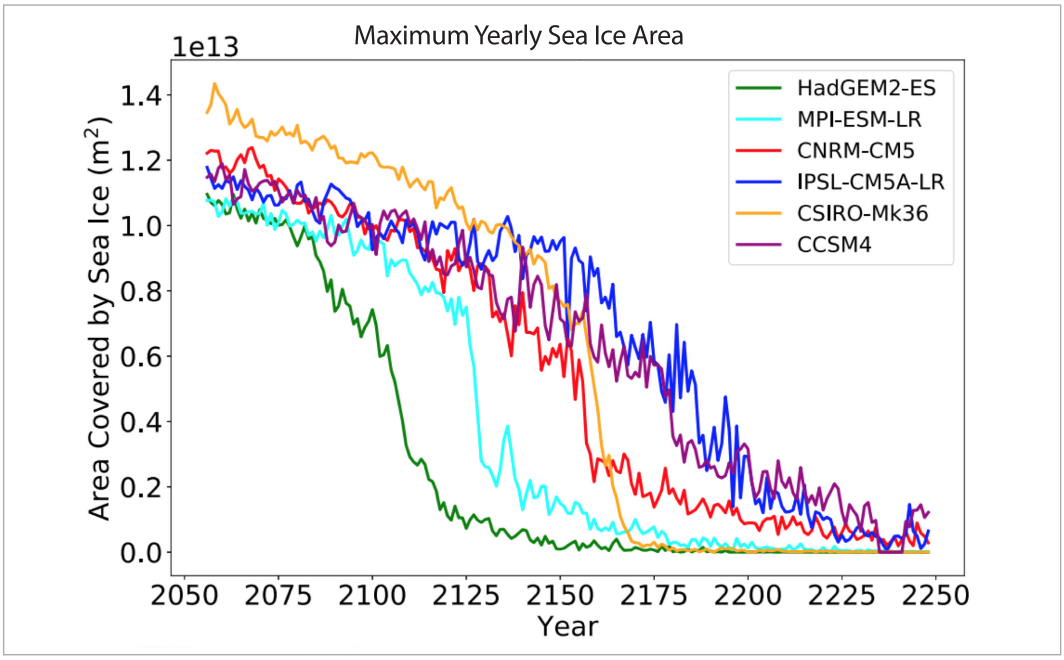
Under a RCP8.5 scenario, however, some models project an abrupt loss of winter sea ice, which would indicate a threshold or tipping point.



Yearly maximum sea ice area evolution in the extended RCP8.5 scenario for the six models[109]

104 https://www.scientistswarning.org/2022/01/12/arctic-death-spiral/
105 https://presentations.copernicus.org/EGU2020/EGU2020-17889_presentation.pdf, Slide 10
106 https://doi.org/10.1175/JCLI-D-20-0558.1
107 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-43 (PDF page 86)
108 Ibid., SPM-29 (PDF page 30)
109 https://doi.org/10.1175/JCLI-D-20-0558.1

This would happen if the Arctic Ocean is no longer cold enough to form winter ice, but could also be impacted by local feedbacks, including increased convective clouds (which absorb outgoing longwave radiation and emit some back to the Earth)[110] and wintertime increases in longwave clear-sky radiation due to a moister and warmer atmosphere, followed by lower springtime surface albedo due to reduced sea ice growth.[111] The science around this is still uncertain, and the IPCC notes a "low confidence in simulations of ice-sheet instabilities, ice-shelf disintegration, and basal melting owing to their high sensitivity to both uncertain oceanic forcing and uncertain boundary conditions and parameters".[112]

Greenland Ice Sheets

The western Greenland Ice Sheet has been losing stability in response to rising temperatures.[113] Melting reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. Other "regional factors such as the melt-albedo feedback, glacier algae growth, cloud phase feedbacks, and atmospheric circulation changes"[114] are also important.

84% of Greenland's decrease in ice mass since 2009 is due to surface runoff,[115] and the IPCC expects this decrease to continue under all emissions scenarios. Near-complete loss of the Greenland Ice Sheet is forecast to occur at 3°C-5°C, and possibly between 2°C and 3°C.[116] This would be irreversible over multiple millennia. Other models give a critical threshold of 1.6°C (0.8°C-3.2°C),[117] or 2.7°C ± 0.2°C.[118]

Depending on the emissions scenario, Greenland's melting ice sheet is expected to increase sea level by 6-13cm by the year 2100.[119] A complete melting of the Greenland Ice Sheet could cause a global sea level rise of more than 7m.[120] It would impact other tipping elements, most notably the Atlantic Meridional Overturning Circulation.[121]

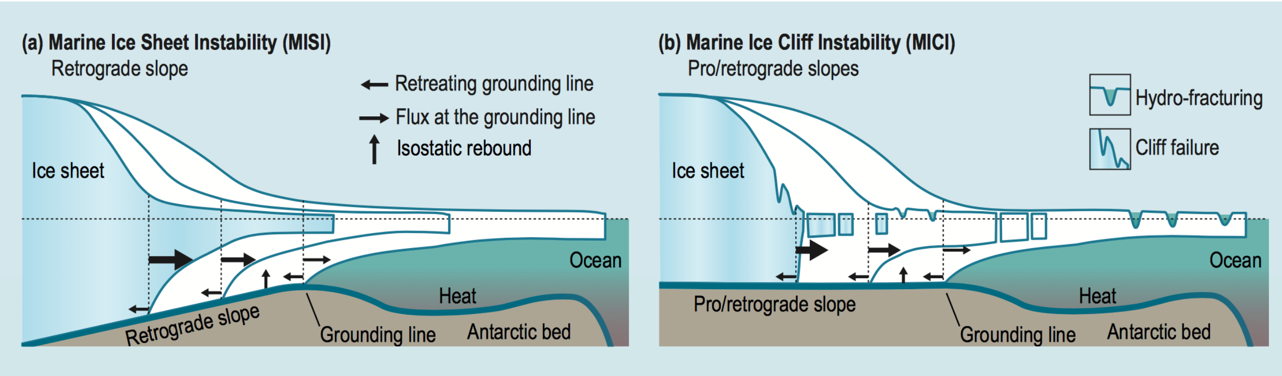
West Antarctic Ice Sheet

"Due to mismatches between model simulations and observations, combined with a lack of understanding of reasons for substantial inter-model spread, there is low confidence in model projections of future Antarctic sea ice changes, particularly at the regional level."[122] Currently there is limited understanding of feedback mechanisms.

110 https://groups.seas.harvard.edu/climate/eli/research/equable/ccf.html
111 https://doi.org/10.1175/JCLI-D-20-0558.1
112 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-17 (PDF page 60)
113 https://www.pnas.org/content/118/21/e2024192118
114 https://doi.org/10.1038/s41467-020-20011-8
115 https://doi.org/10.1002/2013GL059010
116 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-71 (PDF page 114)
117 https://doi.org/10.1038/nclimate1449
118 https://doi.org/10.1029/2020GL090471
119 Ibid.
120 https://www.science.org/doi/10.1126/sciadv.aav9396
121 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-39 (PDF page 82)
122 Ibid., TS-43 (PDF page 86)

At the same time, the IPCC has medium confidence that West Antarctic Ice Sheets will be almost completely lost at 3°C-5°C, and possibly between 2°C and 3°C. This would be irreversible over multiple millennia. "Early-warning signals of accelerated sea level rise from Antarctica could be observed within the next few decades."[123]

The Amundsen Sea Embayment of West Antarctica may already have passed a tipping point with irreversible retreat of the grounding line (the junction between a grounded ice sheet and an ice shelf, where the ice starts to float) and acceleration of ice flow, or flux. The driver for the retreat appears to be relatively warm ocean water – about 2°C warmer than the historical average – causing stronger than usual melting. The grounding line of its largest glacier, Thwaites glacier, is only around 30km away from the subglacial ridge and is retreating at around 1km per year.[124] Scientists suggest the glacier's ice shelf could break up in as little as 5 years.[125] Its collapse could destabilise the whole Amundsen Sea sector, irrevocably contributing "at least 3m to global sea level rise during the coming centuries to millennia."[126]



127

East Antarctic sub-glacial basins

The Wilkes, Aurora, and Recovery Basins in East Antarctica have topography similar to that of West Antarctica's marine ice sheets with an inland-sloping bed below sea level. The "removal of a specific coastal ice volume equivalent to less than 80mm of global sea level rise at the margin of the Wilkes Basin destabilises the regional ice flow and leads to a self-sustained discharge of the entire basin and a global sea level rise of 3m to 4m."[128] The IPCC estimates that substantial parts or all of Wilkes Subglacial Basin in East Antarctica could be lost at 3°C-5°C. Such loss would be irreversible over multiple millennia.[129]

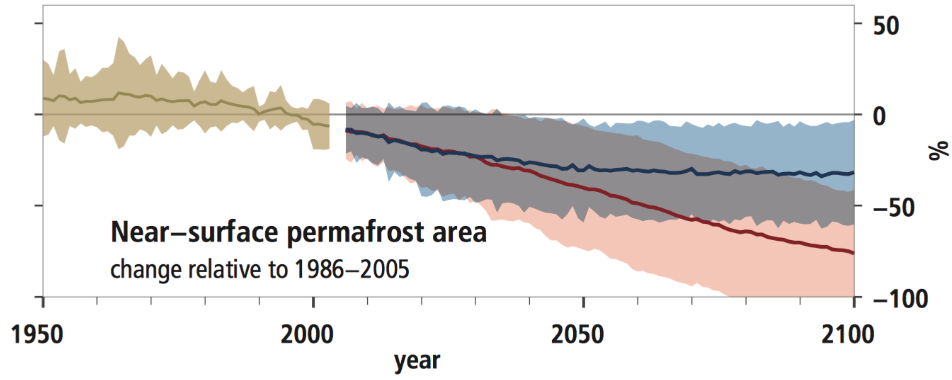
East Antarctic land-based Ice Sheet

"The East Antarctic Ice Sheet makes up the majority of the Antarctic Ice Sheet and has a global sea level equivalent of 53m."[130] Scientists suggest around 1000 parts per million of CO_2 and 8°C-10°C warming could cause its total disintegration, beyond which self-perpetuating feedbacks would amplify ice loss.[131]

123 Ibid., TS-71 (PDF page 114)
124 https://www.essoar.org/doi/10.1002/essoar.10509769.1, p8
125 https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/978762
126 https://doi.org/10.1073/pnas.1512482112
127 https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf, p245
128 http://www.pik-potsdam.de/~anders/publications/mengel_levermann14.pdf
129 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-71 (PDF page 114)
130 https://www.antarcticglaciers.org/antarctica-2/east-antarctic-ice-sheet/
131 https://doi.org/10.1038/s41586-020-2727-5

Arctic Permafrost Thaw

"Arctic and boreal permafrost contain 1460-1600 Gt of organic carbon, almost twice the carbon in the atmosphere".[132] The IPCC estimates that "by 2100, near-surface permafrost area will decrease by 2-66% for RCP2.6 and 30-99% for RCP8.5. This is projected to release 10s to 100s of billions of tonnes (Gt C), up to as much as 240 Gt C, of permafrost carbon as carbon dioxide and methane (CH_4) to the atmosphere with the potential to accelerate climate change."[133] Although increased plant growth will replenish some of the soil carbon, this will not match carbon releases over the long term.[134]



Historical changes (observed and modelled) and projections under ***RCP2.6*** *and* ***RCP8.5***[135]

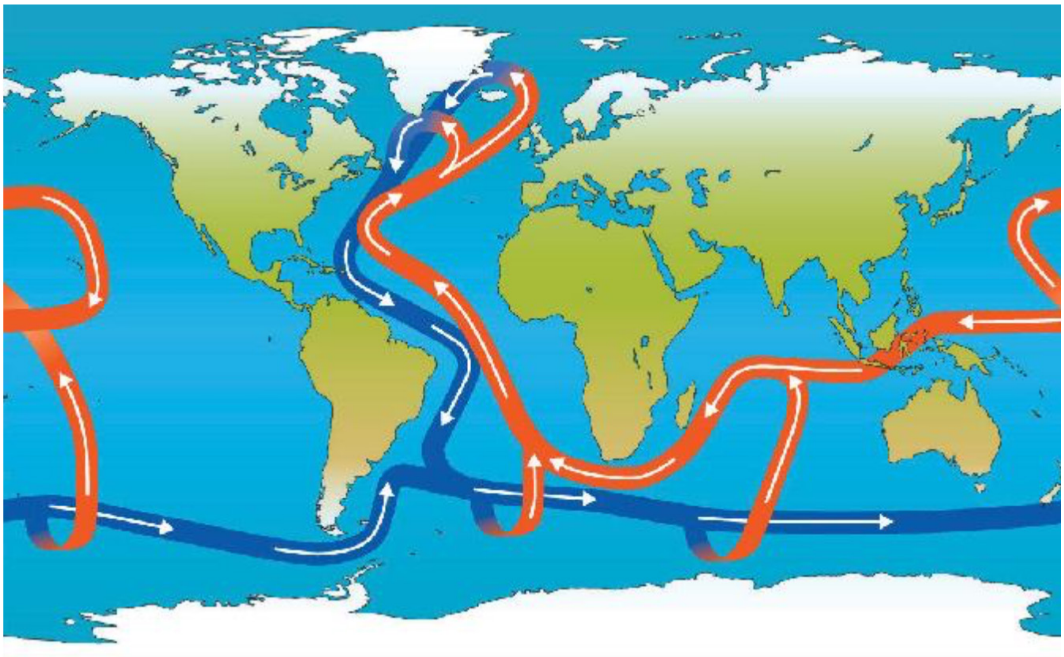
"Methane (CH_4) will contribute a small proportion of these additional carbon emissions (0.01-0.06 Gt CH_4 per year) but could contribute 40%-70% of the total permafrost-affected radiative forcing because of its higher warming potential."[136] Other deleterious emissions from permafrost thaw are nitrous oxide (N_2O)[137] and mercury.[138]

Although much of this will be a gradual thaw, the IPCC estimates that about "20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence".[139] The threshold for this is estimated at 1.5°C over around 200 years.[140] Abrupt permafrost drying at around 4°C could act as a trigger for permafrost collapse, accelerated by internal microbial heat production.[141] This will affect Arctic and mountain hydrology and wildfire, with impacts on vegetation, wildlife, and human activity.

132 https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf, p6
133 Ibid., p54
134 Ibid.
135 Ibid., p7
136 Ibid., p54
137 https://doi.org/10.1038/s43017-020-0063-9
138 https://doi.org/10.1038/s41467-020-18398-5
139 https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf, p54
140 https://www.essoar.org/doi/10.1002/essoar.10509769.1, p10
141 https://doi.org/10.1038/nclimate2590

Atlantic Meridional Overturning Circulation (AMOC)

The Atlantic Meridional Overturning Circulation (AMOC) is the system of ocean currents that carry warm water from the tropics into the North Atlantic, and cold, salty, dense water southwards towards the South Pole.



Schematic of the AMOC: Red shows near-surface transport and blue shows return flow at depth [142]

Arctic warming and Greenland Ice Sheet melting are driving an influx of fresh water into the North Atlantic. This fresh water is less dense, so it slows the circulation. One model suggests the AMOC has slowed by 15% since the mid-twentieth century.[143] The IPCC expects the AMOC to continue to weaken over the 21st century, stating with medium confidence that it is "likely that under stabilisation of global warming at 1.5°C, 2.0°C, or 3.0°C relative to 1850-1900, the AMOC will continue to weaken for several decades by about 15%, 20% and 30% of its strength and then recover to pre-decline values over several centuries".[144]

The IPCC does not expect an abrupt collapse before 2100, but if it did 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."[145] A Met Office study suggests that the AMOC could still recover after a collapse if the freshwater inflow ceases after 20 years, but not after 50 years.[146]

142 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/climate-science/met-office-hadley-centre/risk-management-of-climate-thresholds-and-feedbacks---2-atlantic-meridional-overturning-circulation-amoc.pdf
143 https://doi.org/10.1038/s41586-018-0006-5
144 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, TS-71 (PDF page 114)
145 Ibid., SPM-36 (PDF page 37)
146 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/climate-science/met-office-hadley-centre/risk-management-of-climate-thresholds-and-feedbacks---2-atlantic-meridional-overturning-circulation-amoc.pdf

Boreal Forest[147] Dieback

Boreal forests make up a third of the world's forests. Mainly coniferous and growing in high-latitude environments, about one-third of their extent is underlain by permafrost. Warming and permafrost melt is leading to changes in tree growth, insect outbreaks and increased incidences of wildfire.

The IPCC notes that forest dieback "is not expected to change the atmospheric CO_2 concentration substantially because forest loss at the south is partly compensated by (i) temperate forest invasion into the previous boreal area and (ii) boreal forest gain at the north".[148] However, "a shift from tundra to boreal forests and the associated albedo change leads to increased warming in Northern Hemisphere high latitudes".[149]

Amazon Dieback

The Amazon acts as a carbon sink, helps generate rainfall in the South American region and drives atmospheric circulations in the tropics. An estimated 17% of the Amazon has been lost in the last 50 years due to deforestation.[150] "Both deforestation and drying are projected to increase by 2100, resulting in a worst-case scenario of up to a 50% loss in forest cover by 2050".[151]

The IPCC warns that "the combination of deforestation, drier conditions, and increased fire can push the rainforest ecosystem past a tipping point, beyond which there is rapid land surface degradation, a sharp reduction in atmospheric moisture recycling, an increase in the fraction of precipitation that runs off, and a further shift towards a drier climate".[152] The IPCC notes the "probability that this ecosystem will cross a tipping point into a dry state during the 21st century".[153]

147 "Boreal forests are defined as forests growing in high-latitude environments where freezing temperatures occur for 6 to 8 months and in which trees are capable of reaching a minimum height of 5m and a canopy cover of 10%." "The boreal ecozone principally spans 8 countries: Canada, China, Finland, Japan, Norway, Russia, Sweden and the United States." http://ibfra.org/about-boreal-forests/

148 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 5-80 (PDF page 1232)

149 Ibid., 7-71 (PDF page 1685)

150 https://www.science.org/doi/full/10.1126/sciadv.aba2949

151 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 8-112 (PDF page 1982)

152 Ibid.

153 Ibid., TS-72 (PDF page 115)

7 Mitigating climate change

The IPCC expects "a near-linear dependence of global temperature on cumulative GHG emissions" in the next century.[154]

Latest 2100 median warming projections from UNEP[155], CAT[156], IEA[157], and CR[158] as of 9 November 2021 estimate current policies will lead to around 2.6°C to 2.7°C global warming by 2100 (with an uncertainty range of 2°C to 3.6°C). If countries meet both conditional and established NDCs for the near-term target of 2030, projected warming by 2100 falls to 2.4°C (1.8°C to 3.3°C).

If countries meet their long-term net zero promises, global warming could be reduced to around 1.8°C (1.4°C to 2.6°C) by 2100, though temperatures would likely peak around 1.9°C in the middle of the century before going down.[159 160]

In order to guide policymakers on efforts needed to limit the future rise in global temperature, the IPCC has developed the concepts of the carbon budget and net zero.

7.1 Carbon budget

A carbon budget is the cumulative amount of GHG emissions (sometimes separated into CO_2 and non-CO_2) permitted over a period of time to keep within a certain temperature threshold.[161] The budget depends on the baseline (the IPCC uses 1850-1900), differentiation between anthropogenic and natural forcings, the cut-off date, and modelling assumptions such as mitigation technologies.

The IPCC has estimated the carbon budget remaining from the beginning of 2020 for three temperature limits, and differing likelihoods:

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	

[162]

154 Ibid., 1-66 (PDF page 260)
155 https://wedocs.unep.org/bitstream/handle/20.500.11822/37350/AddEGR21.pdf
156 https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf
157 https://www.iea.org/commentaries/cop26-climate-pledges-could-help-limit-global-warming-to-1-8-c-but-implementing-them-will-be-the-key
158 https://data.climateresource.com.au/ndc/20211109-ClimateResource-1-9C_to2-7C.pdf
159 https://www.carbonbrief.org/analysis-do-cop26-promises-keep-global-warming-below-2c
160 These two paragraphs are reproduced from https://www.actuaries.org.uk/system/files/field/document/Climate%20Change%20Policy%20Briefing.pdf
161 https://carbontracker.org/carbon-budgets-explained/
162 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, SPM-38 (PDF page 39)

At the date of release of the IPCC AR6 WG I report (August 2021) "Carbon Tracker estimates the number of years until the budget is reached at current rates of production … [as] just 9 years for a 66% chance of keeping temperatures under 1.5°C and 16 years for a 1.7°C."[163]

7.2 Net zero

The IPCC defines Net Zero as the "condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period."[164] It is synonymous with 'GHG neutrality', although GHG neutrality is generally used to include emissions and removals both within and beyond the direct control or territorial responsibility of a reporting entity.

As the IPCC notes, "the quantification of net zero GHG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric."[165] Accounting rules specified by GHG programmes or schemes can have a significant influence on the quantification of relevant emissions and removals.

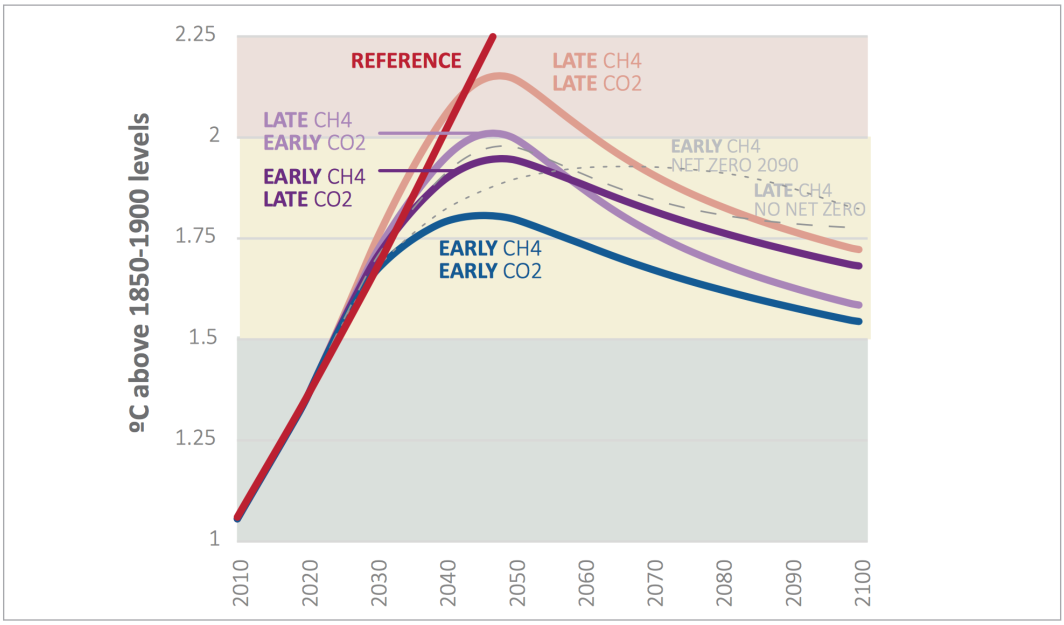
The IPCC has high confidence that reaching net zero GHG emissions as quantified by GWP-100 will lead to reductions from peak global surface temperature, depending on the relative sequencing of mitigation of short-lived and long-lived GHGs.[166]

As carbon continues to be absorbed by the ocean, "reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales".[167] A project looking at 18 different Earth system models found an average of around -0.07°C (-0.36°C to 0.29°C) of cooling 50 years after net zero CO_2 emissions is reached.[168]

7.3 Pace of achieving net zero

As GHGs remain in the atmosphere for an extended period of time (see Page 8), the pace at which the net zero target is realised heavily impacts the global warming outcome, and thus the importance of the carbon budget (see Section 7.1 above). The following graph assumes net zero by 2050 is achieved. Early action on carbon dioxide (-18Gt/yr 2020-2050) and methane (halving emissions by 2030) limits the peak anthropogenic impact on global temperatures to +1.80°C, followed by further reductions to +1.55°C. Late action, i.e. not reducing emissions for carbon dioxide until 2030 and methane until 2040, would result in a peak temperature of +2.15°C, falling to +1.70°C by 2100.

163 https://carbontracker.org/the-ipccs-red-alert/
164 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, AVII-41 (PDF page 3925)
165 Ibid.
166 Ibid., 7-127 (PDF page 1741)
167 https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf, p5 (PDF page 19)
168 https://doi.org/10.5194/bg-17-2987-2020



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7.4 Carbon dioxide removal (CDR)

Even with successful and far-reaching decarbonisation it will be very difficult to reduce greenhouse gas emissions all the way to zero. For example, agriculture and aviation are hard to completely decarbonise. Therefore, to achieve net zero, it will be necessary to offset residual emissions by removing greenhouse gases from the atmosphere.[170] It may even be possible to achieve 'net negative' emissions in the future if more greenhouse gases can be removed than are emitted.

Greenhouse gas removal can be achieved by biological or engineered chemical processes. The gases then need to be stored in reservoirs permanently, or for very long periods. The process is best established for carbon dioxide and some possible methods are summarised below:[171]

- **Reforestation** – Absorbing carbon in trees by planting or restoring forests.
- **Soil carbon sequestration** – Changing agricultural practices to increase the soil carbon content.
- **Wood in construction** – Using more wood as a construction material (e.g. for new houses), creating a store of carbon in the built environment.
- **Enhanced weathering** – Spreading alkaline minerals on land that react with carbon in the air, to store it in solid minerals.
- **Bioenergy with carbon capture and storage (CCS)** – Burning biomass to produce energy, capturing the resulting CO_2 and storing it in deep geological formations.
- **Direct air carbon capture and storage** – Separating the CO_2 from ambient air using chemical processes (and using a low-carbon energy source) and storing it in deep geological formations.

169 https://www.nature.com/articles/s41598-021-01639-y.pdf, pp4-5. Note, with respect to 'No Net Zero': "We could potentially miss net zero by 2050 targets and still succeed at staying below temperature goals, if we act on methane and never exceed the maximum carbon budget allowed to stay below 2°C" (grey lines and markers). The grey dotted line shows that taking early action on methane allows for a larger maximum carbon budget for similar end-of century temperature outcomes.

170 Key source for this section https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-executive-summary-2018.pdf

171 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, 5-100 (PDF page 1252), Table 5.9

For context, the UK's Climate Change Committee's 'balanced net zero pathway'[172] allows for engineered removals of 58 Mt CO_2 / year (mainly bioenergy with carbon capture and storage), and nature-based removals of 39 Mt CO_2 / year by 2050 (compared with total UK territorial emissions in 2019 of 522 Mt CO_2 / year).

Some greenhouse gas removal methods provide co-benefits (e.g. reforestation, improving biodiversity). Others involve costs and trade-offs, such as crops for bioenergy competing with food production. There are practical constraints on the total scale of removals that can be achieved (there is only so much land worldwide that be converted into forest). Finally, many of the industrial technologies have yet to be fully demonstrated at the scale required.

For these reasons, emissions reductions will remain the most important element in reaching net zero: according to the Royal Society: "Large-scale greenhouse gas removal is challenging and expensive and not a replacement for reducing emissions."[173] To offset residual emissions it is likely that a balanced portfolio of different removal approaches will be most effective and avoid the worst environmental and social impacts.

172 https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf, Table 2, page 27
173 https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-executive-summary-2018.pdf, p11

8 Acronym / Abbreviation Key

°C	degrees Celsius
°F	degrees Fahrenheit
AMOC	Atlantic Meridional Overturning Circulation
AR6	Sixth Assessment Report of the IPCC covering *The Physical Science Basis* (WG I),[174] *Impacts, Adaption and Vulnerability* (WG II),[175] and *Mitigation of Climate Change* (WG III).[176] The Synthesis Report is due for release in 2022.
CAT	Climate Action Tracker
CBES	Climate Biennial Exploratory Scenario
CC	climate change
CCS	carbon capture and storage
CCUS	carbon capture, usage, and storage
CDR	carbon dioxide removal
CFC	chlorofluorocarbon
CFRF	Climate Financial Risk Forum
CH_4	methane
cm	centimetre
CMIP	Coupled Model Intercomparison Project
CMIP6	Coupled Model Intercomparison Project Phase 6
CO_2	carbon dioxide
CO_2-eq	CO_2 equivalent (note: sometimes 'CO_2-e' is also used)
COP26	26th United Nations Climate Change Conference of the Parties; held in Glasgow on 31 October - 12 November 2021
CPD	Continuing Professional Development
CR	Climate Resource, an Australian-based climate analysis group
EIT	economies in transition (the Russian Federation, the Baltic States, and several Central and Eastern European States) who are non-OECD countries and who are parties to the UNFCCC (as of 1992)
FCA	Financial Conduct Authority
F-gas	fluorinated gas (note: sometimes 'F gas' is also used)
FRC	Financial Reporting Council
GHG	greenhouse gas[177]
GMSL	global mean sea level
Gt	gigatonne
GtC	gigatonne of carbon (note: sometimes 'Gt C' is also used)
GWP	global warming potential
GWP-100	global warming potential over a 100-year period
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
IEA	International Energy Agency
IFoA	Institute and Faculty of Actuaries
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IR	infrared

174 https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/
175 https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/
176 https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/
177 Often called Well-Mixed GHG (WMGHG): the WMGHG are well-mixed in the atmosphere because they are long-lived. WMGHG include CO_2, CH_4, and N_2O (among others), but not O_3.

ISSB	International Sustainability Standards Board
JFAR	Joint Forum on Actuarial Regulation
km	kilometre
kt	kilotonne
LED	light-emitting diode
LLHI	low-likelihood, high-impact
LULUCF	land use, land-use change and forestry (activities)
m	metre
MICI	marine ice cliff instability
MISI	marine ice sheet instability
mm	millimetre
Mt	megatonne
N_2O	nitrous oxide
NDC	nationally determined contribution
NF_3	nitrogen trifluoride
NGFS	Network for Greening the Financial System
O_3	ozone
ODP	ozone-depleting potential
ODS	ozone-depleting substance
OECD	Organisation for Economic Co-operation and Development
PA	Paris Agreement
PFC	perfluorocarbon
ppb	parts per billion
PRA	Prudential Regulation Authority
RCP	representative concentration pathway
RPD	Reflective Practice Discussion
SF_6	sulphur hexafluoride
SIA	sea ice area
SIF	Sustainable Insurance Forum
SM	Supplementary Material
SPM	Summary for Policymakers
SRCCL	Special Report on Climate Change and Land (August 2019)
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate (September 2019)
SSP	shared socioeconomic pathway
TAS	Technical Actuarial Standard
TCFD	Task Force on Climate-Related Financial Disclosures
TPR	The Pensions Regulator
TS	Technical Summary
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UV	ultraviolet
$W{\cdot}m^{-2}$	watts per square metre
WG I	Working Group I (of the IPCC) assesses the physical science of climate change
WG II	Working Group II (of the IPCC) assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting to it
WG III	Working Group III (of the IPCC) focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere
WMGHG	well-mixed greenhouse gas
WMO	World Meteorological Organisation

9 Glossary

albedo	"the proportion of the incident light or radiation that is reflected by a surface"[178]
anthropogenic	originating in human activity
biome	"A grouping of ecosystems into a larger group occupying a major terrestrial region (e.g. tropical rainforest biome)."[179]
biosphere	"The whole of the region of the Earth's surface, the sea, and the air that is inhabited by living organisms."[180]
cryosphere	"That part of the Earth where the surface is frozen, comprising the area covered by ice sheets and glaciers, permafrost regions, and sea areas covered by ice, at least in winter."[181]
CO_2 equivalent	a "measure used to compare the emissions from various greenhouse gases on the basis of their global warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential."[182]
forcing	usually used to refer to a factor (climate variable, or 'forcing factor') that may affect the climate. For example: GHG, aerosol, volcanic, oceanic, ozone, solar. Can be natural or anthropogenic.
LULUCF	"A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities."[183]
net zero	achieving a balance between the amount of anthropogenic greenhouse gases emitted into the atmosphere and the amount of anthropogenic greenhouse gases removed from the atmosphere
permafrost	"Ground (soil or rock, and included ice and organic material) that remains at or below 0°C for at least two consecutive years"[184]
radiative forcing	"Radiative forcing by a climate variable is a change in Earth's energy balance between incoming solar radiation energy and outgoing thermal IR [infrared] emission energy when the variable is changed while all other factors are held constant."[185] Synonymous with 'climate forcing'.
sink	"any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere"[186]

178 https://www.lexico.com/definition/albedo
179 https://www.oxfordreference.com/view/10.1093/oi/authority.20110803095507295
180 https://www.oxfordreference.com/view/10.1093/oi/authority.20110803095507469
181 https://www.oxfordreference.com/view/10.1093/oi/authority.20110803095651483
182 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent
183 https://unfccc.int/process-and-meetings/the-convention/glossary-of-climate-change-acronyms-and-terms#l
184 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, AVII-46 (PDF page 3930)
185 https://www.acs.org/content/acs/en/climatescience/atmosphericwarming/radiativeforcing.html
186 https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf, p7

10 Climate Change: The Broader Context

This Climate Change Deep Dive has tightly focused on bringing to life the 'science' of climate change. Naturally the science of climate change sits in the broader context of JFAR member regulators' actions and their applicability to actuaries and the work performed by actuaries.

FRC

- maintaining Technical Actuarial Standards (TASs)
- working on Task Force on Climate-Related Financial Disclosures (TCFD)[187]
- working with International Sustainability Standards Board (ISSB)[188]

IFoA

- a Risk Alert on *Climate change and sustainability related issues*[189]
- Continuing Professional Development (CPD) Reflective Practice Discussion (RPD) Toolkit on climate change and sustainability[190]
- Climate Risk and Sustainability course[191]
- Climate Change curated library[192]
- Sustainability Board practical guides[193]

TPR

- establishing requirements for *Governance and reporting of climate-related risks and opportunities*[194]

FCA

- together with the PRA, establishing the Climate Financial Risk Forum (CFRF)
- setting out ESG priorities[195]

PRA

- together with the FCA, establishing the CFRF[196]
- publication of *Climate-related financial risk management and the role of capital requirements* (Climate Change Adaptation Report 2021)[197]
- member (and current chair) of the Sustainable Insurance Forum (SIF)[198]
- published *Enhancing banks' and insurers' approaches to managing the financial risks from climate change* (SS3/19)[199] which sets expectations on regulated firms for managing the risks from climate change

In addition, there was a renewed supranational effort during COP26, resulting in the Glasgow Climate Pact[200] which focused on mitigation, adaption, finance, and collaboration.

187 https://www.frc.org.uk/getattachment/09b5627b-864b-48cb-ab53-8928b9dc72b7/FRCLab-TCFD-Report_October-2021.pdf
188 https://www.frc.org.uk/getattachment/683f2146-6101-4999-b03e-1527ff35ea8f/FRC-Response-to-ISSB-on-prototype_February-2022.pdf
189 https://www.actuaries.org.uk/system/files/field/document/2022%20Climate%20change%20and%20sustainability%20Risk%20Alert%20final.pdf
190 https://www.actuaries.org.uk/system/files/field/document/RPD%20Toolkit%20Climate%20Science.pdf
191 https://www.actuaries.org.uk/learn-and-develop/lifelong-learning/sustainability-and-lifelong-learning/climate-risk-and-sustainability-course
192 https://www.actuaries.org.uk/system/files/field/document/Wider%20Horizons_V6_Jan22.pdf
193 https://actuaries.org.uk/about-us/sustainability-hub/sustainability-practice-area-practical-guides/
194 https://www.thepensionsregulator.gov.uk/en/document-library/scheme-management-detailed-guidance/funding-and-investment-detailed-guidance/climate-related-governance-and-reporting
195 https://www.fca.org.uk/publications/corporate-documents/strategy-positive-change-our-esg-priorities
196 https://www.bankofengland.co.uk/climate-change/climate-financial-risk-forum
197 https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/publication/2021/october/climate-change-adaptation-report-2021.pdf
198 https://www.sustainableinsuranceforum.org/
199 https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/supervisory-statement/2019/ss319
200 https://ukcop26.org/wp-content/uploads/2021/11/COP26-Presidency-Outcomes-The-Climate-Pact.pdf

JFAR

Joint Forum on
Actuarial Regulation