The Physical Science Basis of Climate Change

6.S891/6.S893/12.S992 AI for Climate Action

Spring 2026

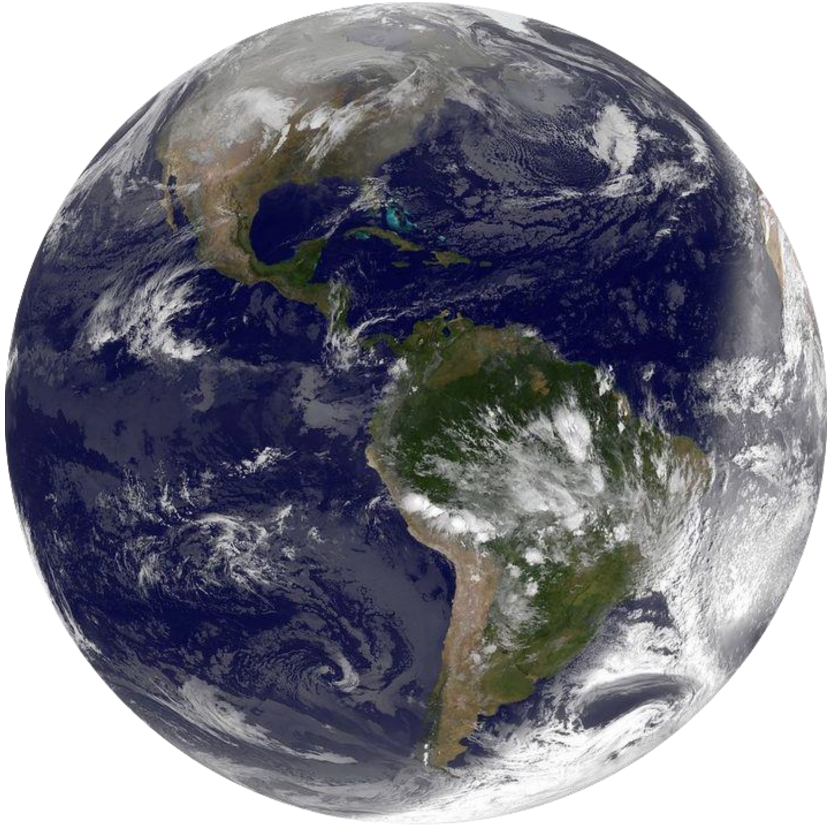
Speaker: Abigail Bodner

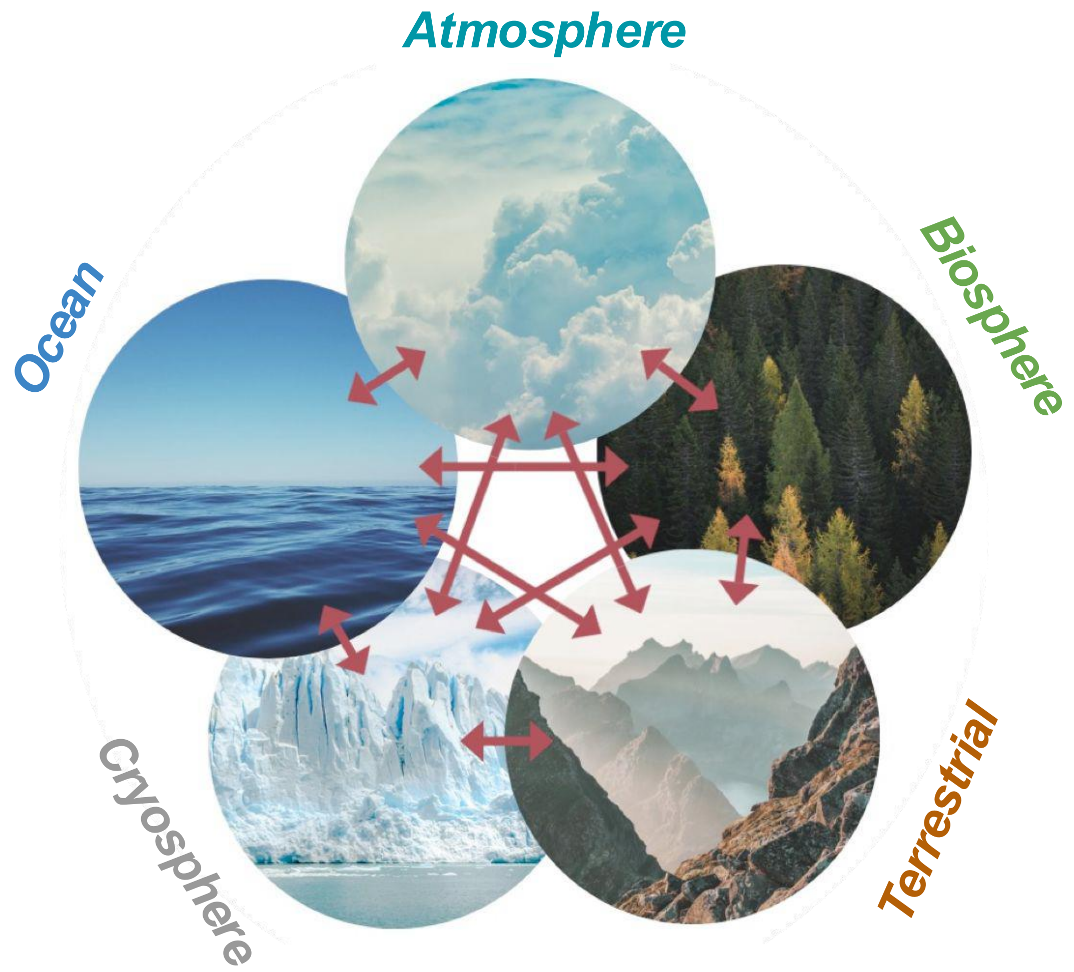
”how do we know what we know”

- What is climate?
- How to monitor the climate system?
- How to estimate future changes?

Content adapted from Climatematch Academy

What is climate?



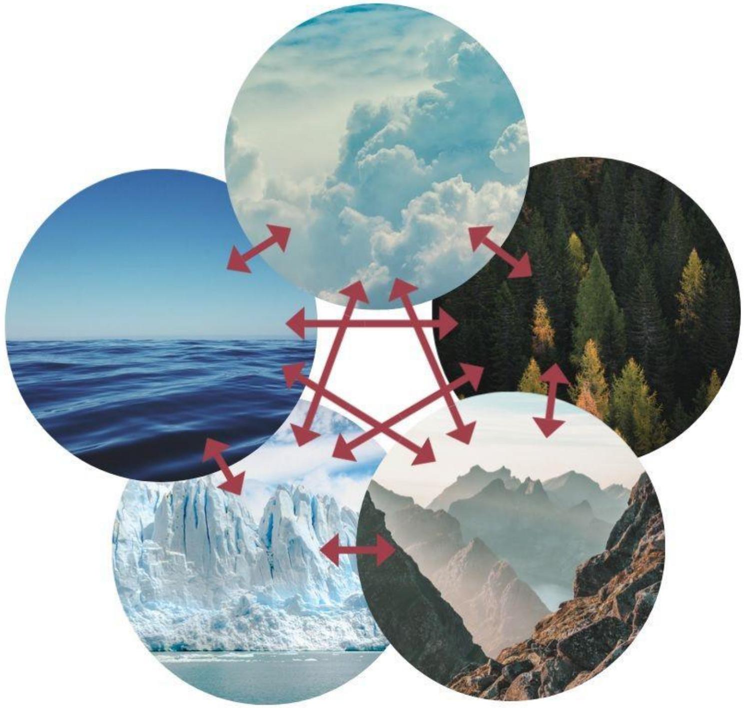


Climate System Forcings and Variables

Climate Forcings

Natural Forcings:
- Solar radiation
- Orbital cycles
- Carbon cycle

Anthropogenic



Climate Variables

- Temperature
- Precipitation
- Atmospheric composition
- Vegetation

Variations in Earth's Climate System

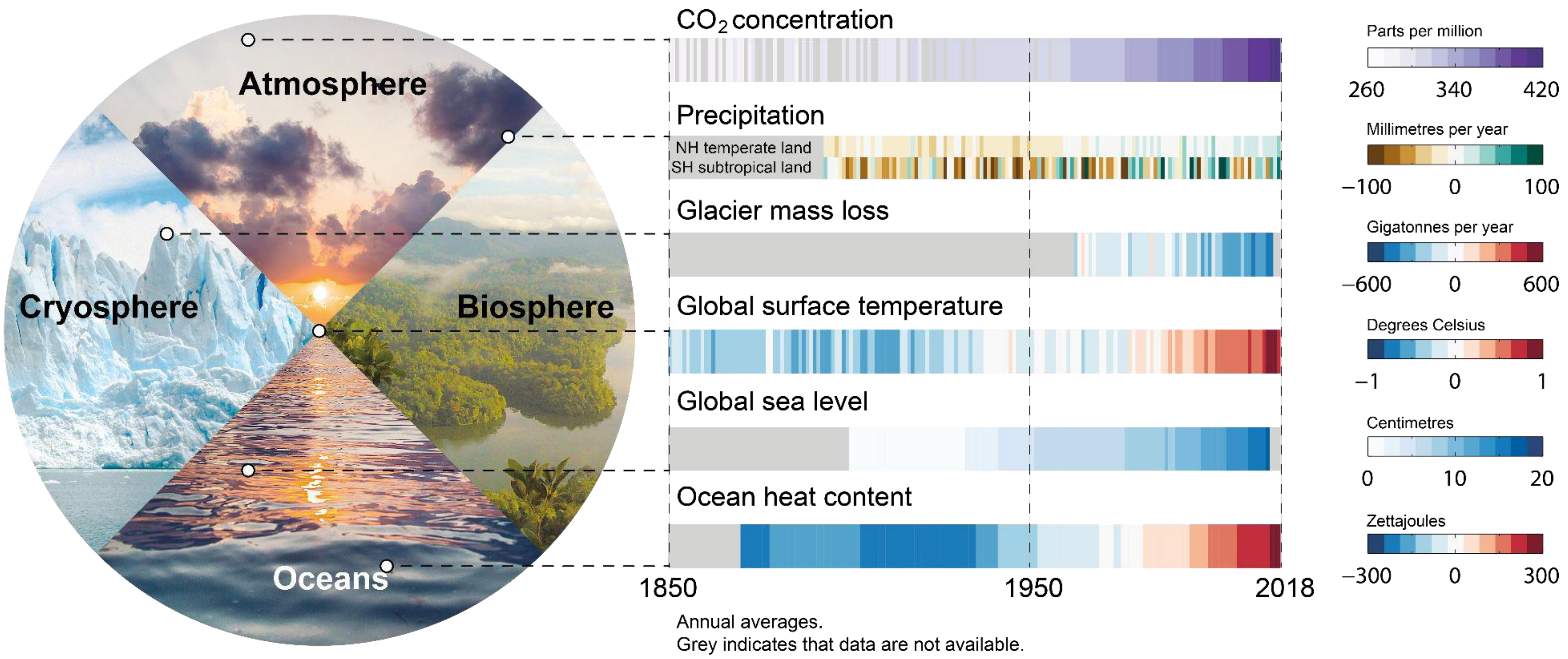
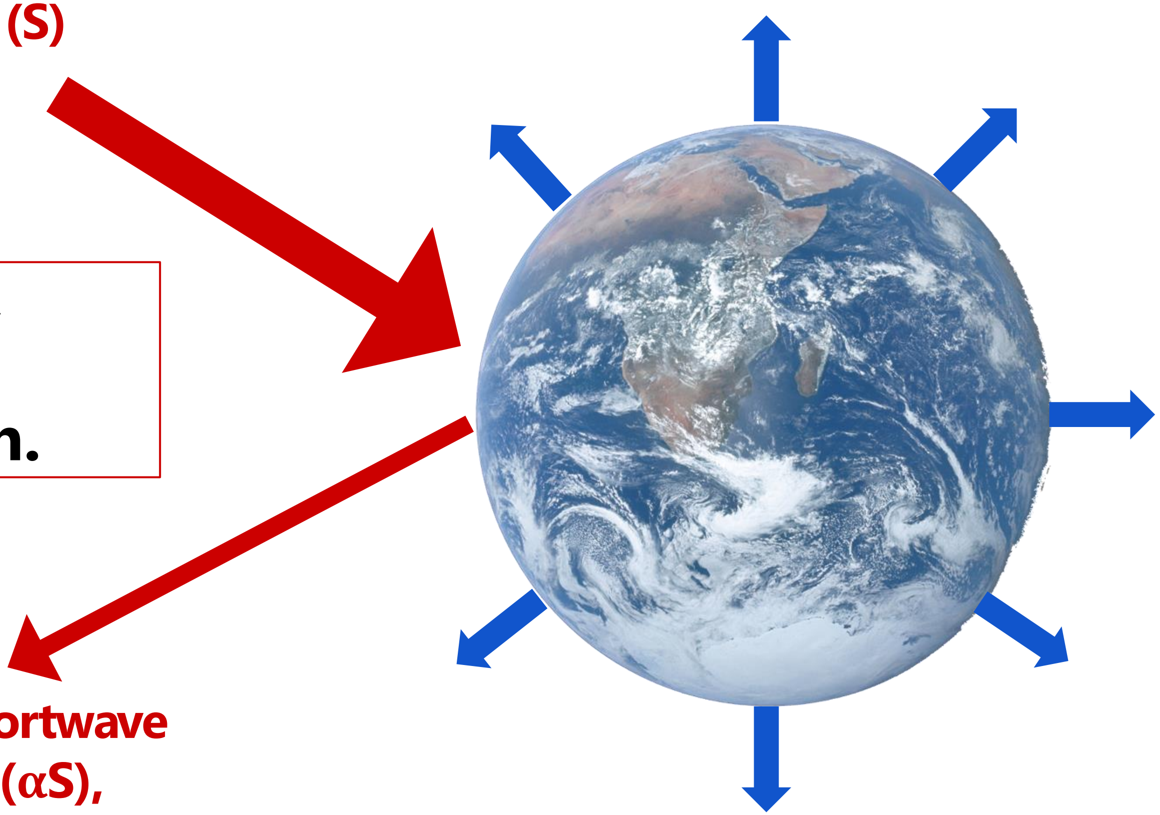


Figure 1.4 | Changes are occurring throughout the climate system. Left: Main realms of the climate system: atmosphere, biosphere, cryosphere and ocean. Right: Six key indicators of ongoing changes since 1850, or the start of the observational or assessed record, through 2018. Each stripe indicates the global (except for precipitation which shows two latitude band means), annual mean anomaly for a single year, relative to a multi-year baseline (except for CO2 concentration and glacier mass loss, which are absolute values). Grey indicates that data are not available. Datasets and baselines used are: (i) CO2: Antarctic ice cores (Lüthi et al., 2008; Bereiter et al., 2015) and direct air measurements (Tans and Keeling, 2020) (see Figure 1.5 for details); (ii) precipitation: Global Precipitation Climatology Centre (GPCC) V8 (updated from Becker et al., 2013), baseline 1961–1990 using land areas only with latitude bands 33°N–66°N and 15°S–30°S; (iii) glacier mass loss: Zemp et al. (2019); (iv) global surface air temperature (GMST): HadCRUT5 (Morice et al., 2021), baseline 1961–1990; (v) sea level change: (Dangendorf et al., 2019), baseline 1900–1929; (vi) ocean heat content (model–observation hybrid): Zanna et al. (2019), baseline 1961–1990. Further details on data sources and processing are available in the chapter data table (Table 1.SM.1).

Figure 1.4 in IPCC, 2021: Chapter 1. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chen, D. et al.)

A Radiating Earth

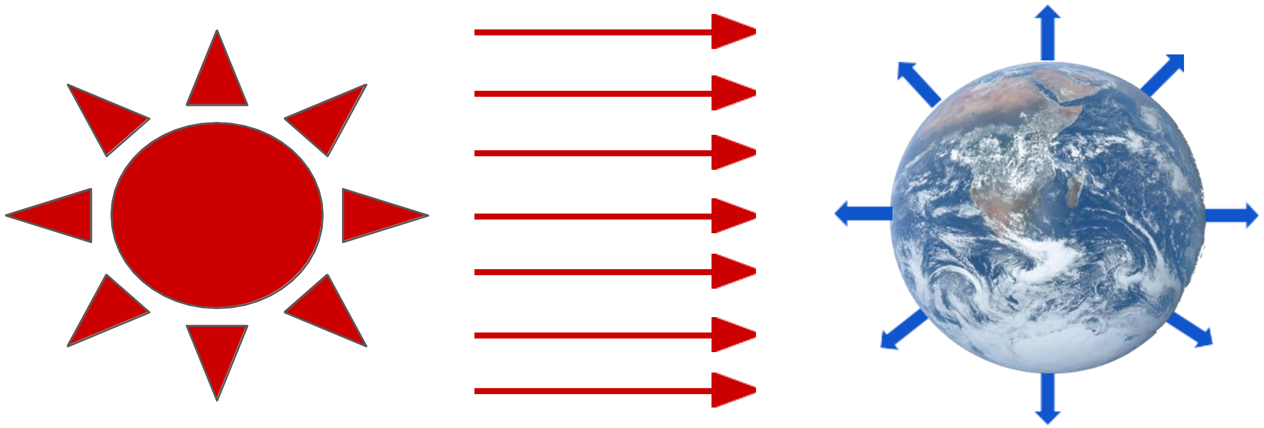


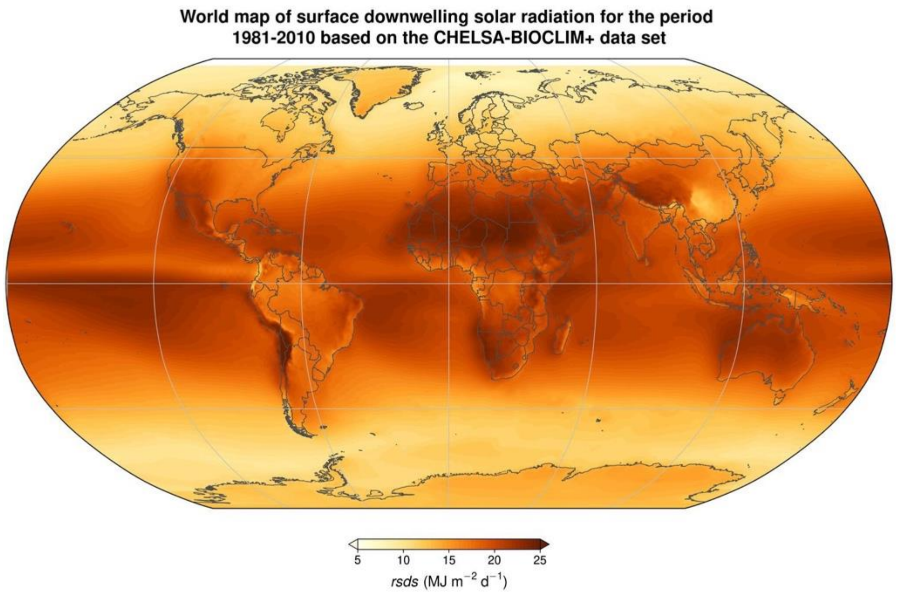
Earth is heated by energy from the sun.

Earth cools by emitting energy back to space.

https://en.wikipedia.org/wiki/Earth

A Radiating Sun



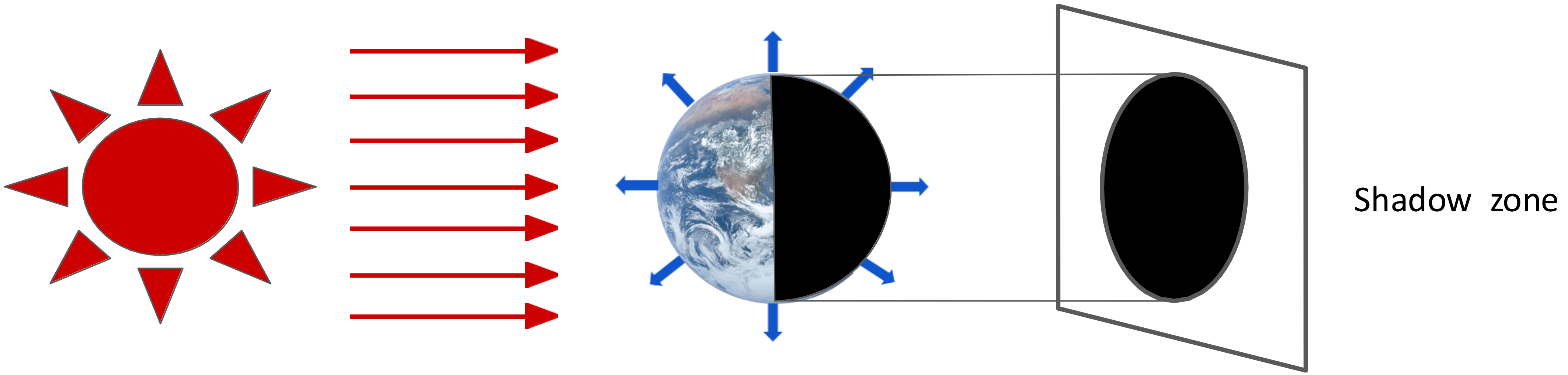


- The sun and Earth and very a far a part, and the difference between their radii is large.
- This allows us to assume that the rays arrive nearly parallel to the lines adjoining their centers, and is called the **parallel beam approximation**.

https://en.wikipedia.org/wiki/Earth

Incoming Solar Radiation

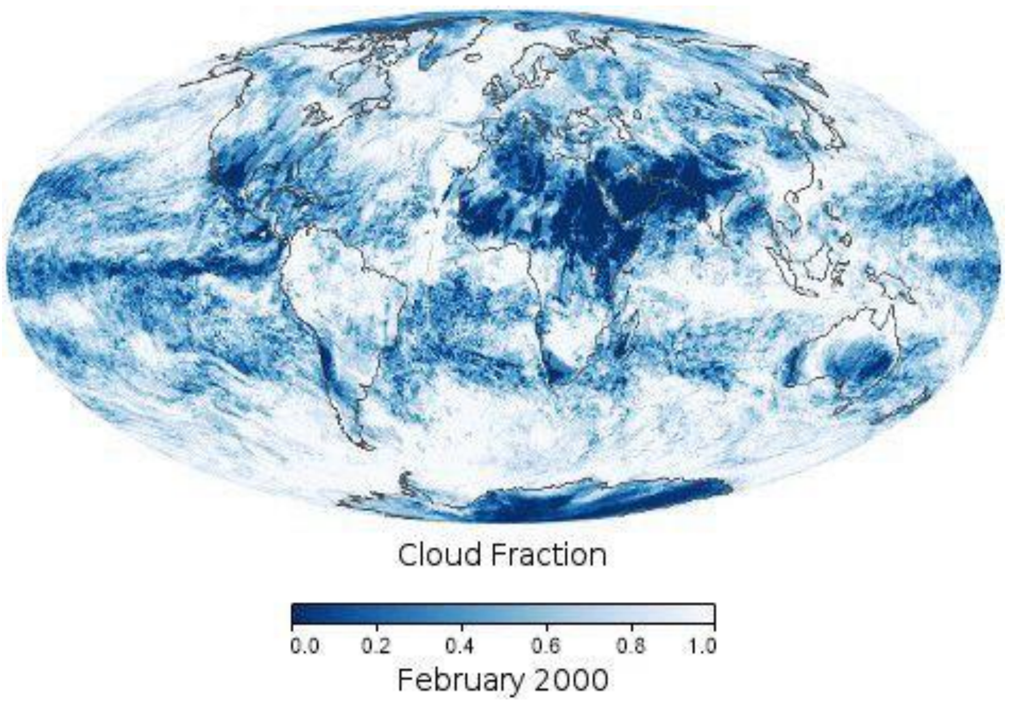
Area = πr^2
r = radius of Earth



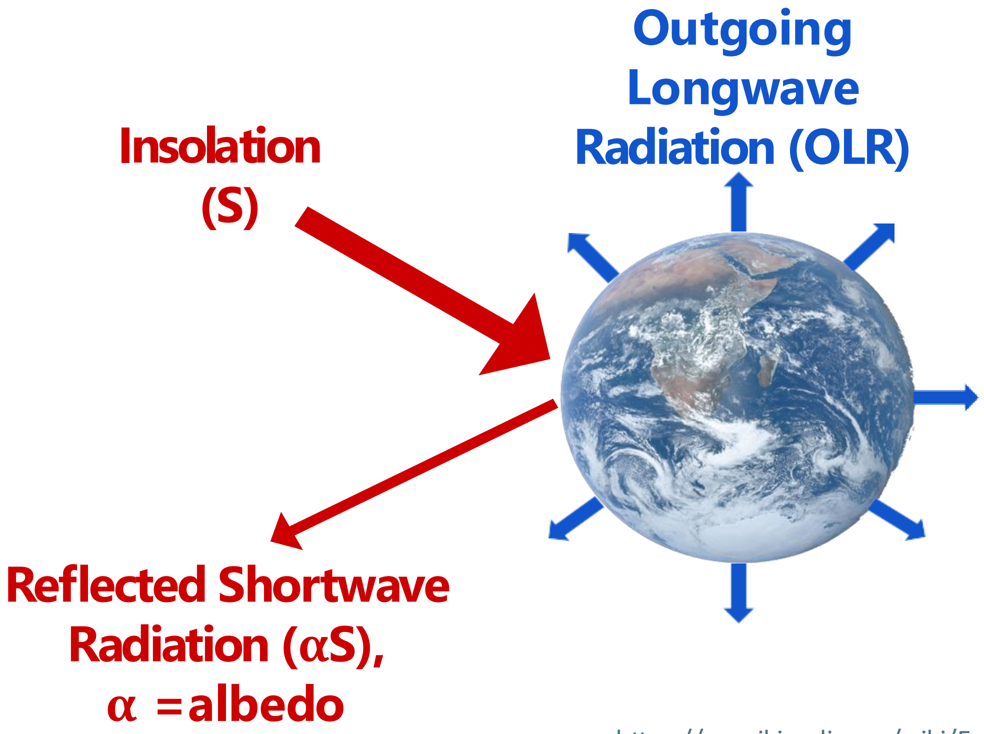
- Viewed from the sun, Earth is a disc with the same radius as Earth.
- The amount of radiation that flows through this disc (i.e. reaches Earth) if Earth if absorbed all radiation it received is $S \pi r^2$ where **S** is in the **insolation (incoming solar radiation)**.

https://en.wikipedia.org/wiki/Earth

Albedo

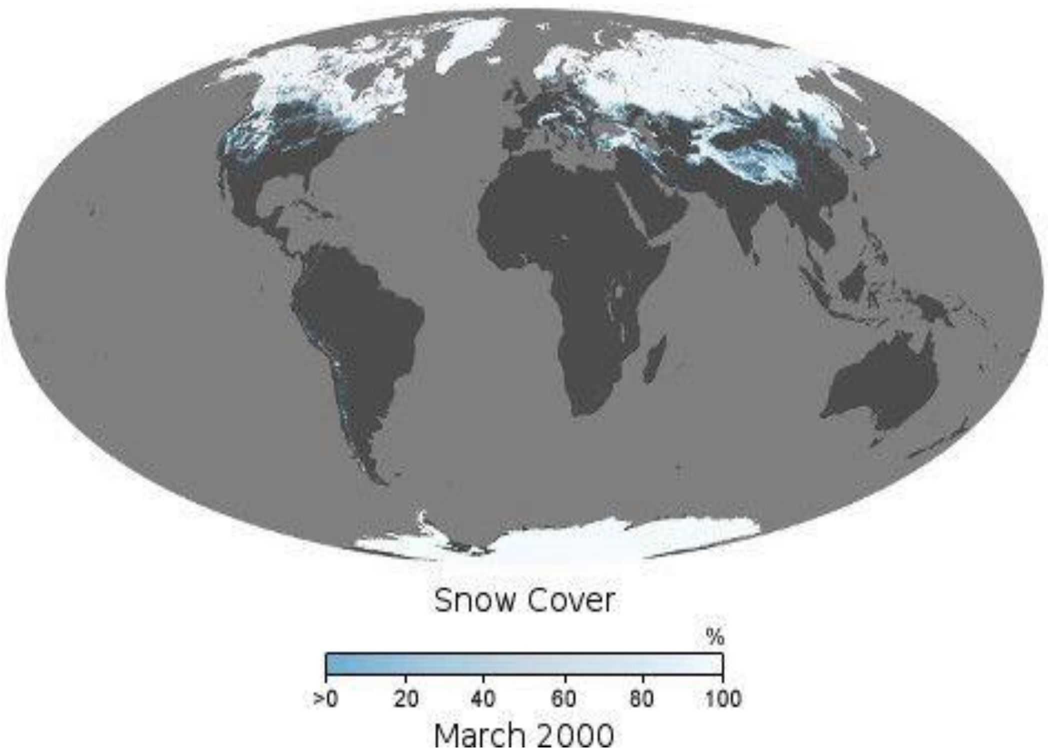


https://earthobservatory.nasa.gov/global-maps/MODAL2_M_CLD_FR

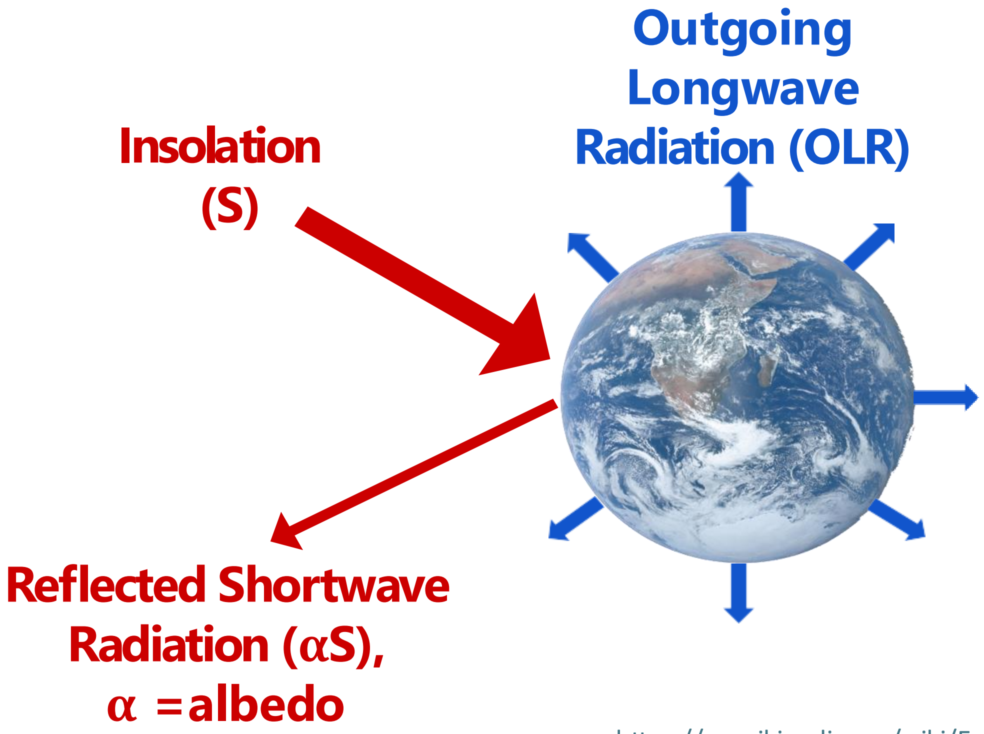


https://en.wikipedia.org/wiki/Earth

Albedo



https://earthobservatory.nasa.gov/global-maps/MOD10C1_M_SNOW



https://en.wikipedia.org/wiki/Earth

Absorbed Shortwave Radiation

After considering albedo, the total radiation

that is absorbed by the Earth system is called the **absorbed shortwave radiation (ASR)** and is given by

$$ASR = (1 - \alpha)S\pi r^2$$

Effects of Greenhouse Gases

https://climate.nasa.gov/internal_resources/2282

- The absorption and re-emission of radiation within Earth's atmosphere by **greenhouse gases** is called the **greenhouse effect**.

- We can represent the greenhouse effect by a **transmissivity coefficient** (**τ**):

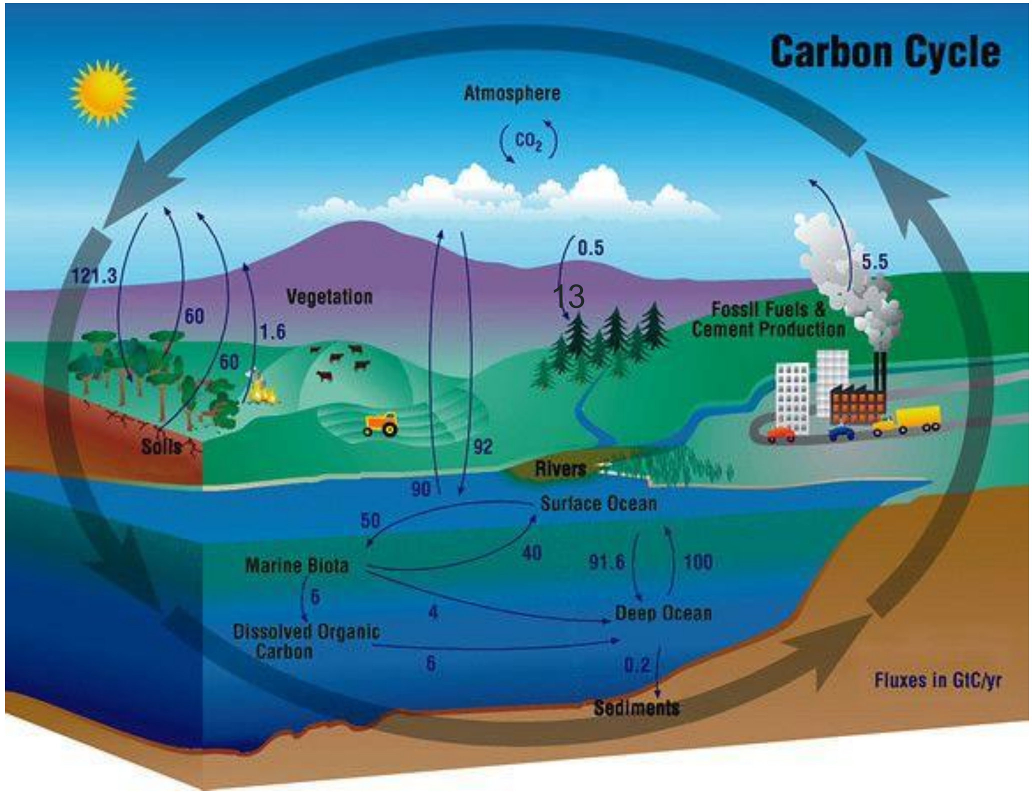
$$OLR = \tau \sigma T^4$$

Earth’s Carbon Cycle

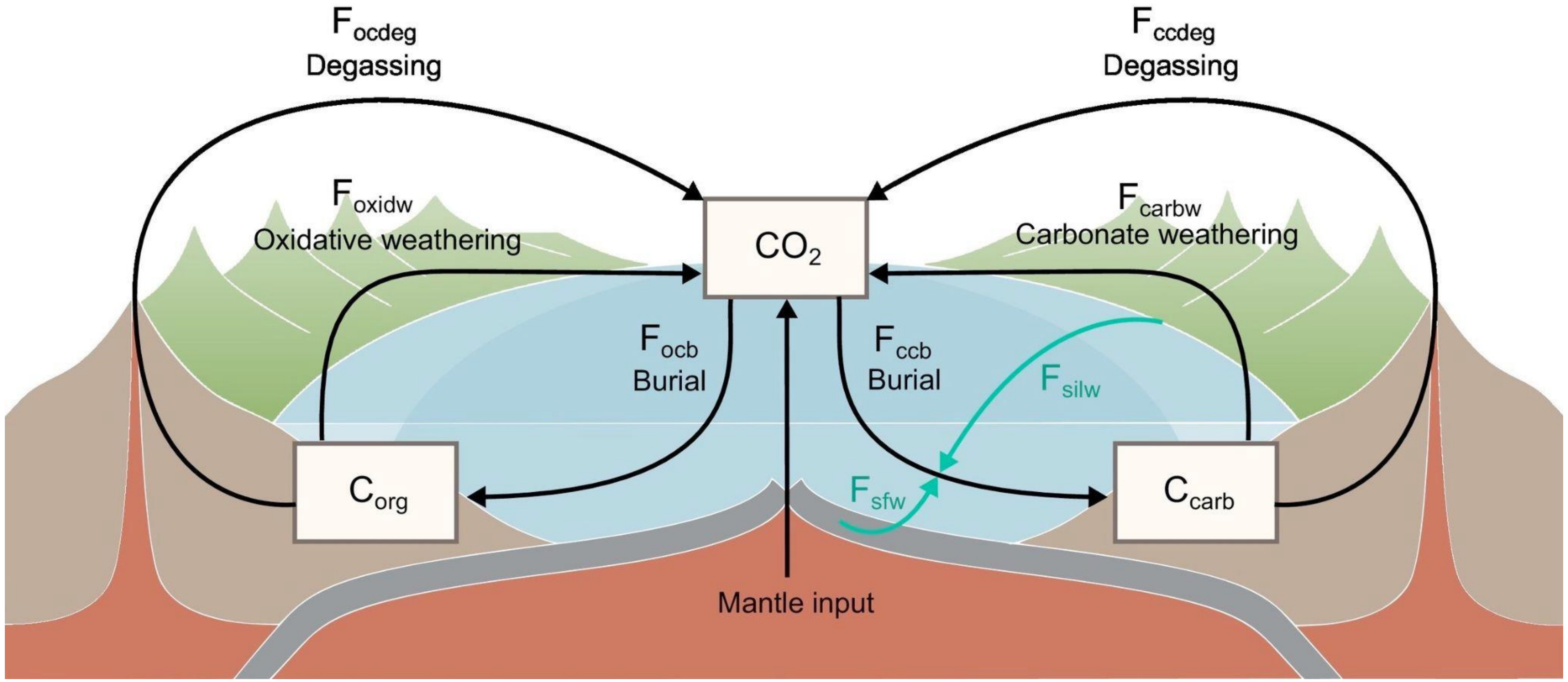
• Carbon in different forms is cycled through reservoirs via various processes:

- *Biosphere*
- *Atmosphere*
- *Soil*
- *Ocean*

(Atmospheric Infrared Sounder, CC BY 2.0)



Long-Term Carbon Cycle



On even longer timescales, tectonics play a role in carbon cycling and atmospheric CO_2 concentration:

- **Sources**: degassing from volcanic emissions and spreading centers
- **Sinks**: silicate rock weathering and carbon burial

Energy Balance

- While insolation is assumed to through a disk,
  Earth loses energy over its entire surface area.
- The total energy Earth radiated outward is $4\boldsymbol{\pi} r^2 \boldsymbol{\tau\sigma} T^4$.
- For a balanced system where energy in equals energy out we have

$$\underbrace{ASR = (1-\alpha)Q}_{\text{energy in}} = \underbrace{\tau\sigma T^4 = OLR}_{\text{energy out}} \qquad Q = S/4$$

- The temperature at which this balance occurs is called the **equilibrium temperature**.

Observed global energy budget

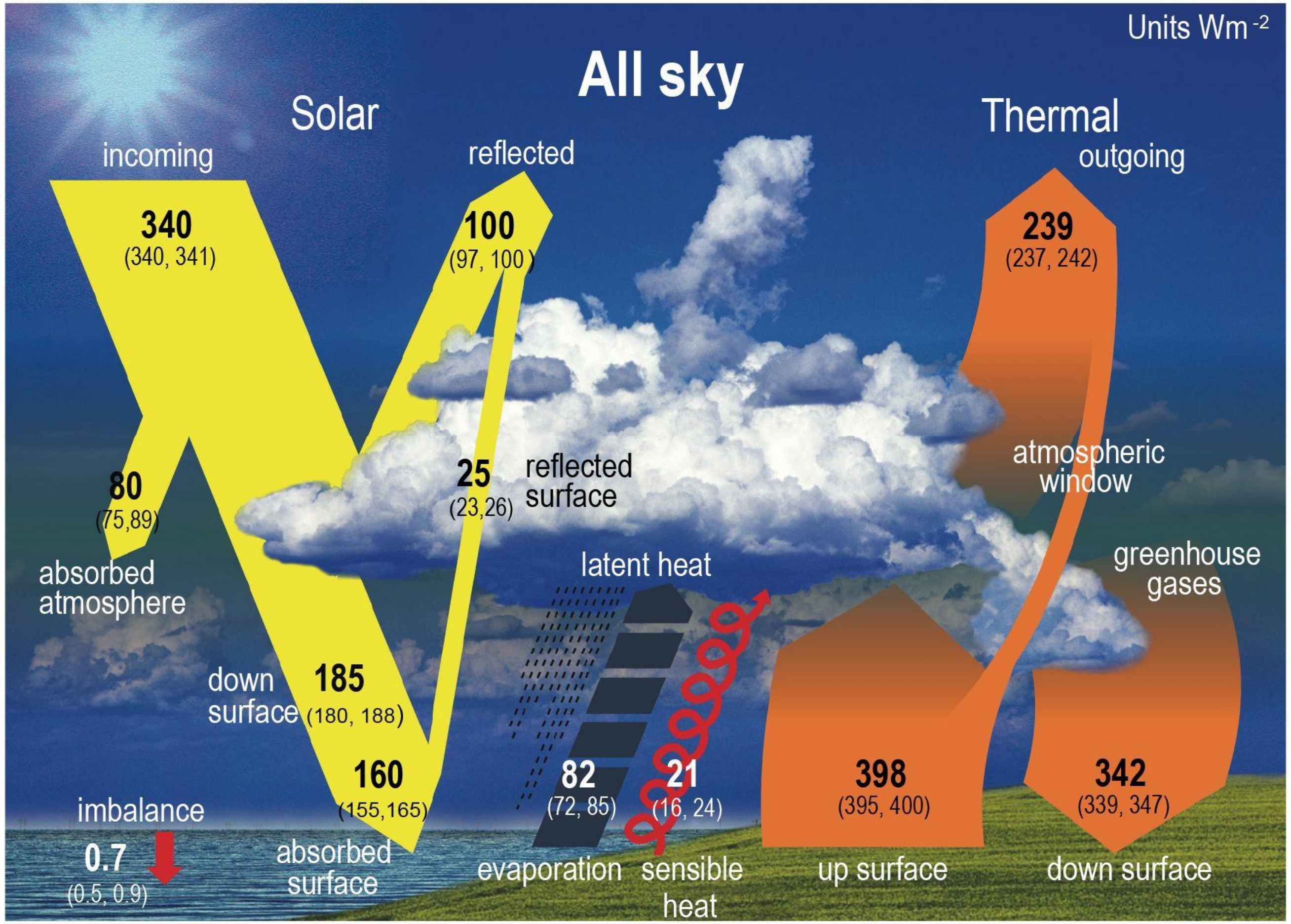
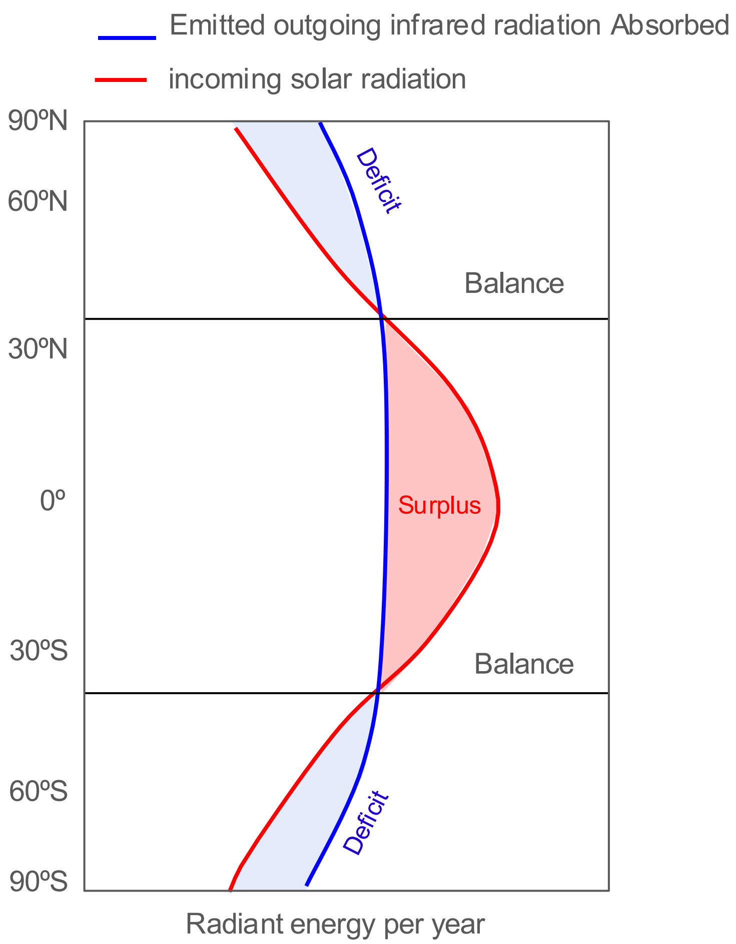
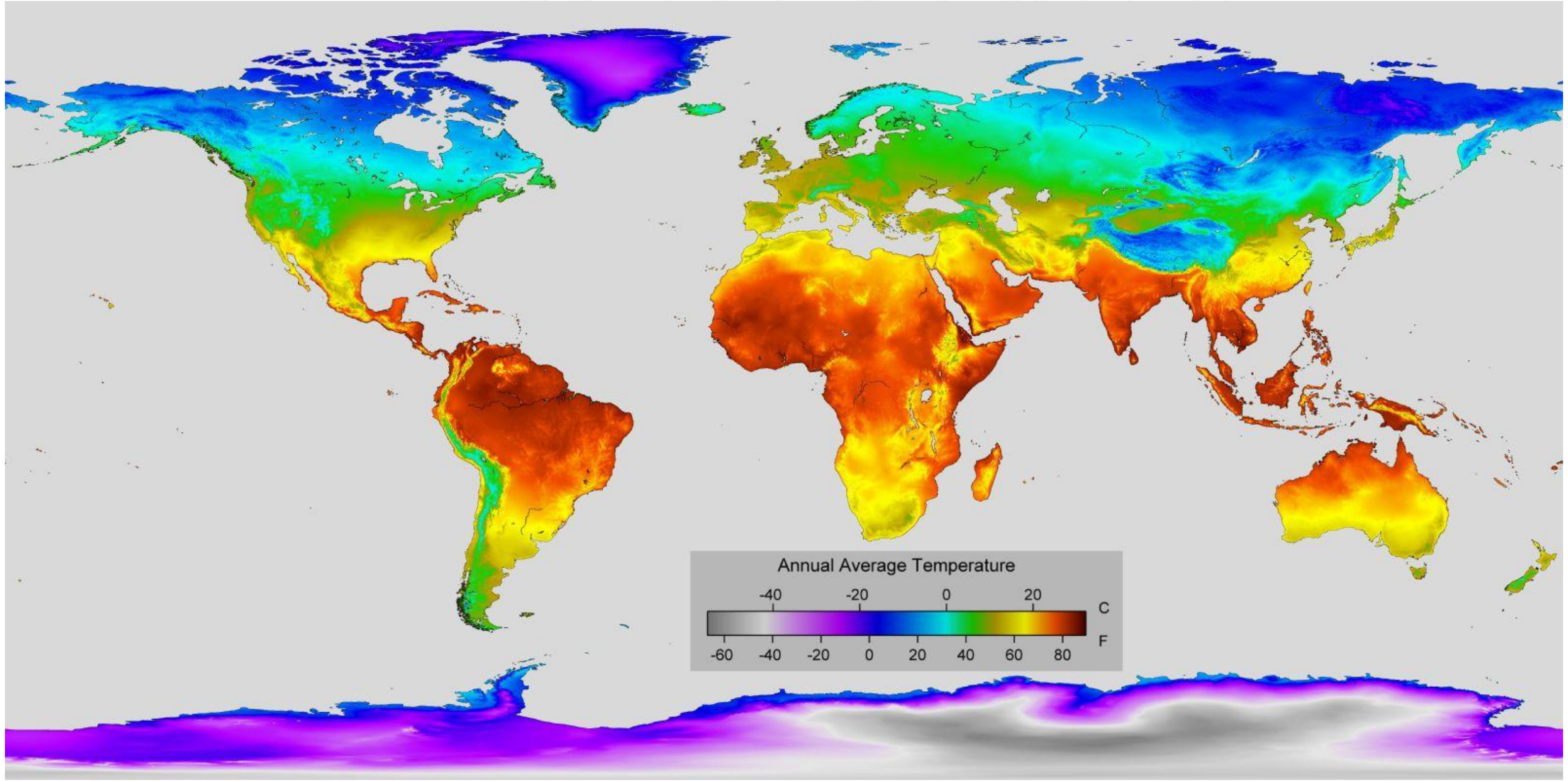


Figure 7.2 | Schematic representation of the global mean energy budget of the Earth (upper panel), and its equivalent without considerations of cloud effects (lower panel). Numbers indicate best estimates for the magnitudes of the globally averaged energy balance components in W m^{-2} together with their uncertainty ranges in parentheses (5–95% confidence range), representing climate conditions at the beginning of the 21st century. Note that the cloud-free energy budget shown in the lower panel is not the one that Earth would achieve in equilibrium when no clouds could form. It rather represents the global mean fluxes as determined solely by removing the clouds but otherwise retaining the entire atmospheric structure.
This enables the quantification of the effects of clouds on the Earth energy budget and corresponds to the way clear-sky fluxes are calculated in climate models. Thus, the cloud-free energy budget is not closed and therefore the sensible and latent heat fluxes are not quantified in the lower panel. Figure adapted from Wild et al. (2015, 2019).

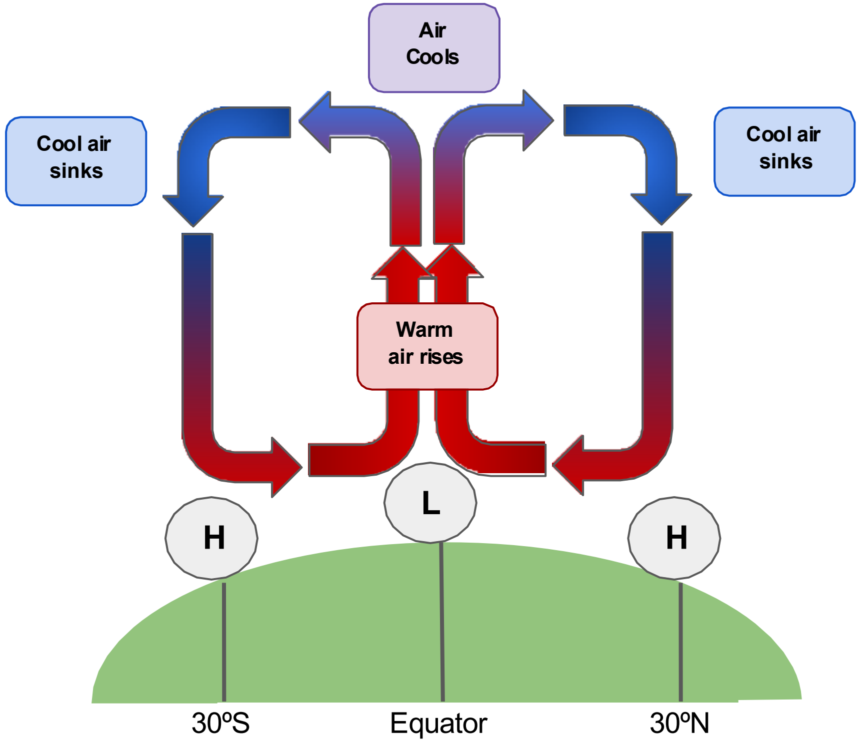
Forster et al., 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, doi:10.1017/9781009157896.009.

Solar Radiation and Temperature

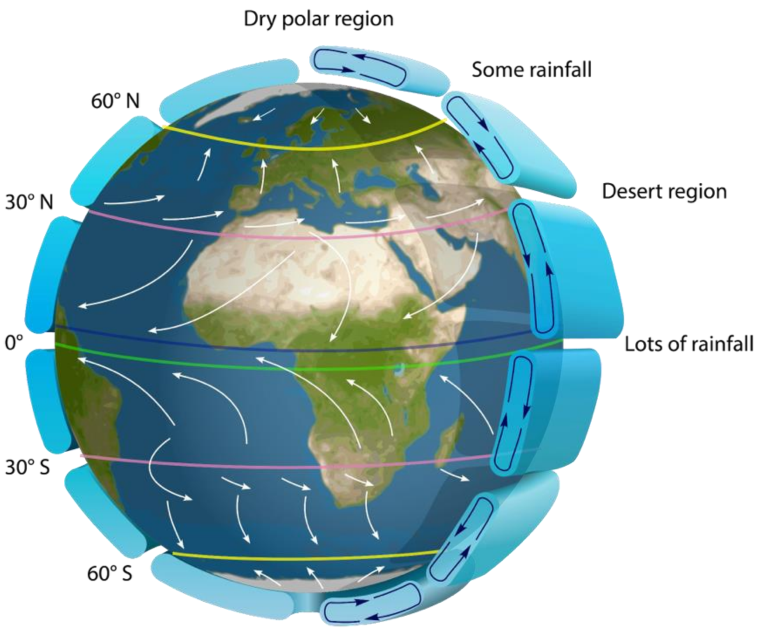


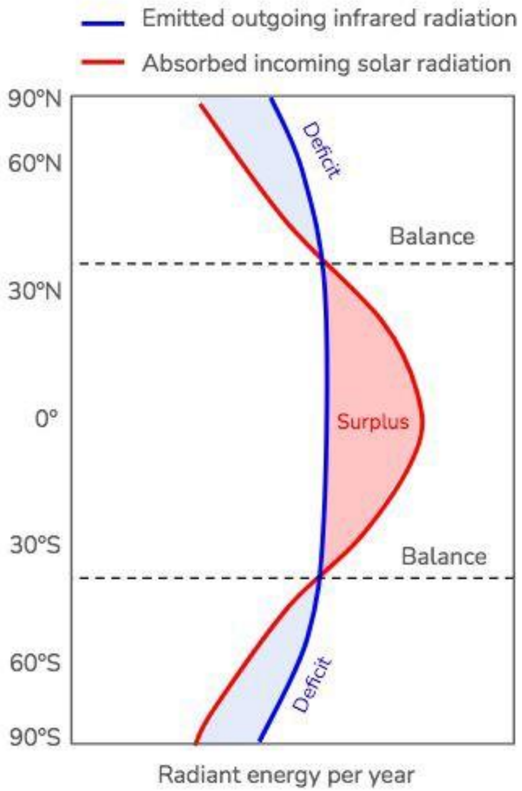


Atmospheric Circulation

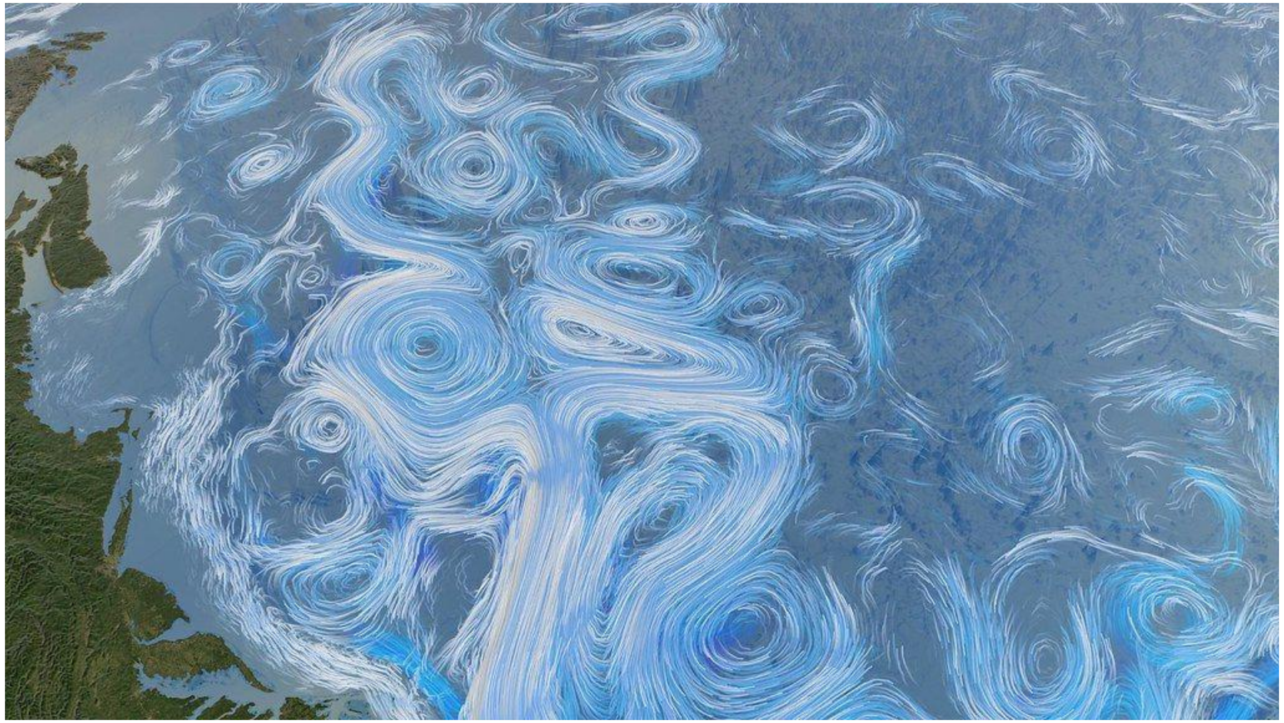


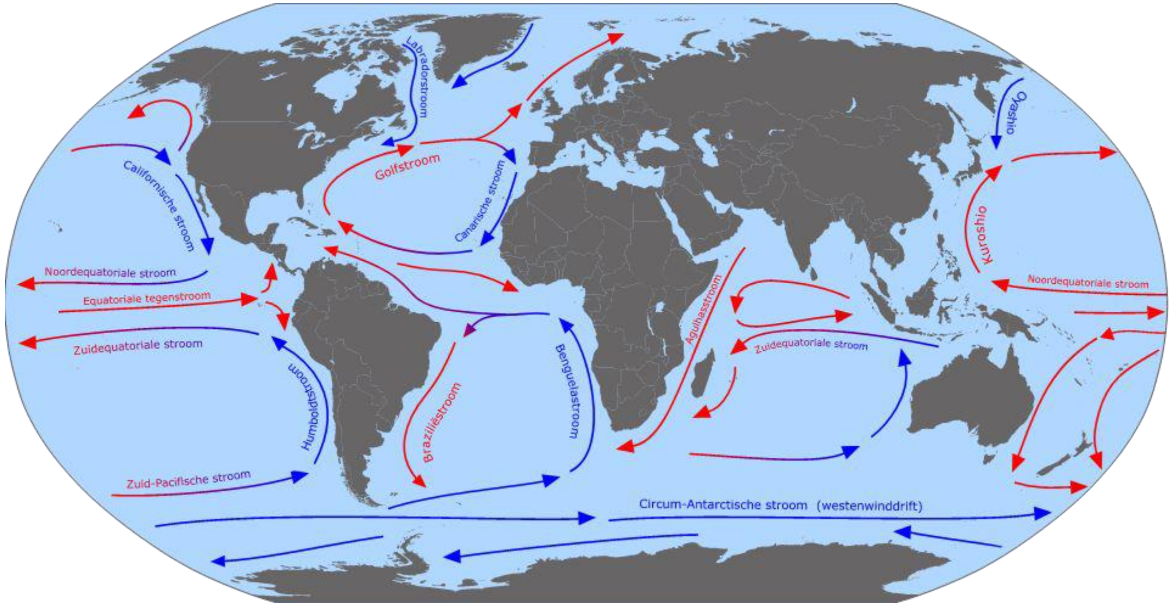
Hadley Cells: large-scale air circulation driven by atmospheric pressure and temperature gradients





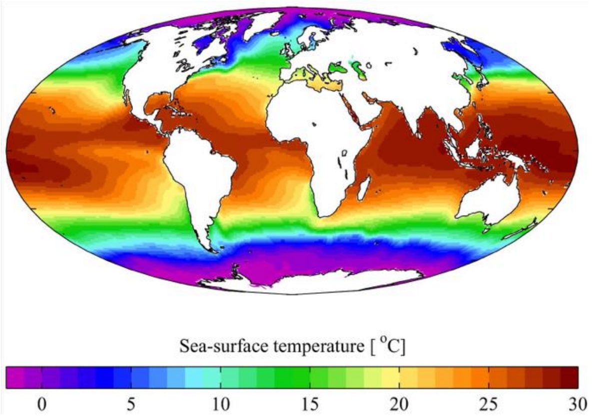
Surface Ocean Currents

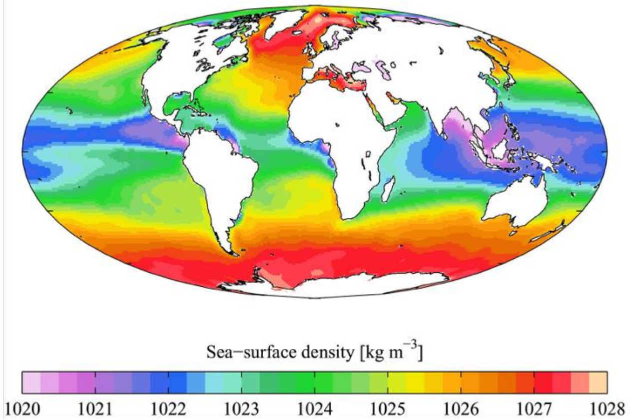




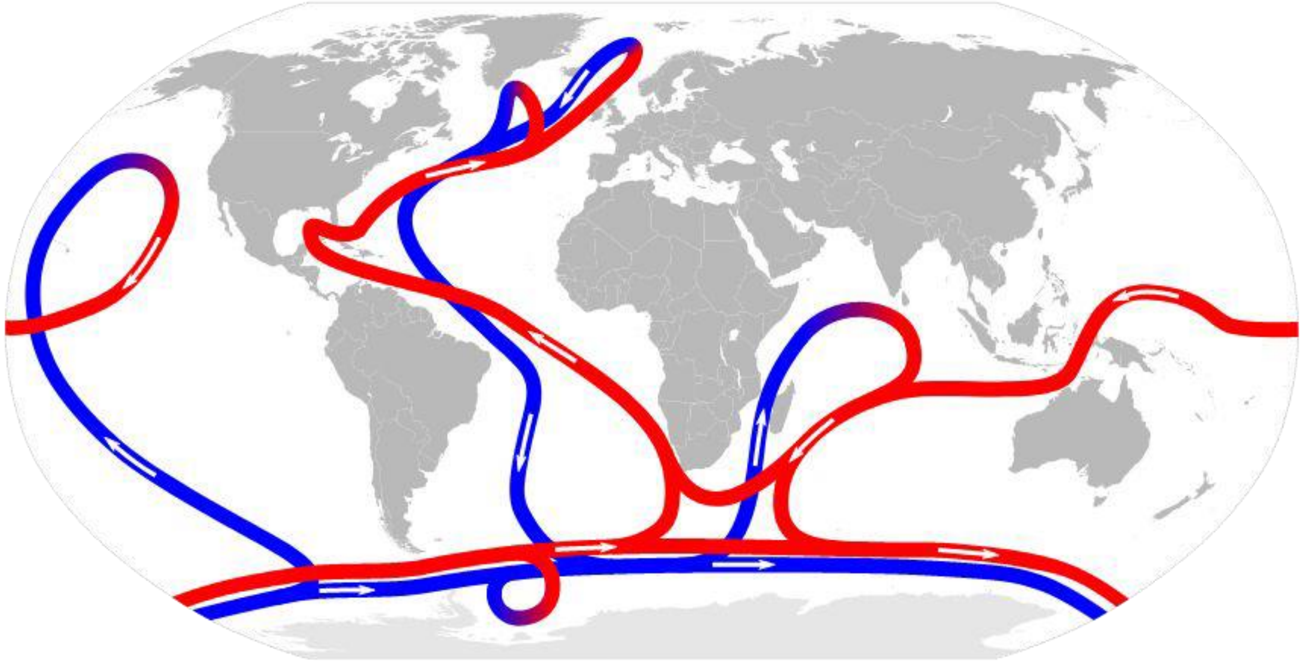
Currents in the upper 100 meters of the ocean are driven by wind

Deep-Water Ocean Circulation



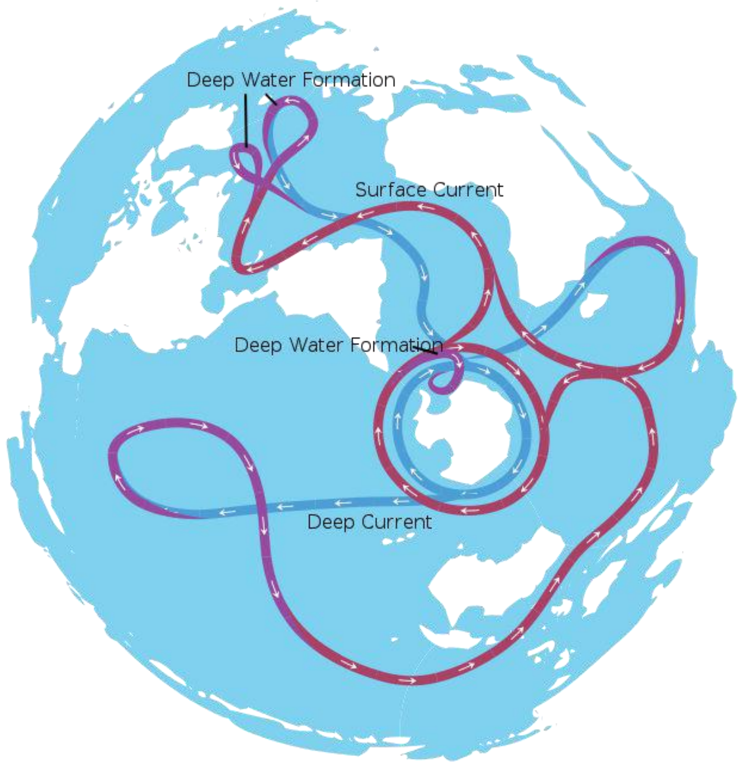


Deep-ocean currents are driven by differences in water density, controlled by water temperature and salinity

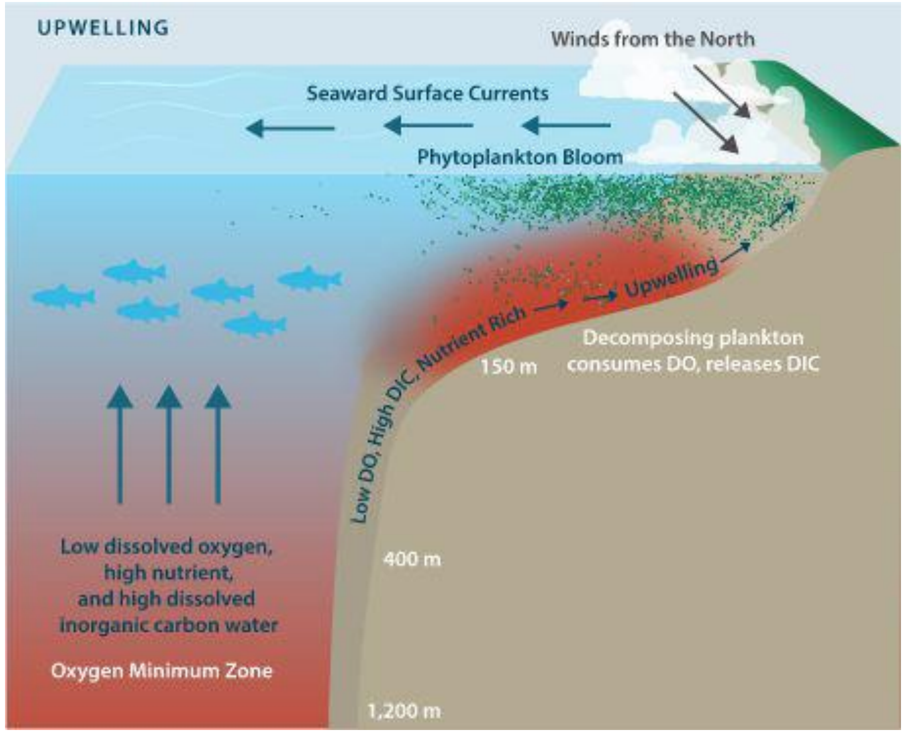


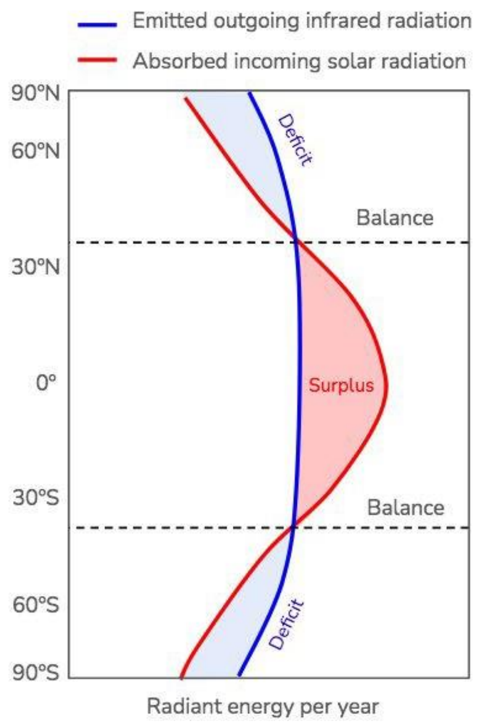
Surface and Deep-Water Interactions

North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW)

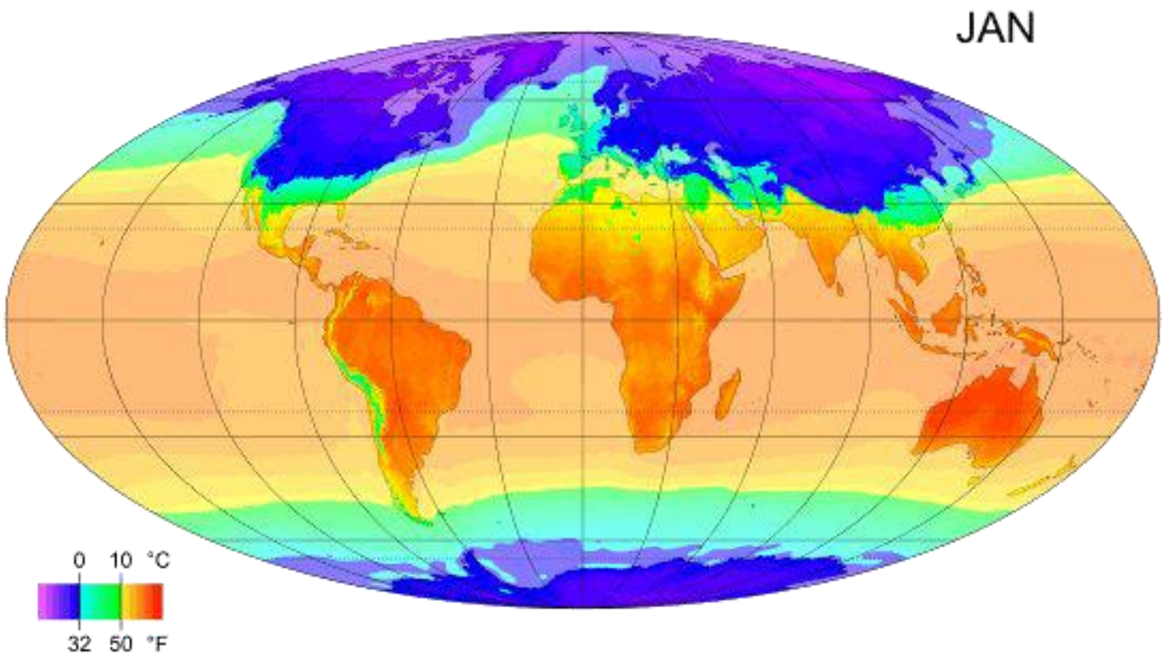


Ocean Upwelling





Land and Sea Surface Temperature Variations



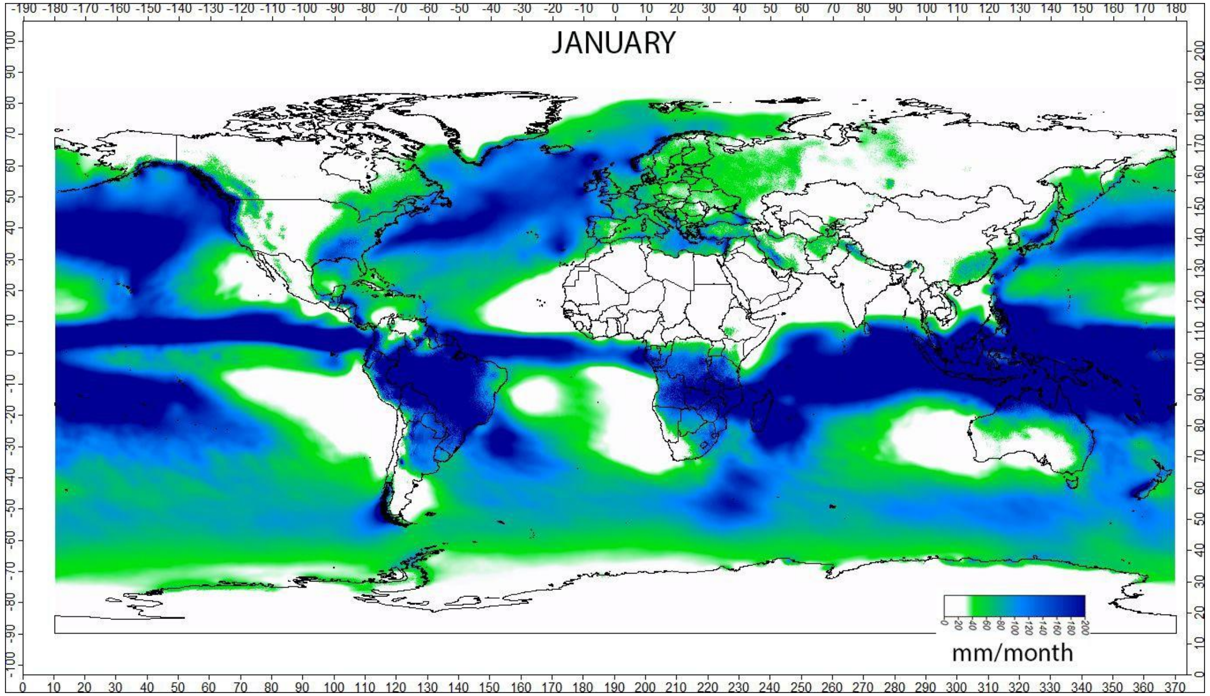
Seasonal variations in temperature cause changes in:

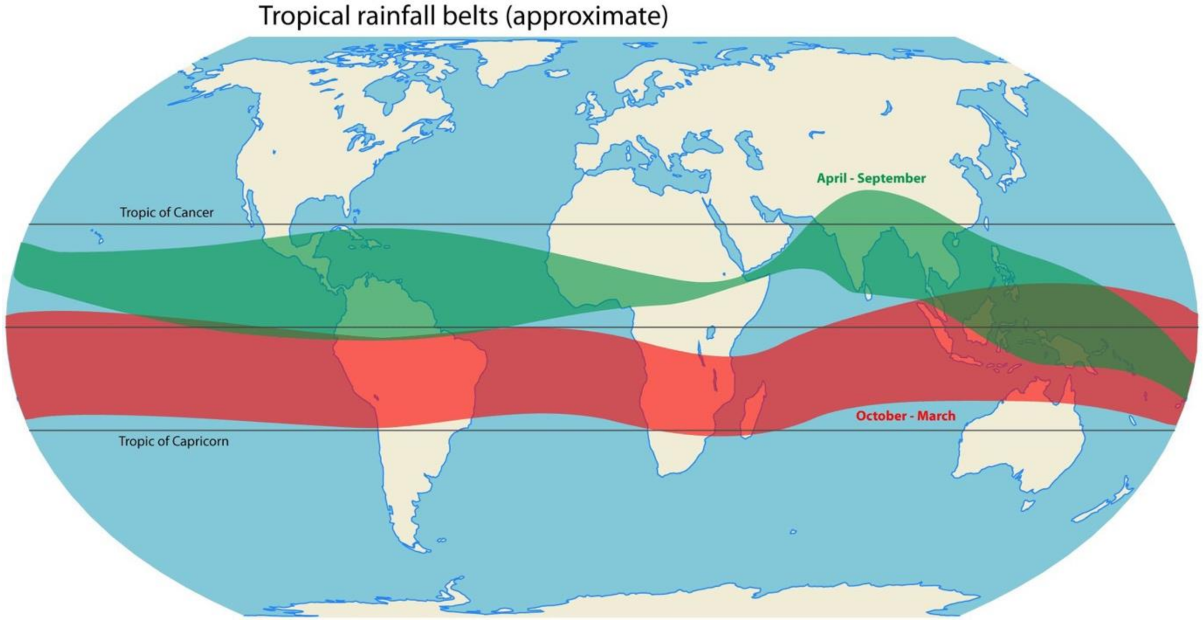
- Northern and Southern Hemisphere temperature gradients
- Land-sea temperature gradients

*Both of these changes affect **rainfall***

Intertropical Convergence Zone (ITCZ)

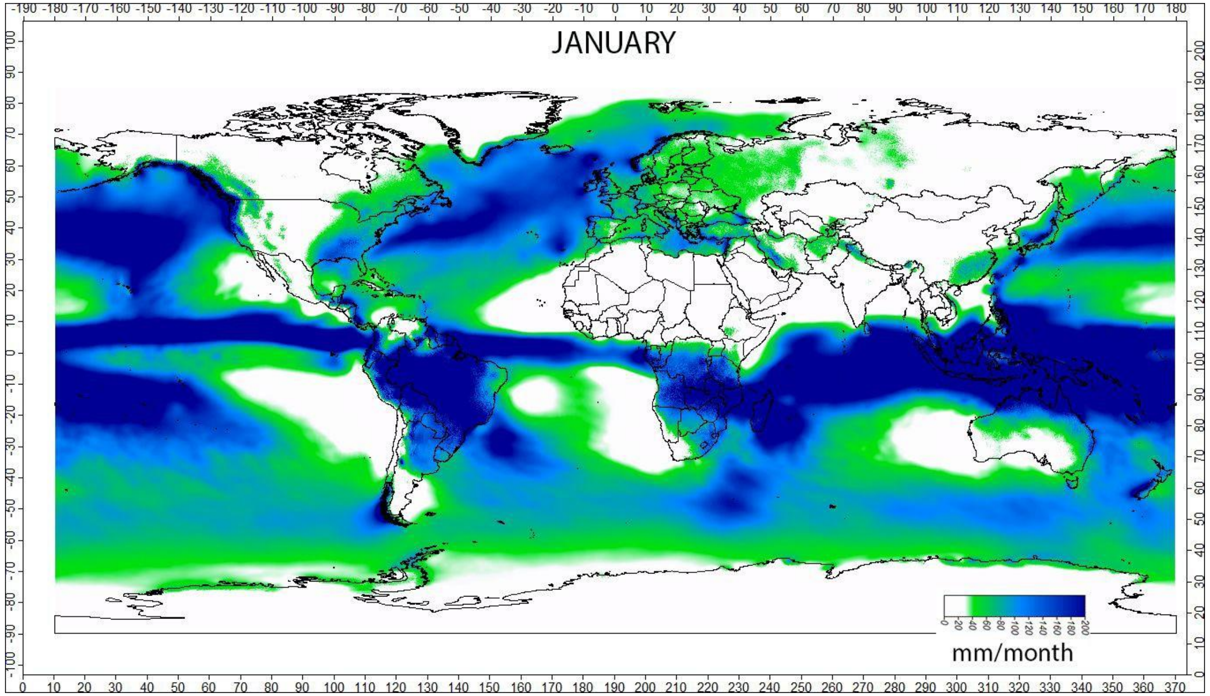
The ITCZ is a band of moist, converging air in the tropics that produces large amounts of rainfall and migrates seasonal in a north-south direction towards the warmer hemisphere

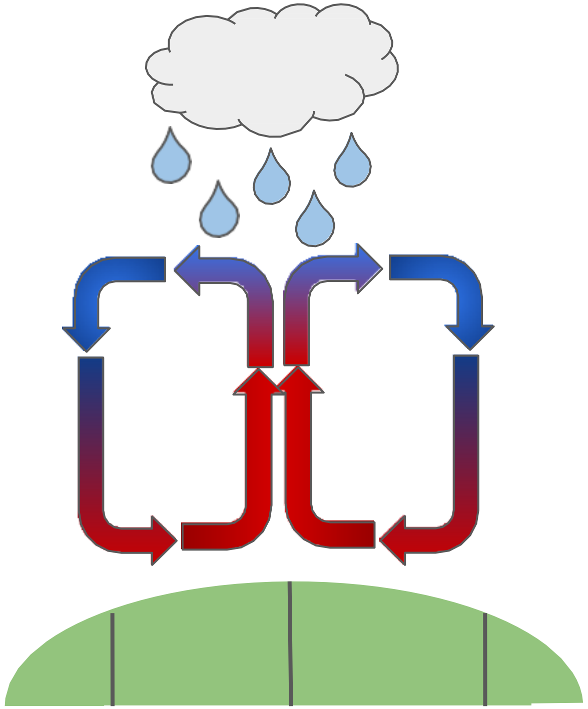




Intertropical Convergence Zone (ITCZ)

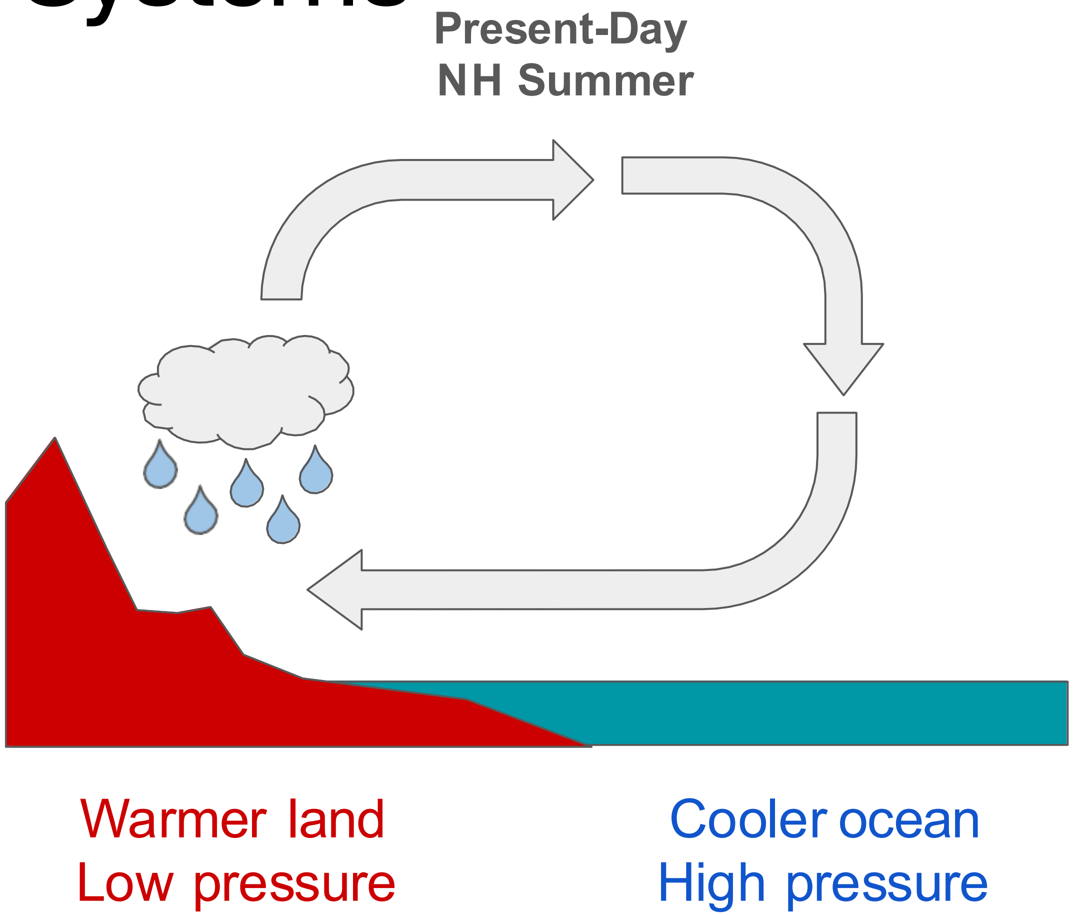
The ITCZ is a band of moist, converging air in the tropics that produces large amounts of rainfall and migrates seasonal in a north-south direction towards the warmer hemisphere

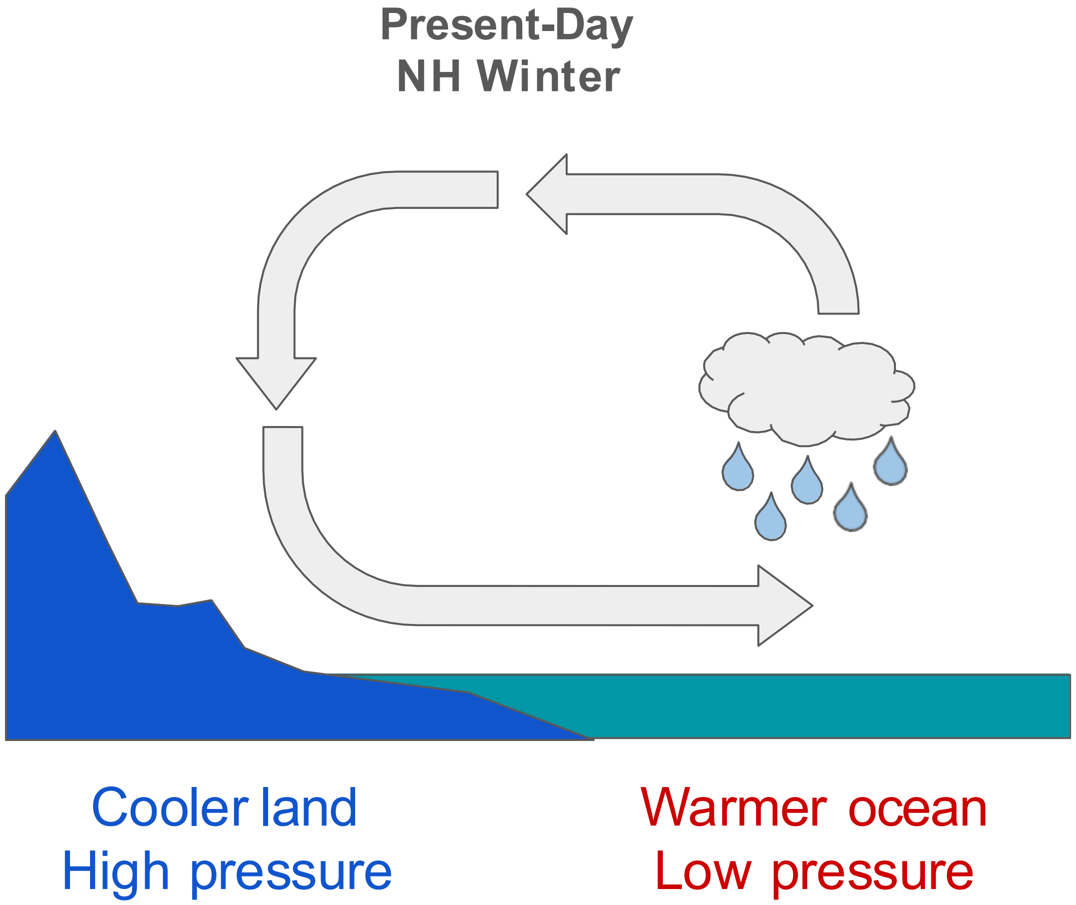




The ITCZ forms where equatorial air masses converge and rise!

Monsoon Systems



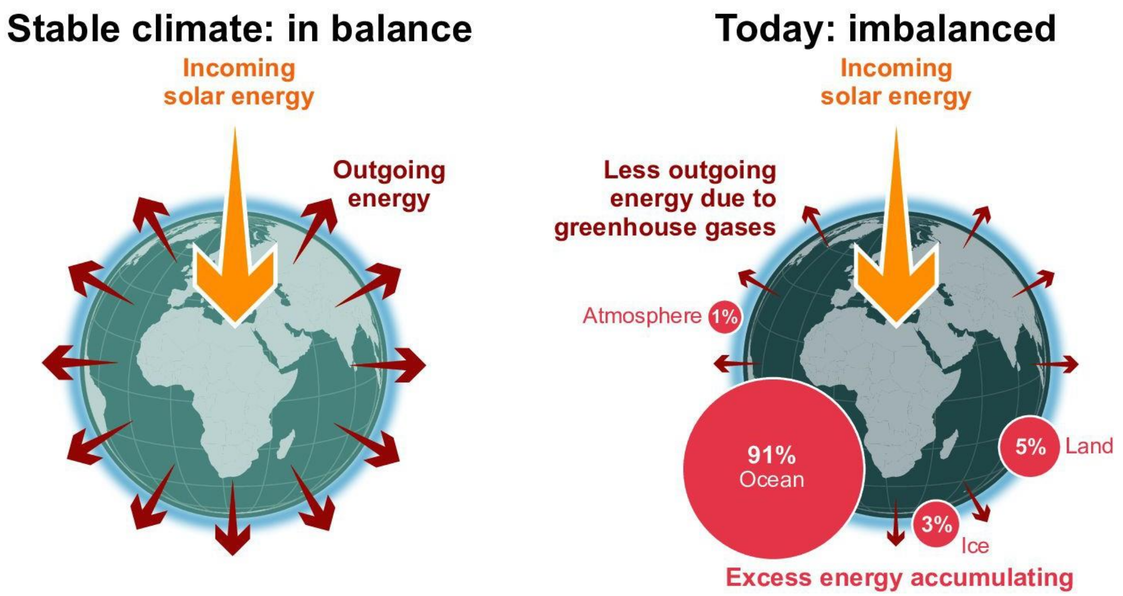


Energy Imbalance

- Human activity has caused an imbalance in Earth's energy budget.
- This has been primarily through increased greenhouse gases and pollutants.

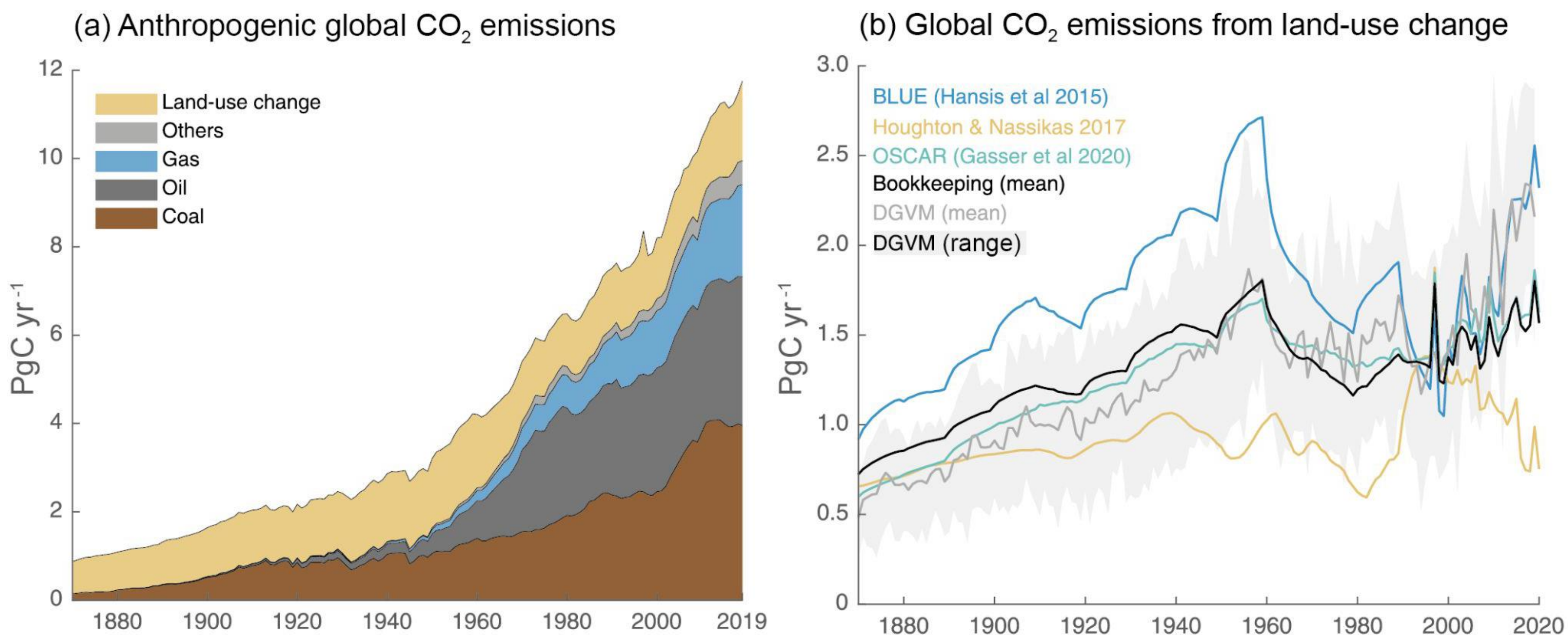
FAQ 7.1: **The Earth's energy budget and climate change**

Since at least 1970, there has been a persistent imbalance in the energy flows that has led to excess energy being absorbed by different components of the climate system.



https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/faq-7-1-figure-1/

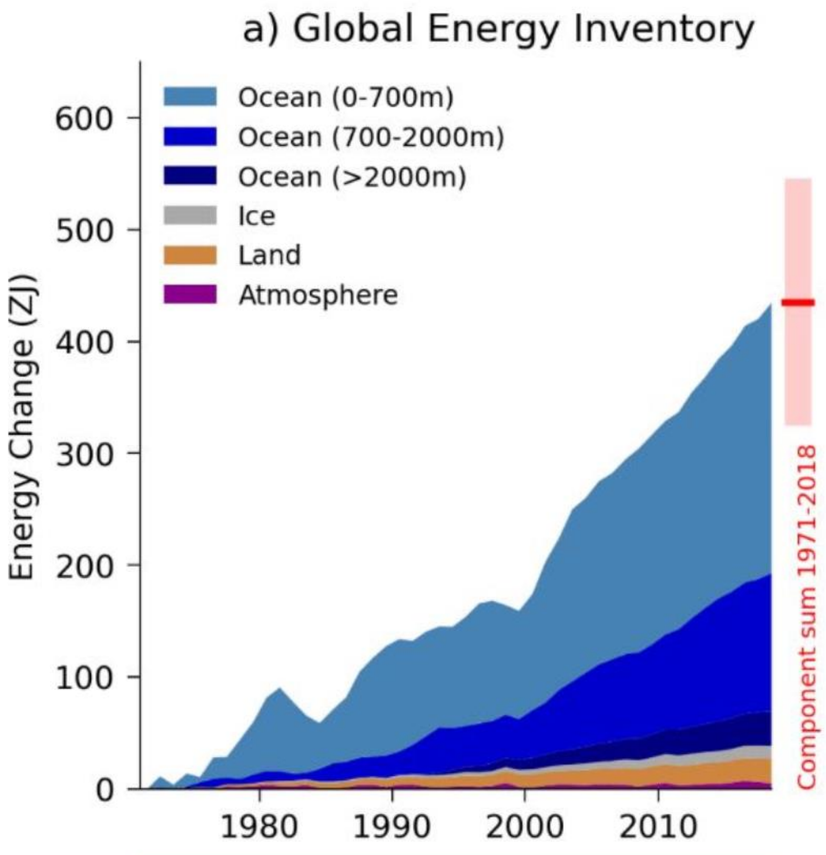
Anthropogenic Greenhouse Gas Emissions



(Figure 5.5 in IPCC, 2021: Chapter 5. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Canadell, J.G, et al.)

Figure 5.5 | Global anthropogenic CO_2 emissions. (a) Historical trends of anthropogenic CO_2 emissions (fossil fuels and net land-use change, including land management, called LULUCF flux in the main text) for the period 1870 to 2019, with 'others' representing flaring, emissions from carbonates during cement manufacture. Data sources: (Boden et al., 2017; IEA, 2017; Andrew, 2018; BP, 2018; Le Quéré et al., 2018a; Friedlingstein et al., 2020). (b) The net land-use change CO_2 flux (PgC yr^{-1}) as estimated by three bookkeeping models and 16 Dynamic Global Vegetation Models (DGVMs) for the global annual carbon budget 2019 (Friedlingstein et al., 2020). The three bookkeeping models are from Hansis et al., 2015; Houghton and Nassikas, 2017; Gasser et al., 2020 and are all updated to 2019. Their average is used to determine the net land-use change flux in the annual global carbon budget (black line). The DGVM estimates are the result of differencing a simulation with and without land-use changes run under observed historical climate and CO_2, following the Trendy v9 protocol (https://sites.exeter.ac.uk/trendy/protocol/); they are used to provide an uncertainty range to the bookkeeping estimates (Friedlingstein et al., 2020). All estimates are unsmoothed annual data. Estimates differ in process comprehensiveness of the models and in definition of flux components included in the net land use change flux. Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

Ocean heat uptake



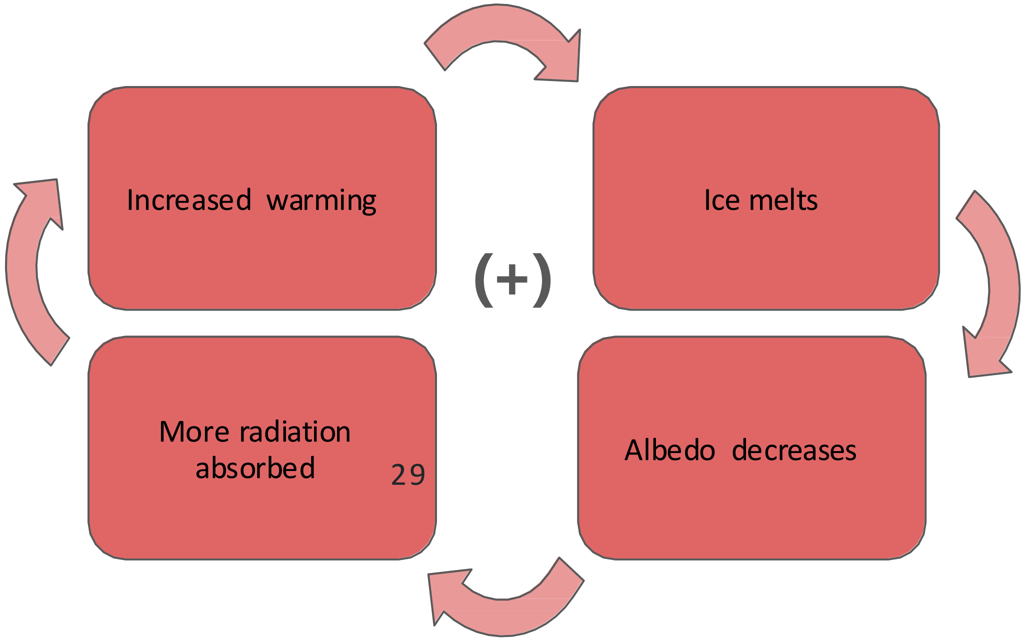
Cross-Chapter 9.1, Figure 1 | Global Energy Inventory and Sea Level Budget. (a) Observed changes in the global energy inventory for 1971–2018 (shaded time series) with component contributions as indicated in the figure legend. Earth System Heating for the whole period and associated uncertainty is indicated to the right of the plot (red bar = central estimate; shading = *very likely* range); **(b)** Observed changes in components of global mean sea level for 1971–2018 (shaded time series) as indicated in the figure legend. Observed global mean sea level change from tide gauge reconstructions (1971–1993) and satellite altimeter measurements (1993–2018) is shown for comparison (dashed line) as a three-year running mean to reduce sampling noise. Closure of the global sea level budget for the whole period is indicated to the right of the plot (red bar = component sum central estimate; red shading = *very likely* range; black bar = total sea level central estimate; grey shading = *very likely* range). Full details of the datasets and methods used are available in Annex I. Further details on energy and sea level components are reported in Table 7.1 and Table 9.5.

- **The planet is warming**
- **Heat capacity of water is greater than heat capacity of air**
- **91% of the heat goes into the ocean**
- **56% of the heat goes into the top 700m of the ocean**

AR6 WG1 Cross-Chapter Box 9.1, Figure 1 (left panel)

Ice-Albedo Feedback

- When Earth **warms**/**cools**:
  - Ice and snow **melt**/**form**,
  - Earth's surface is **less**/**more** reflective
  - The albedo **lowers**/**rises**
  - Earth absorbs **more**/**less** energy.
- This is a **positive feedback**, meaning it amplifies the direction of change.



Key feedbacks

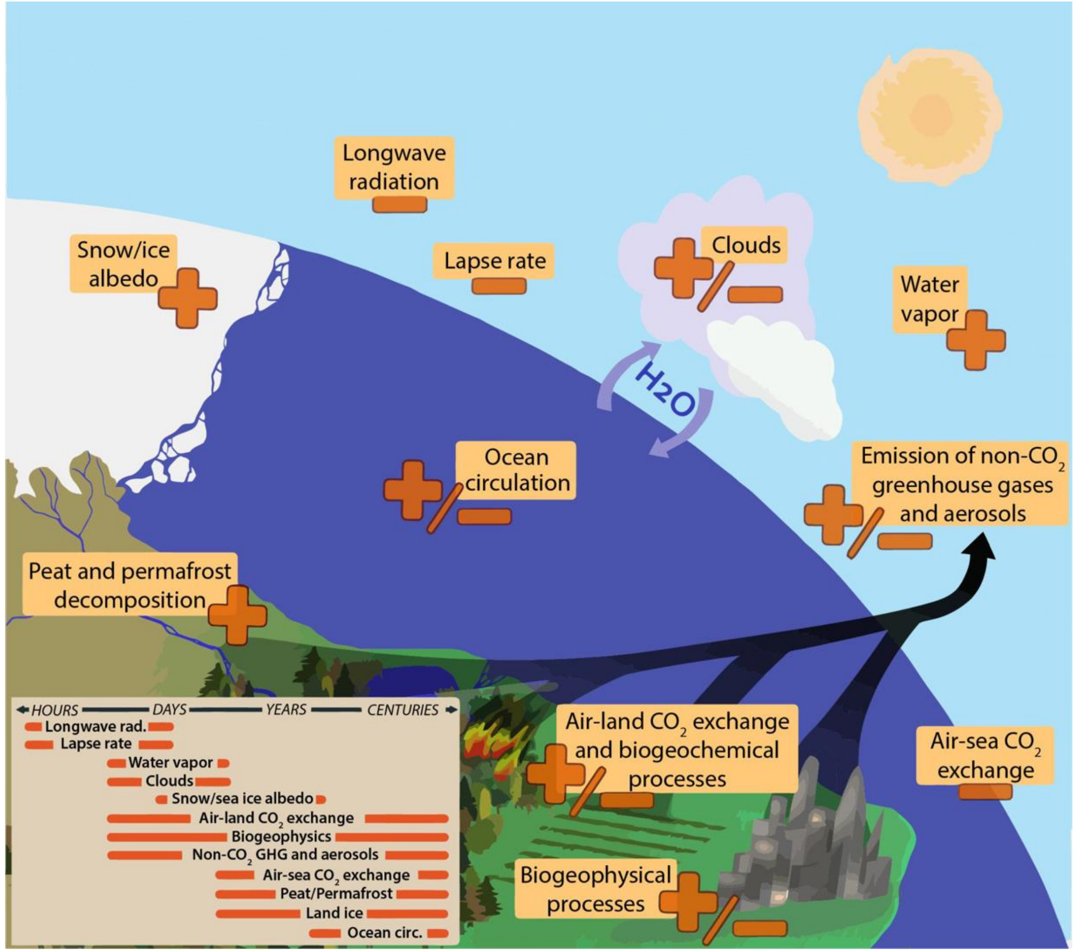
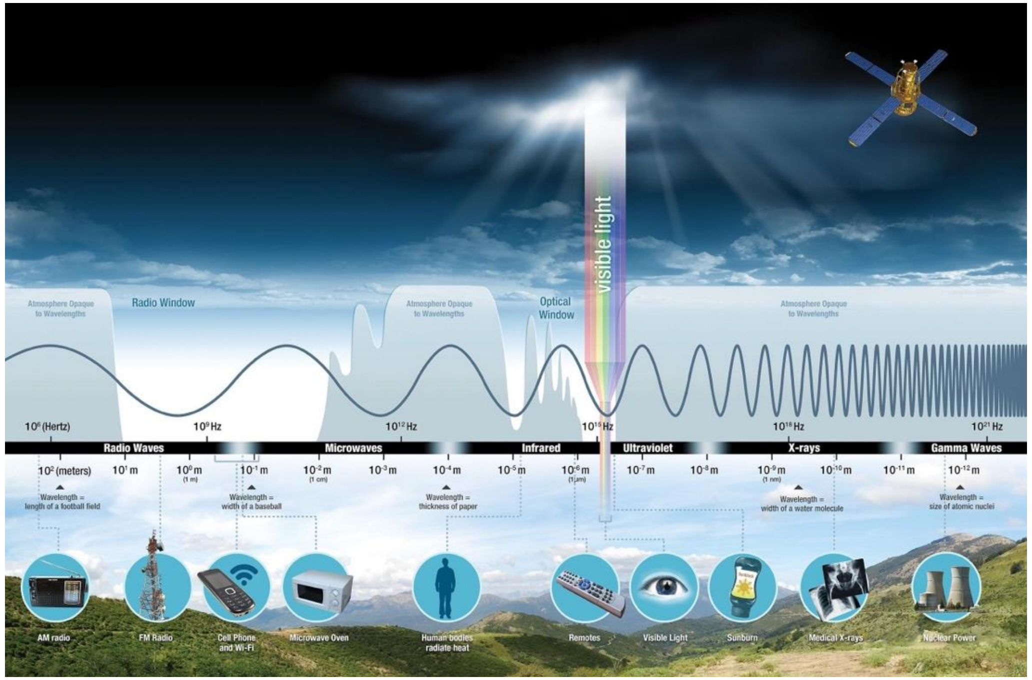


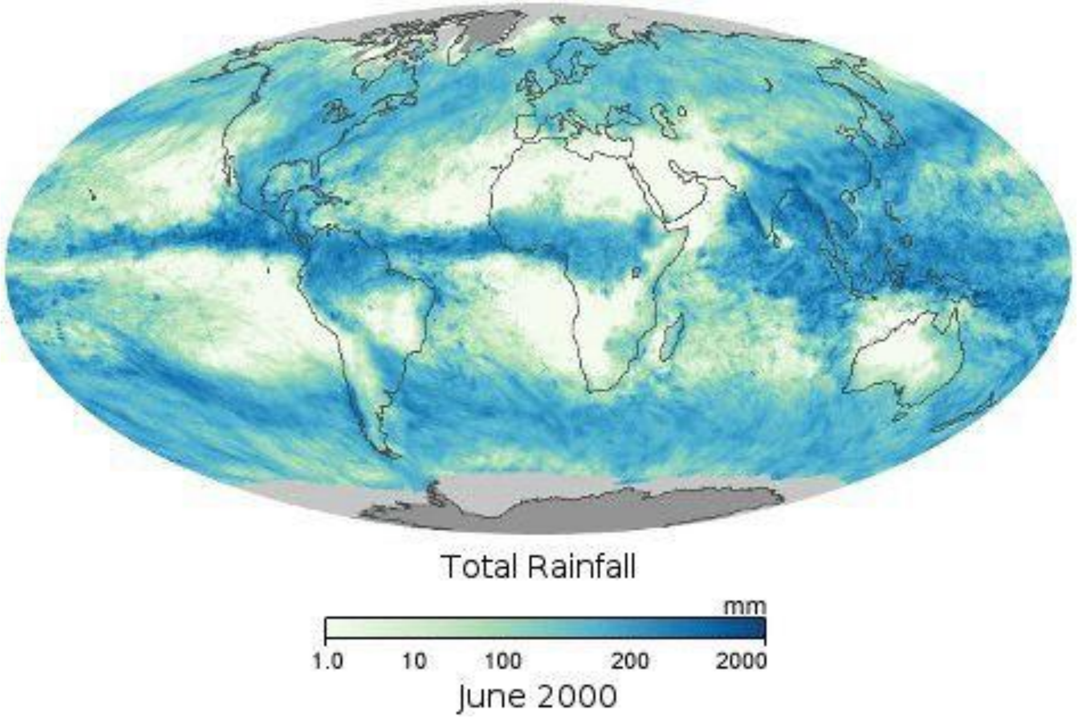
Figure 1.2 | Climate feedbacks and timescales. The climate feedbacks related to increasing CO2 and rising temperature include negative feedbacks (–) such as LWR, lapse rate (see Glossary in Annex III), and air–sea carbon exchange and positive feedbacks (+) such as water vapour and snow/ice albedo feedbacks. Some feedbacks may be positive or negative (±): clouds, ocean circulation changes, air–land CO2 exchange, and emissions of non-GHGs and aerosols from natural systems. In the smaller box, the large difference in timescales for the various feedbacks is highlighted.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Remote sensing

- Remote sensing is the technique of getting information from a distance.
- The most common remote sensing in our daily life – photography.
- In Earth science context, we often refer to satellite and airborne platforms.





Satellite Climate Data Records (CDR)

- Climate Data Records (CDR): *A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.*

- Essential Climate Variable (ECV): *A physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth' s climate (e.g., rainfall, temperature).*

Finding Satellite Climate Data Records

NOAA

Climate Data Records

Access: National Centers for Environmental Information & public cloud storage

~40 data sets for land, ocean, and atmosphere

NASA

Earth System Data Records

Access: NASA Earthdata

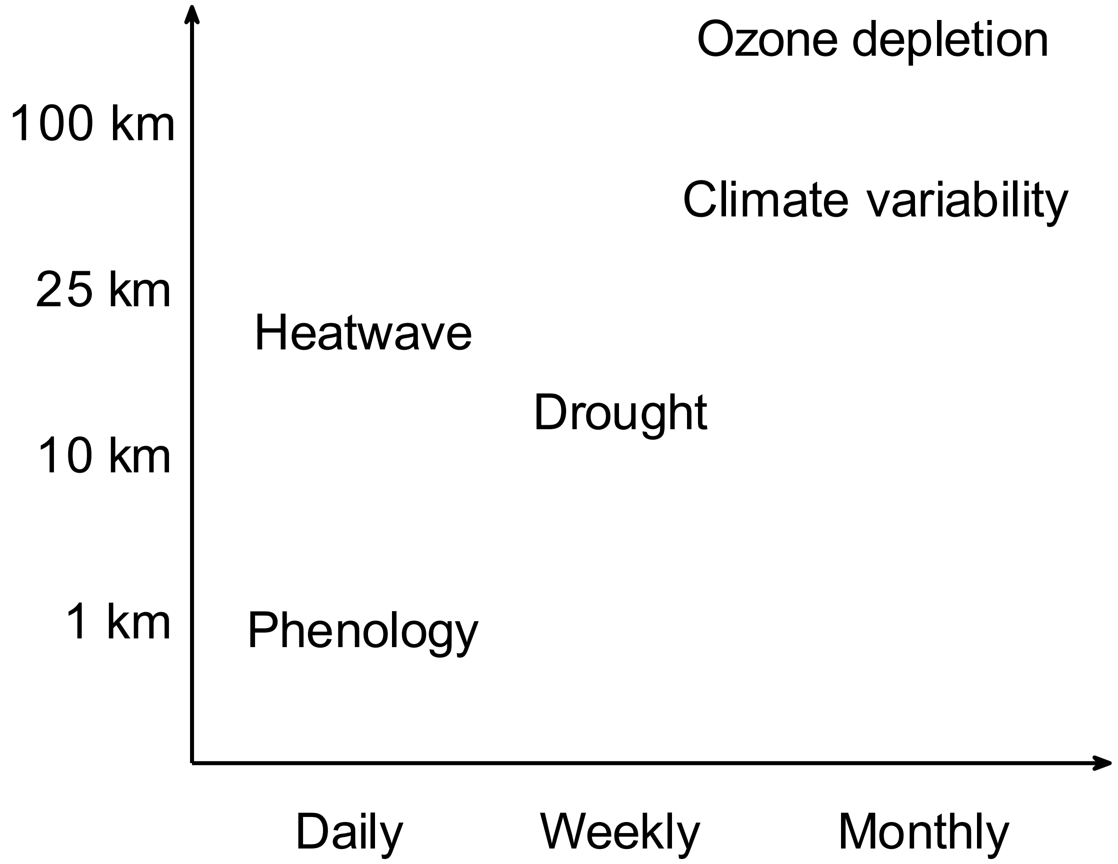
A selection of research quality long term records that may be used for climate applications

ESA

Climate Change Initiatives

Access: ESA CCI Open Data Portal

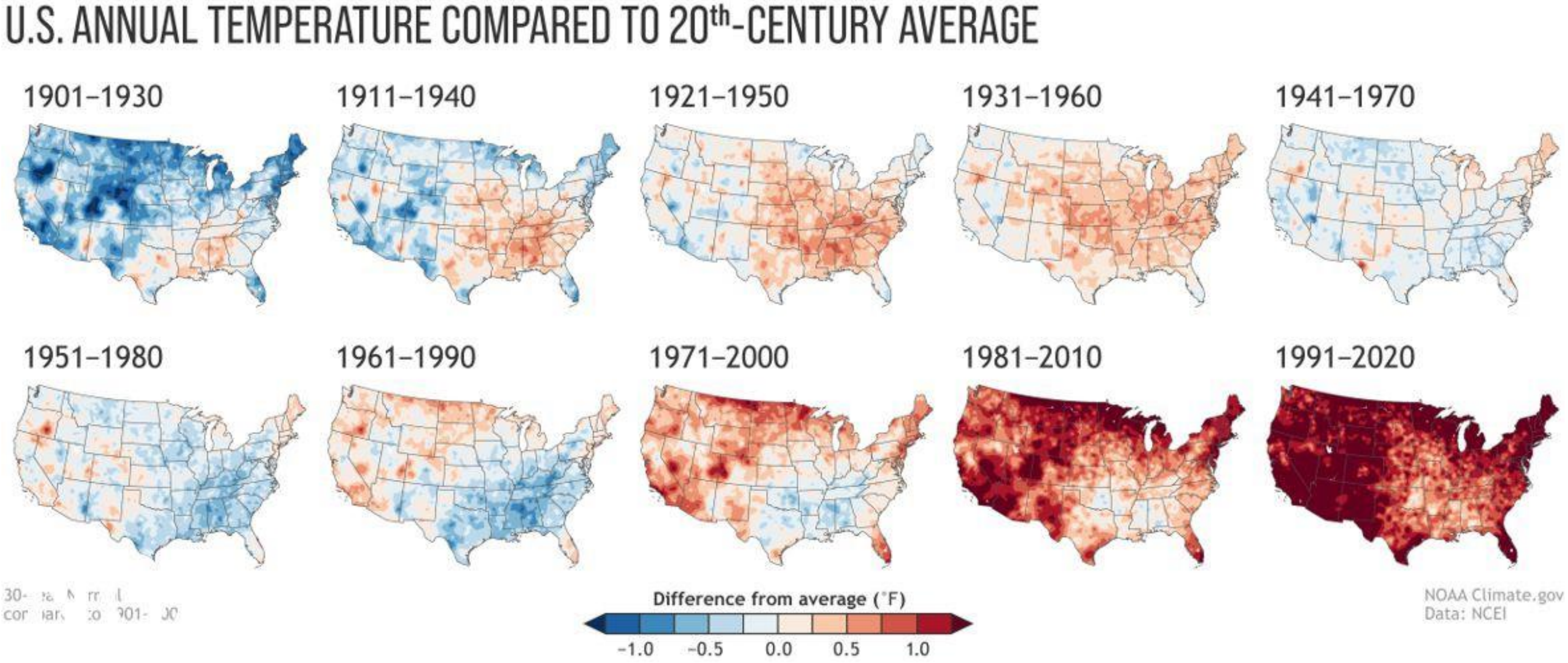
26 essential climate variables to study land, ocean, and atmosphere



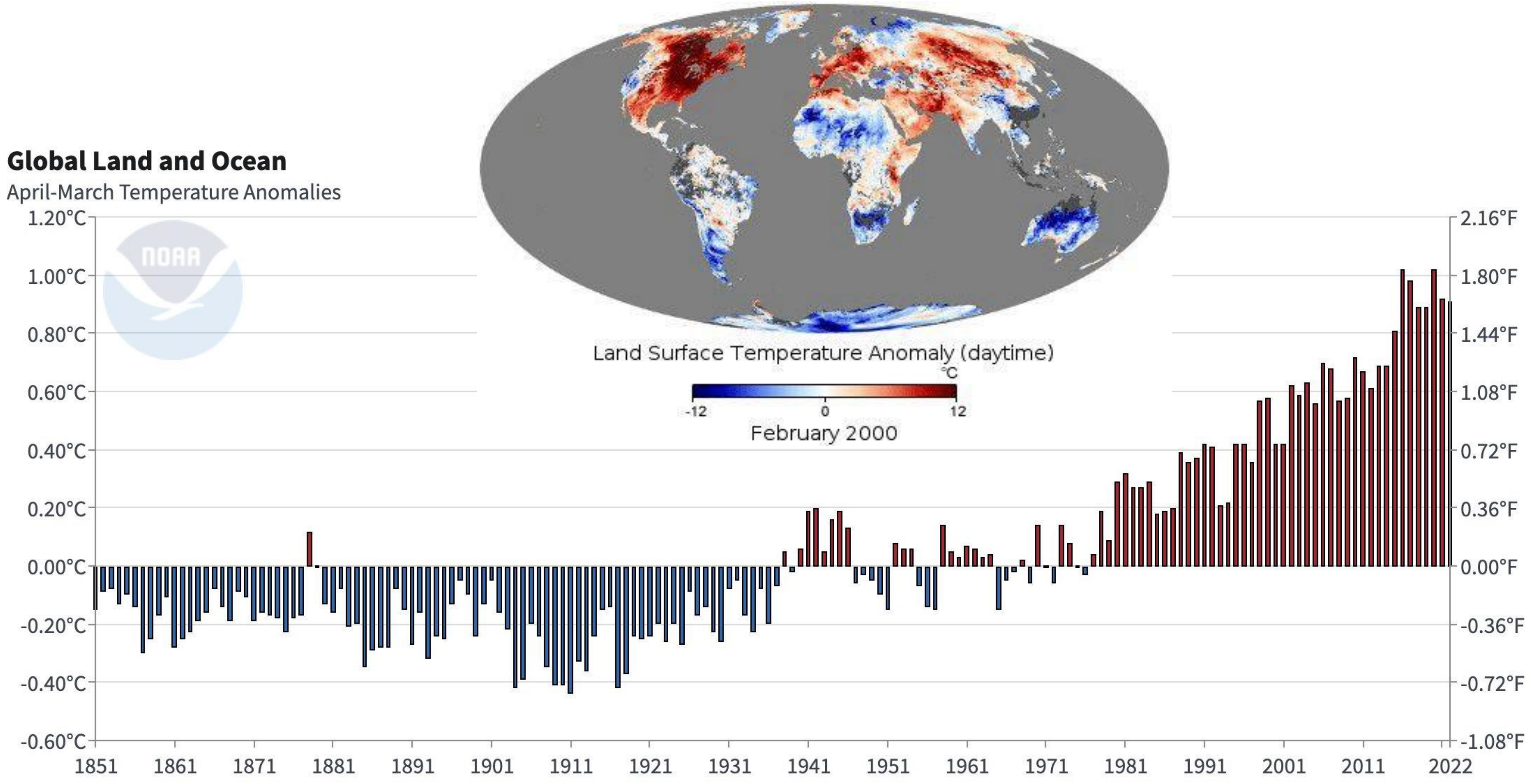
The spatial and temporal resolution of satellite CDR are critical for different climate applications.

The variety of the satellite CDR can be used for climate research from local to global scale.

Change of Climatology



Anomaly for Climate Monitoring

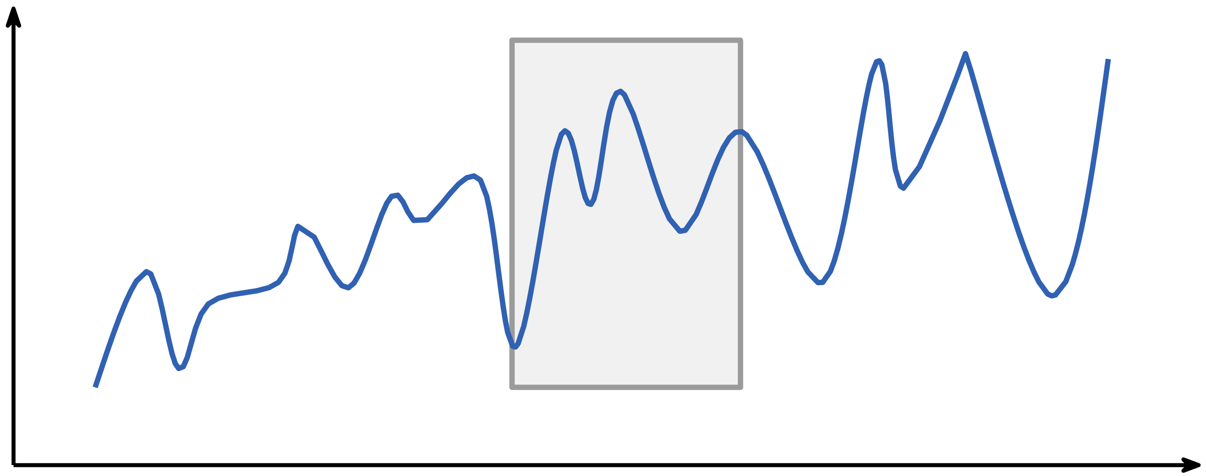


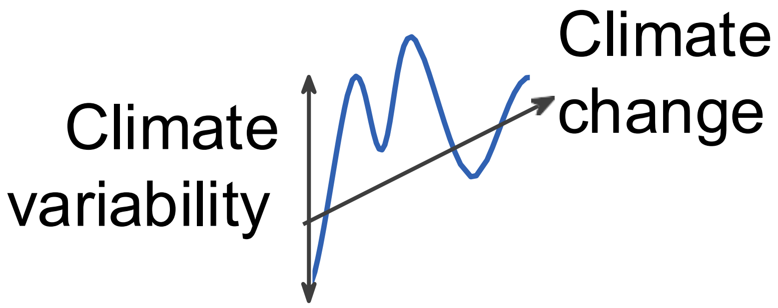
Observed global average surface temperature anomaly are one of the key indicators for monitoring climate change.

Credit: NOAA

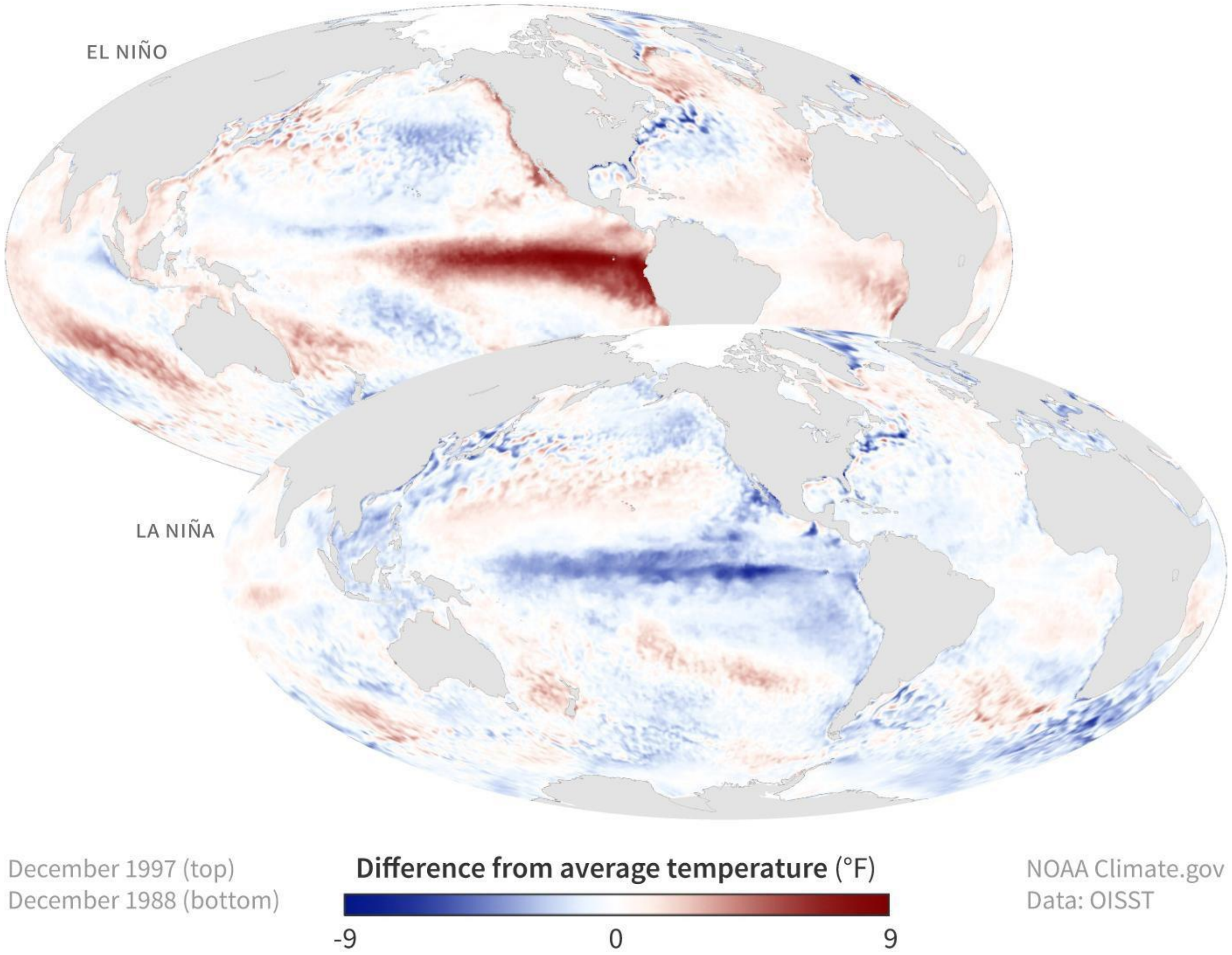
Climate Variability

- Climate variability is often defined as the temporal variations of the atmosphere–ocean system around a mean state. This usually occurs at a longer time scale (i.e., monthly/seasonal to decadal).





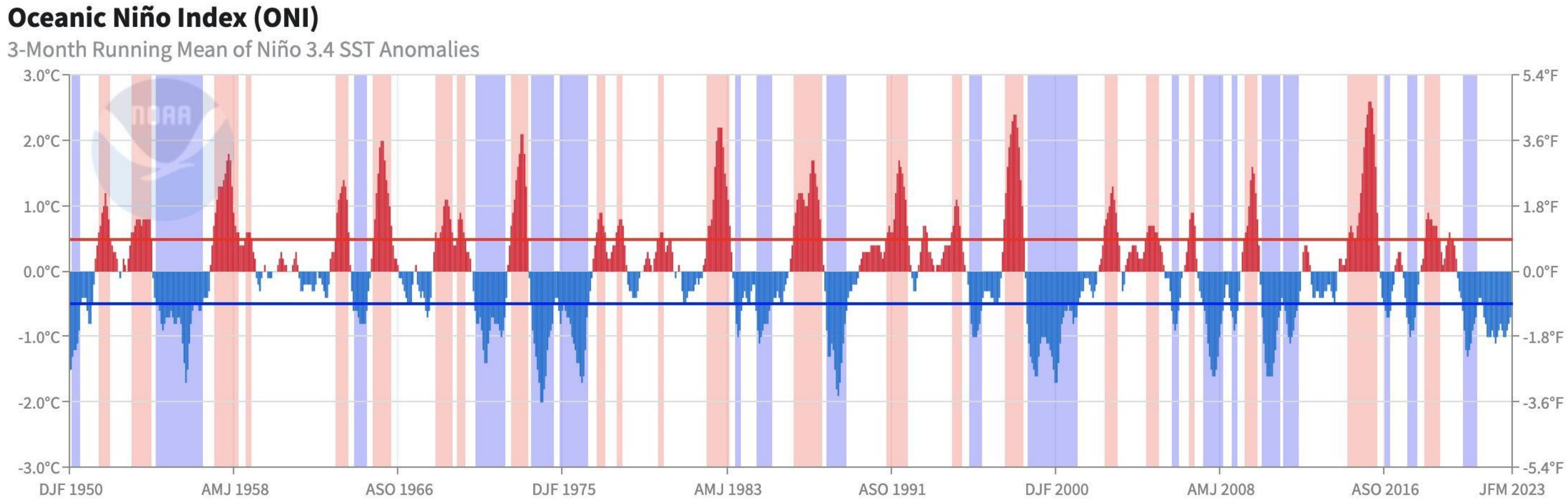
ONI TEMPERATURE PATTERNS



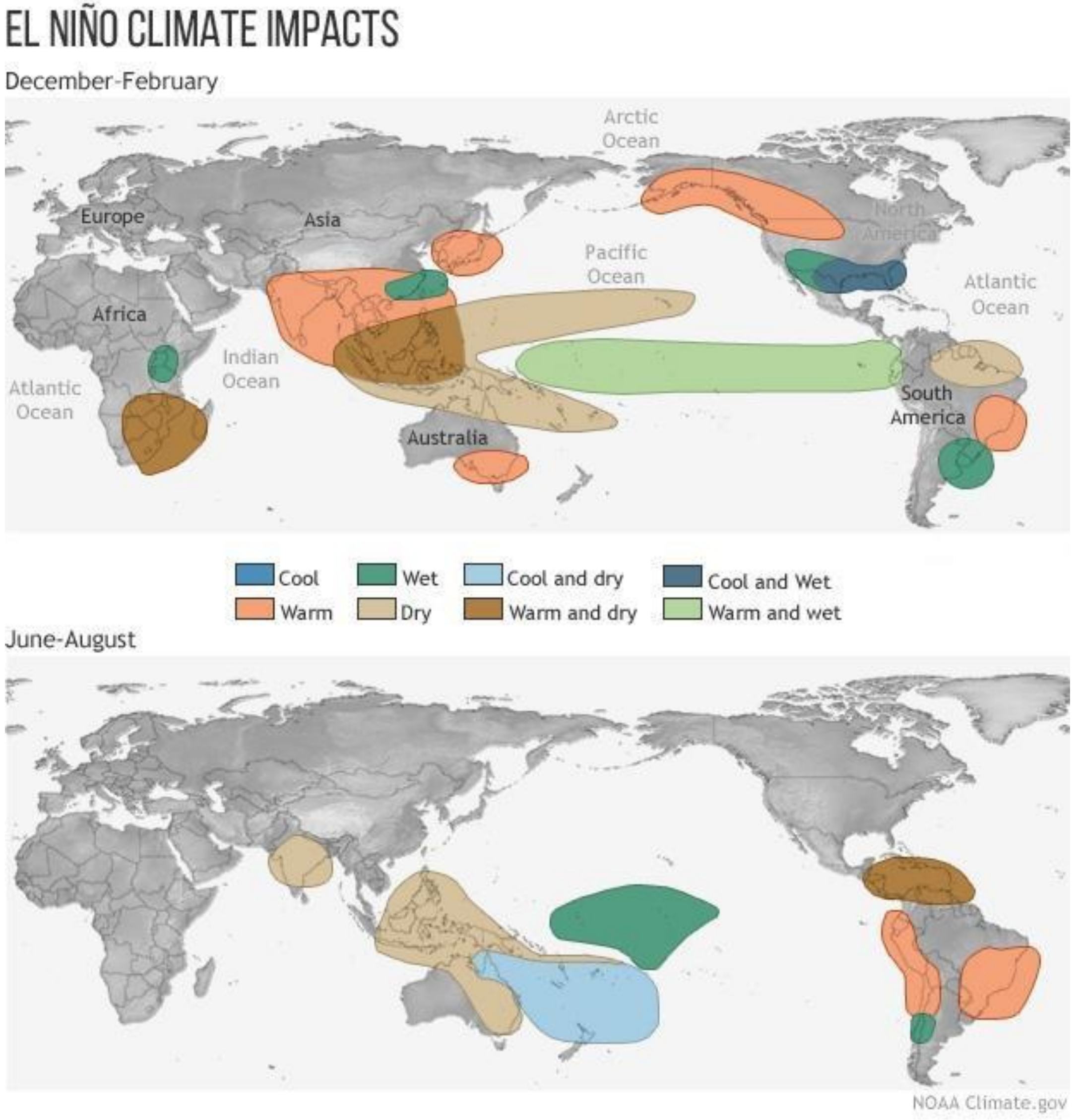
El Niño and ***La Niña*** are the warm and cool phases of a recurring climate pattern across the tropical Pacific—the **El Niño-Southern Oscillation (ENSO).**

El Niño-Southern Oscillation (ENSO)

- One of the most important climate phenomena with impact on ocean temperature, precipitation, wind, and global impact.
- ***El Niño:*** warmer than usual SST in the central and eastern tropical Pacific Ocean
- ***La Niña:*** below-average SST in the central and eastern tropical Pacific Ocean
- ***Neutral phase:*** usually tropical Pacific SSTs are generally close to average.



3-month running mean of Niño 3.4 region SST anomalies.



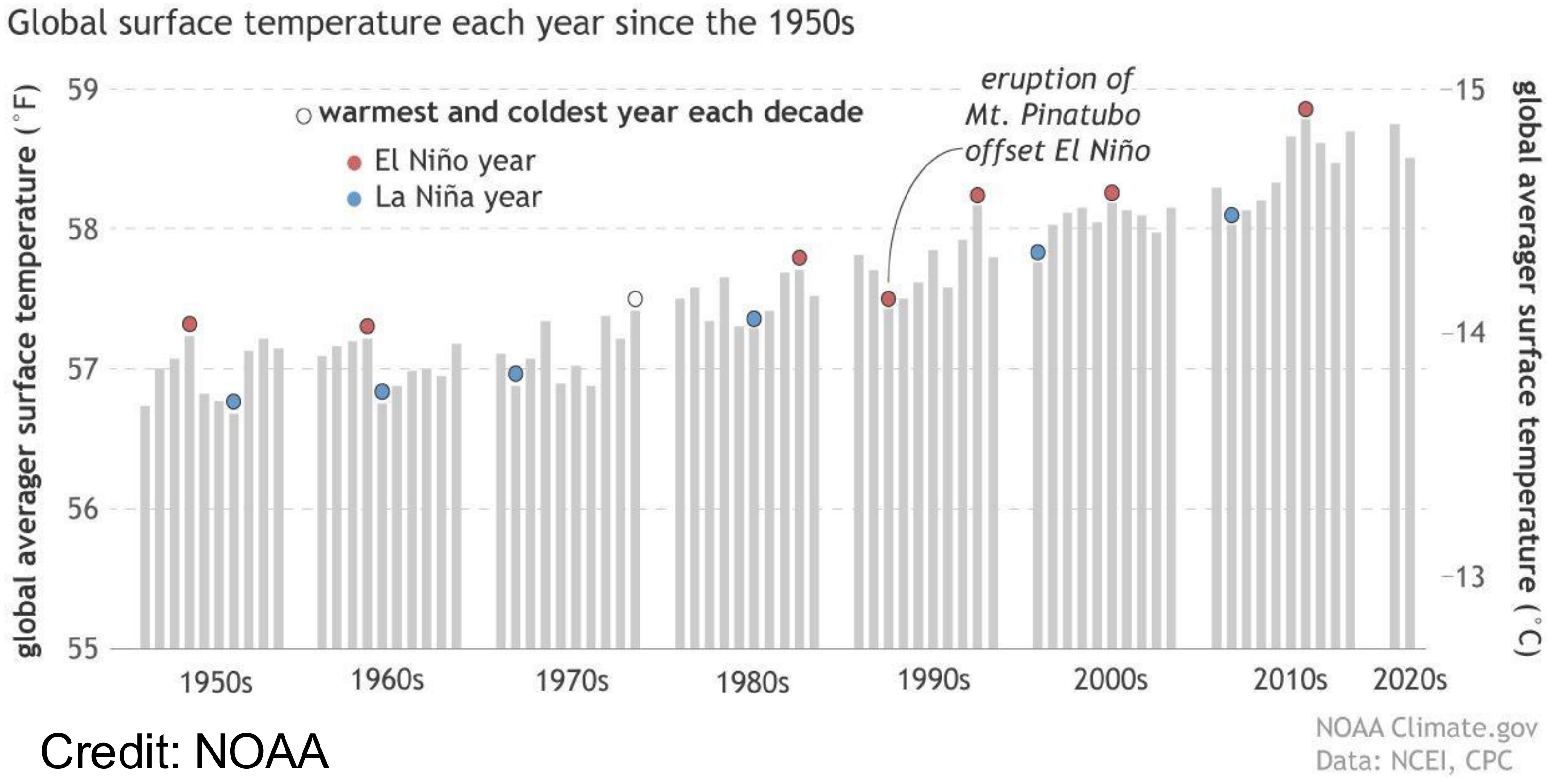
Credit: NOAA

El Niño will disrupt the usual rainfall pattern across different regions that may lead to extreme events like flooding or drought.


Aaron Brothers Art Marts

What Causes Climate Variability?

Climate variability can be caused by both natural events and human activities – e.g., volcanic eruption, El Niño, and La Niña.

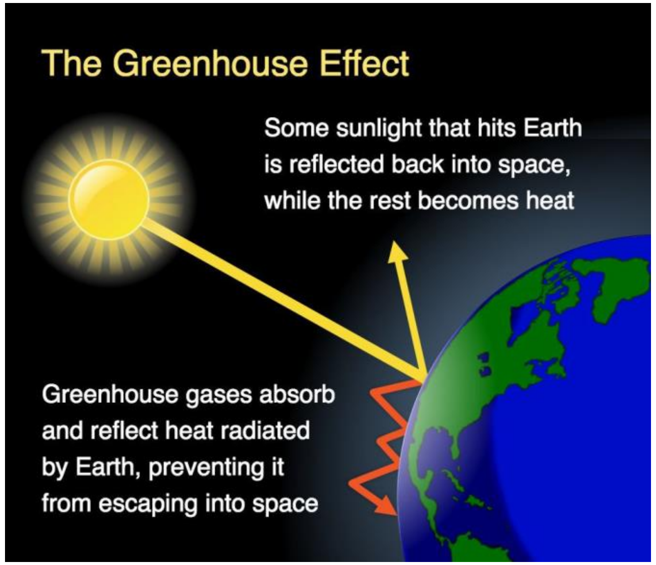


Credit: NOAA

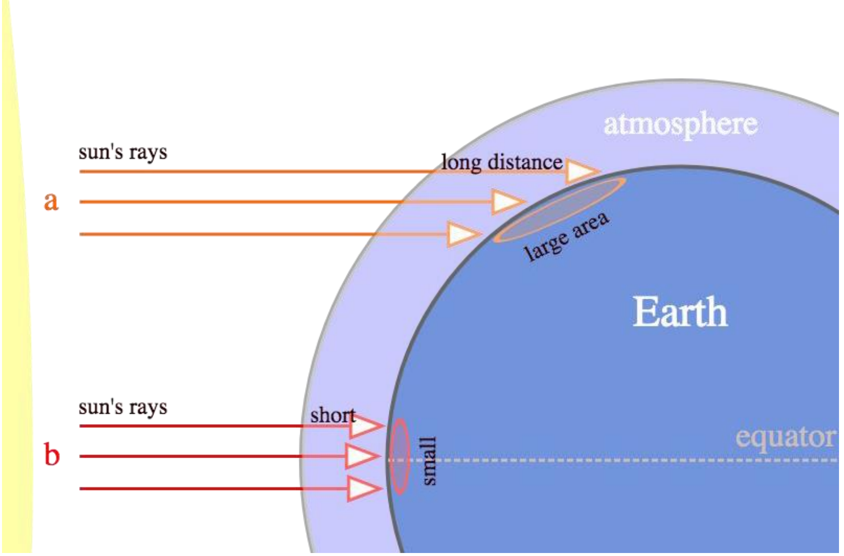
Climate Forcings

- There are multiple factors controlling Earth's climate, including:

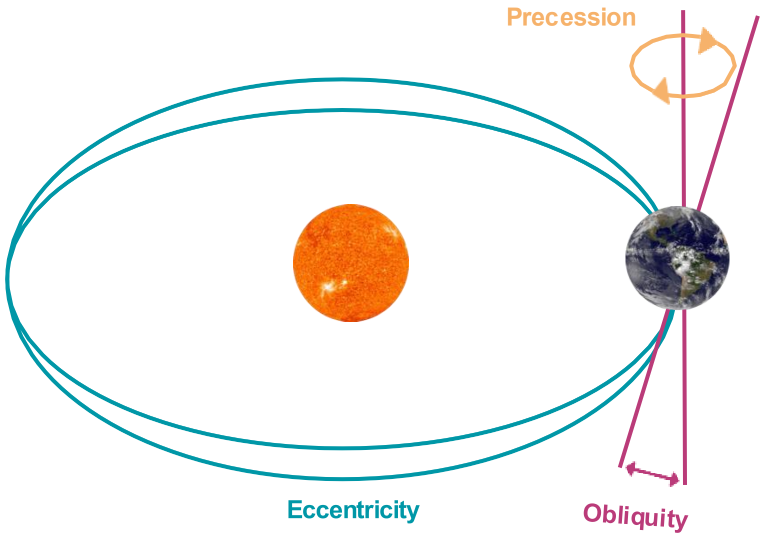
Greenhouse Effect



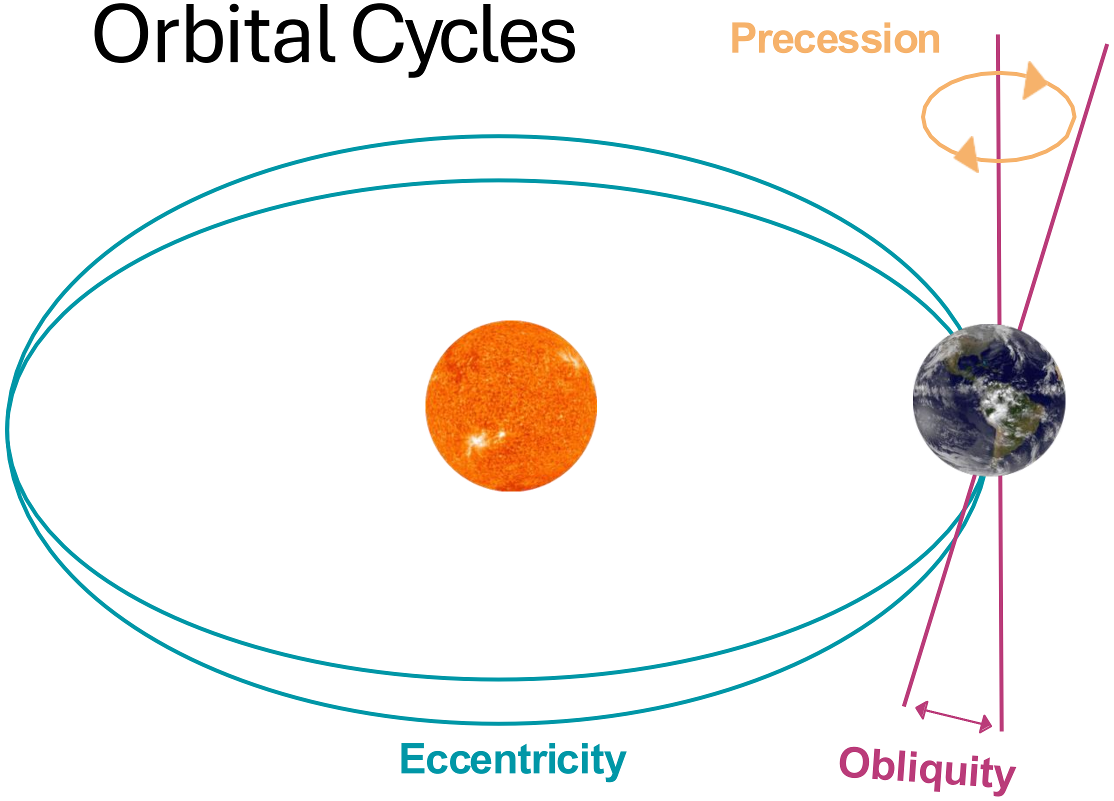
Incoming Solar Radiation



Orbital Cycles



Orbital Cycles

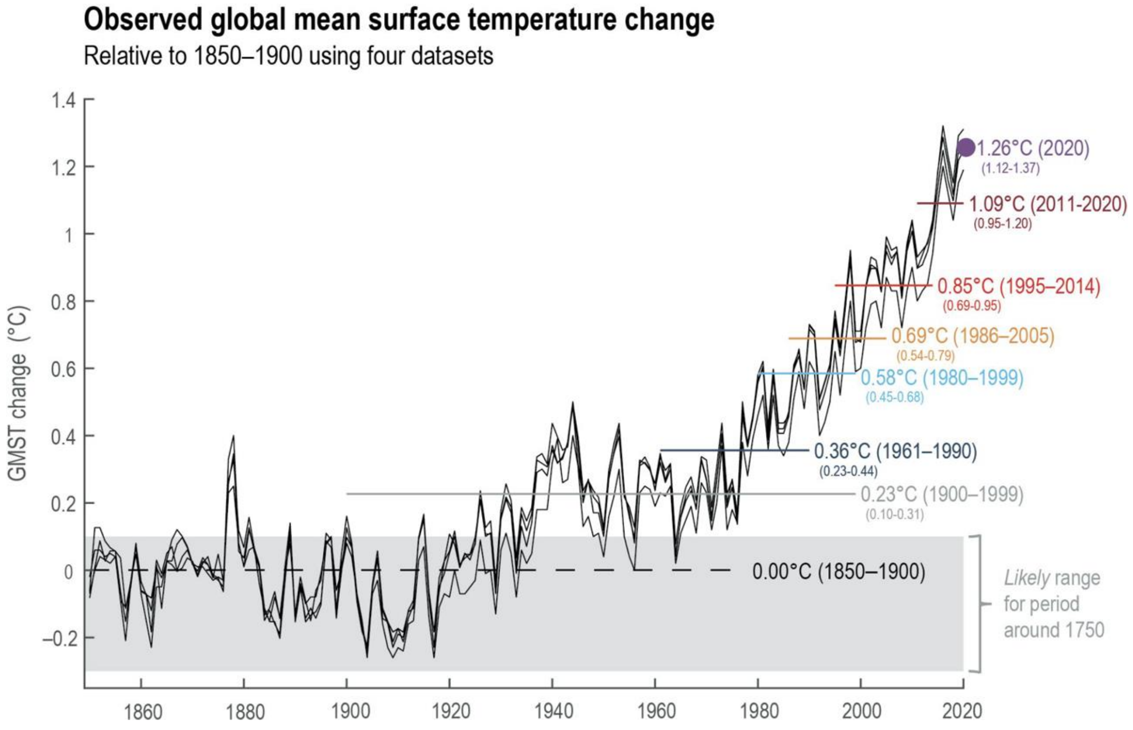


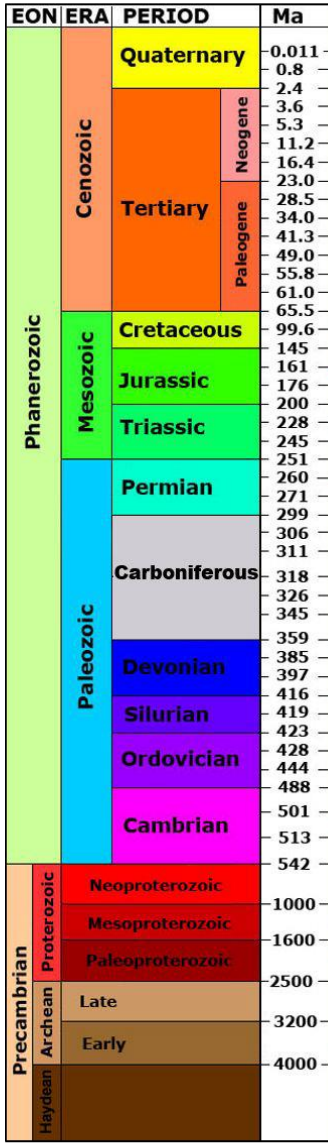
Eccentricity: shape of Earth’s orbit (100,000 years)

Obliquity: tilt of Earth’s axis (41,000 years)

Precession: wobble of Earth’s axis (21,000 years)[4]

Paleoclimate

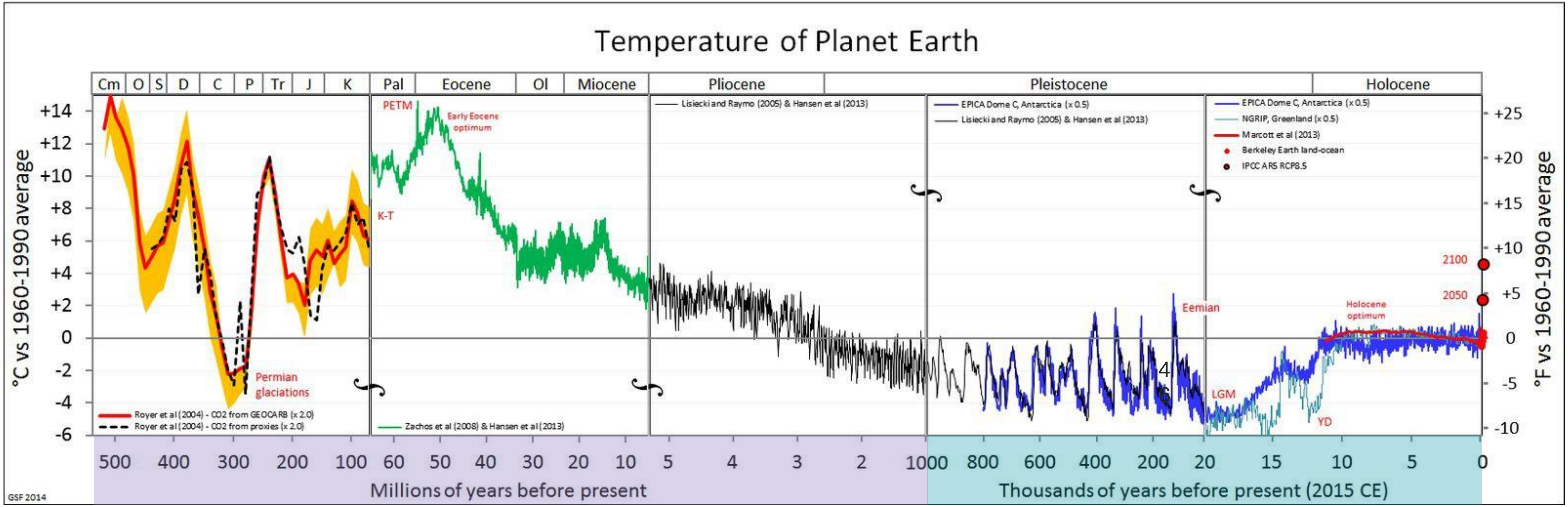




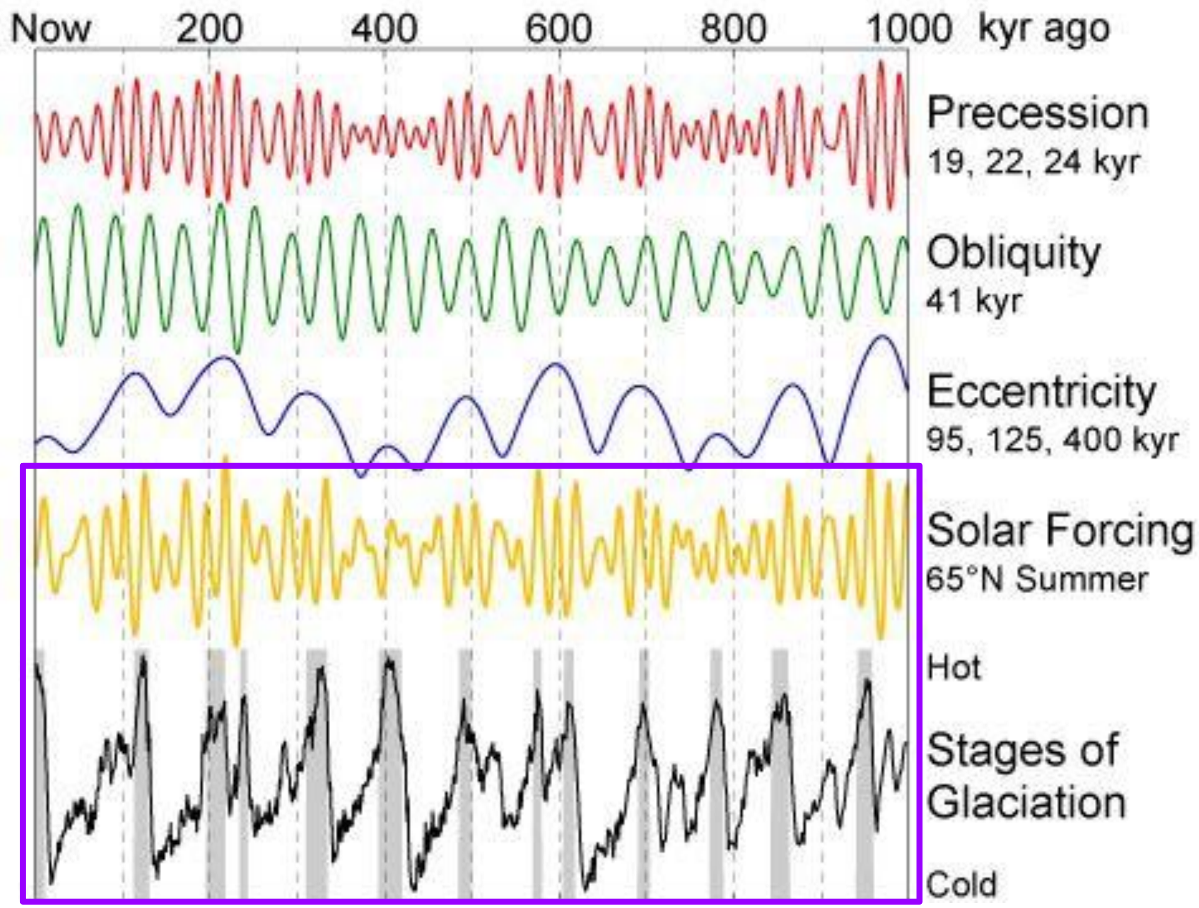
But how do we know about Earth's climate before 1860?

Paleoclimate: the study of ancient climates, prior to the widespread availability of instrumental records

Climate of the past

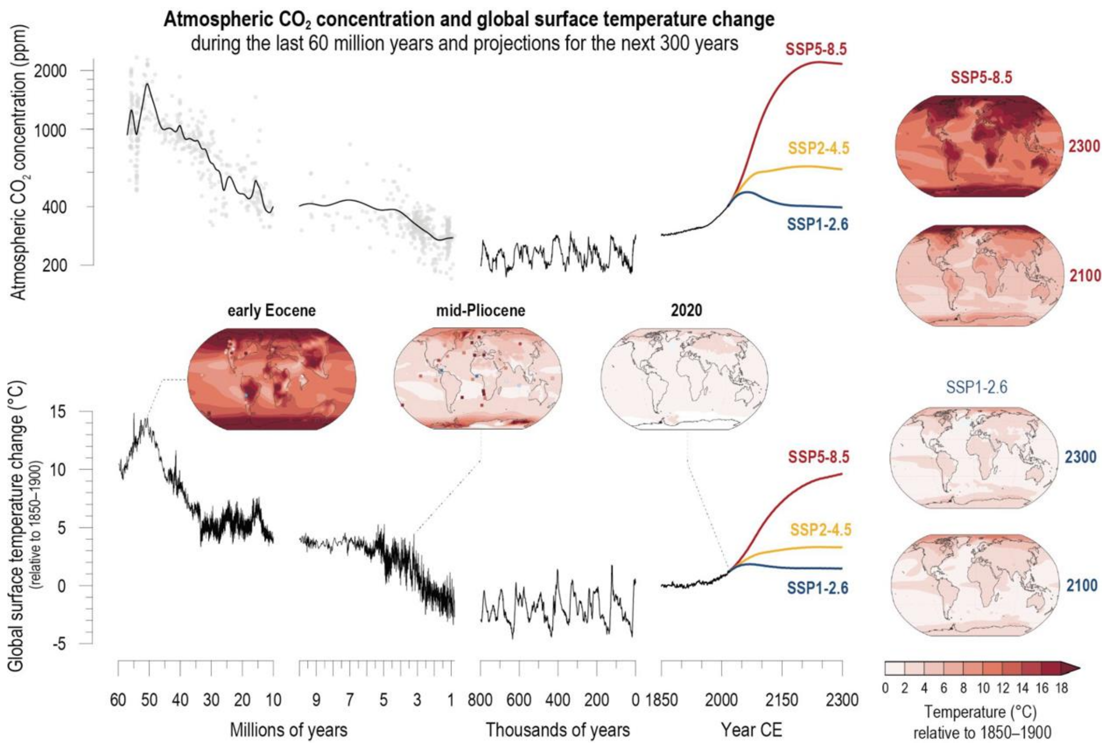


Impact of Orbital Cycles on Climate



- Changes in the orbital cycles drive changes in insolation
- These long-term variations in insolation resulted in glacial cycles
  - **Interglacial**: more insolation, warmer climate, smaller ice sheets
  - **Glacial**: less insolation, cooler climate, larger ice sheets

Why is it important to study paleoclimate?



Past climate states can serve as analogs for future warming

Understanding the response of Earth's climate systems in the past, can help to:

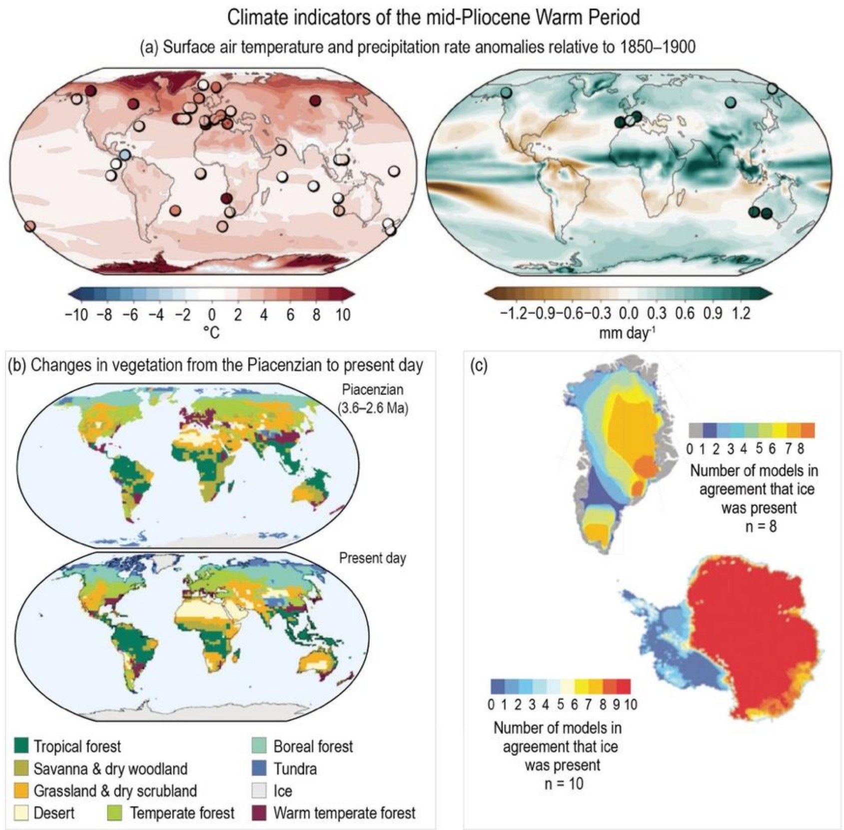
- Assess future changes in the climate system
- Evaluate the environmental response to these climate changes
- Validate/improve models & their projections

Cross-Chapter Box 2.4, Figure 1 | Climate indicators of the mid-Pliocene Warm Period (MPWP; 3.3–3.0 million years ago, Ma) from models and proxy data. (a) Simulated surface air temperature (left) and precipitation rate anomaly (right) anomaly (relative to 1850–1900) from the Pliocene Model Intercomparison Project Phase 2 multi-model mean, including CMIP6 (n = 4) and non-CMIP6 (n = 12) models. Symbols represent site-level proxy-based estimates of sea-surface temperature for KM5c (n = 32), and terrestrial temperature (n = 8) and precipitation rate for the MPWP (n = 8). (b) Distribution of terrestrial biomes was considerably different during the Piacenzian Stage (3.6–2.6 Ma) (upper) compared with present-day (lower). Biome distributions simulated with a model (BIOME4) in which Pliocene biome classifications are based on 208 locations, with model-predicted biomes filling spatial gaps, and the present day, with the model adjusted for CO_2 concentration of 324 parts per million (ppm). (c) Ice-sheet extent predicted using modelled climate forcing and showing where multiple models consistently predict the former presence or absence of ice on Greenland (n = 8 total) and Antarctica (n = 10 total). Further details on data sources and processing are available in the chapter data table (Table 2.SM.1).

Cross-Chapter Box 2.4, Figure 1 in IPCC, 2021: Chapter 2. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, J.A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Schuckmann, and R.S. Vose, 2021: Changing State of the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 287–422, doi:* 10.1017/9781009157896.004 *.]*

Tools for Reconstructing Paleoclimate

Paleoclimate Models



Cross-Chapter Box 2.4, Figure 1 in IPCC, 2021: Chapter 2. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Gulev, S.K.,

Proxies and Archives

"Travertine speleothem (Crystal Cave, Main Island, Bermuda) 1" by James St. John is licensed under CC BY 2.0.

"Tree rings" by Out of the Fire Blog is licensed under CC BY 2.0

"A volcanic ash layer in the WAIS Divide ice core. Volcanic markers like these were used in the new study to synchronize ice cores from across Antarctica." by Oregon State University is licensed under CC BY-SA 2.0.

"2016 Lake sediment core. Forlorn Lakes. Gifford Pinchot National Forest, Washington." by USDA Forest Service is marked with Public Domain Mark 1.0.

"Diploria fossil brain coral on Devil's Point Hardground (Cockburn Town Member, Grotto Beach Formation, Upper Pleistocene, ~120-123 ka; Cockburn Town Fossil Reef, San Salvador Island, Bahamas) 3" by James St. John is licensed under CC BY 2.0.

Marine Climate Proxies

What can we reconstruct?

Ocean Salinity

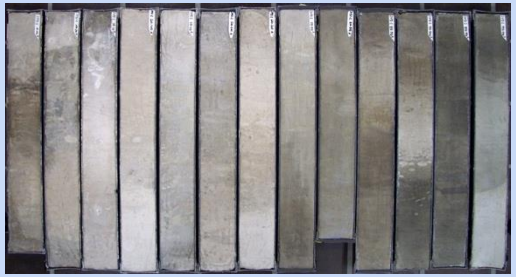
Primary Productivity

Sea Surface Temperature (SST)

How can we reconstruct it?

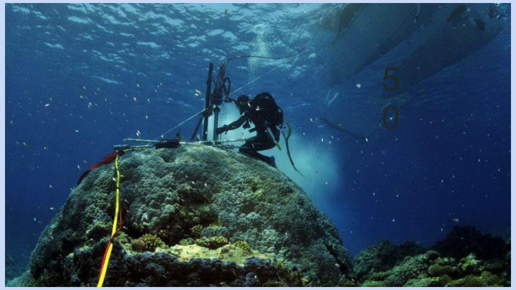
Marine sediments

Organic biomarkers
Oxygen isotopes

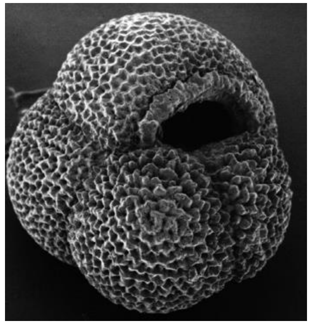


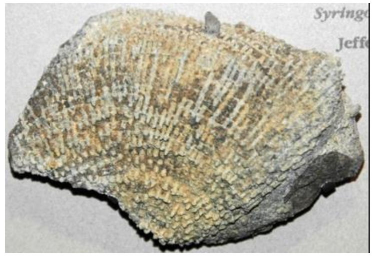
Corals

Layer growth
Oxygen isotopes



Measure oxygen isotopes of:





Terrestrial Climate Proxies

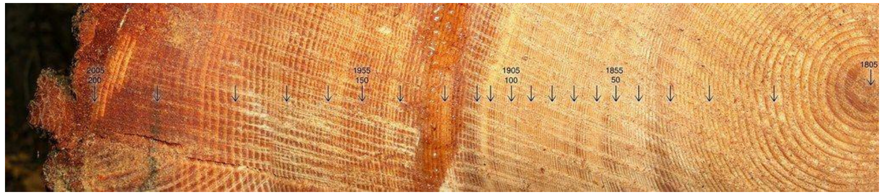
What can we reconstruct?

- Precipitation
- Vegetation
- Surface Air Temperature

How can we reconstruct it?

- **Speleothems**

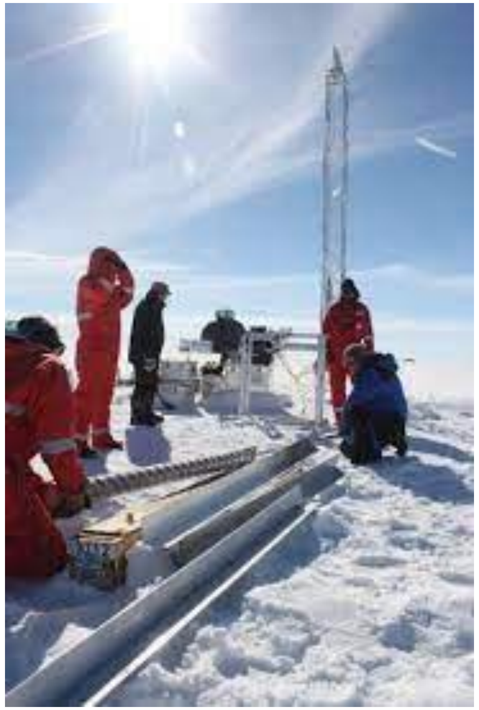
- **Tree rings**



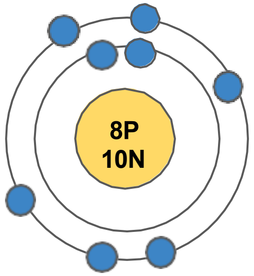
- **Lake sediments**

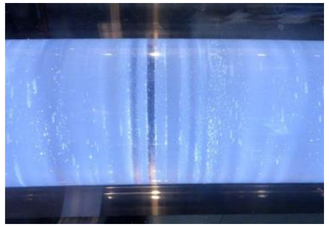
Atmospheric Climate Proxies

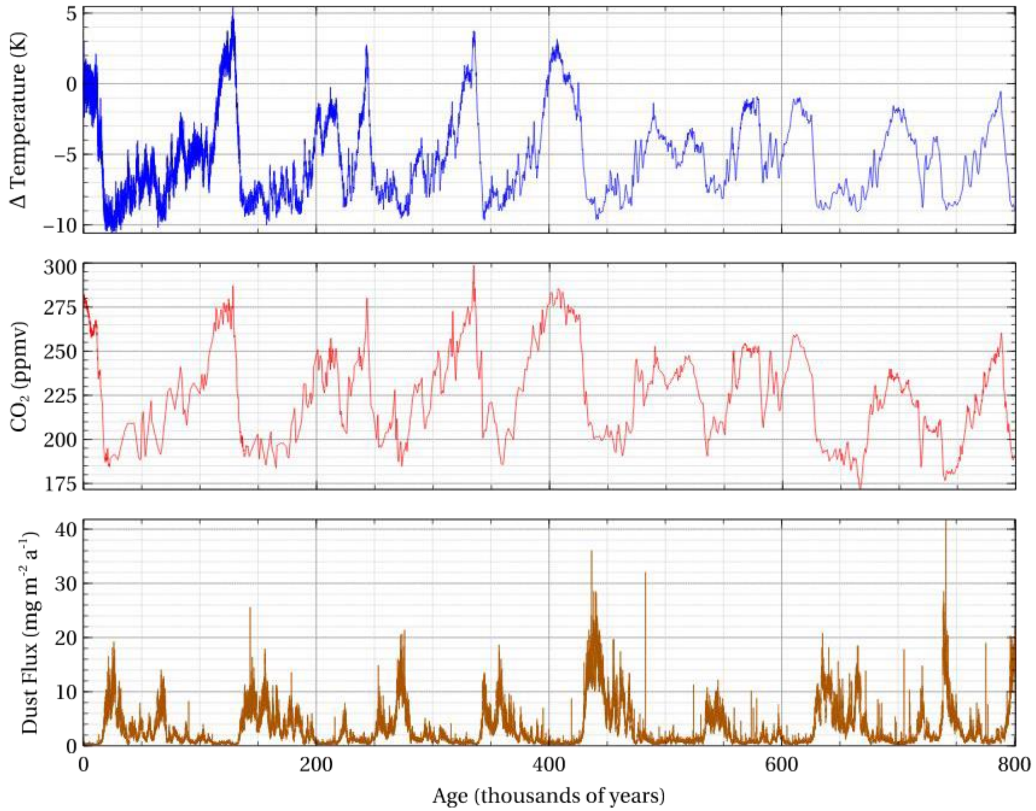
Ice Cores



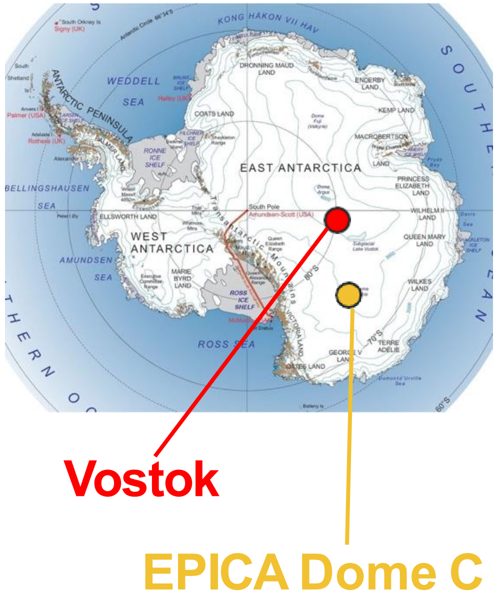
What can we reconstruct?	*How can we reconstruct it?*
Surface air temperature	O and H isotopes
GHG concentration	Air bubbles
Atmospheric dust flux	Dust layers

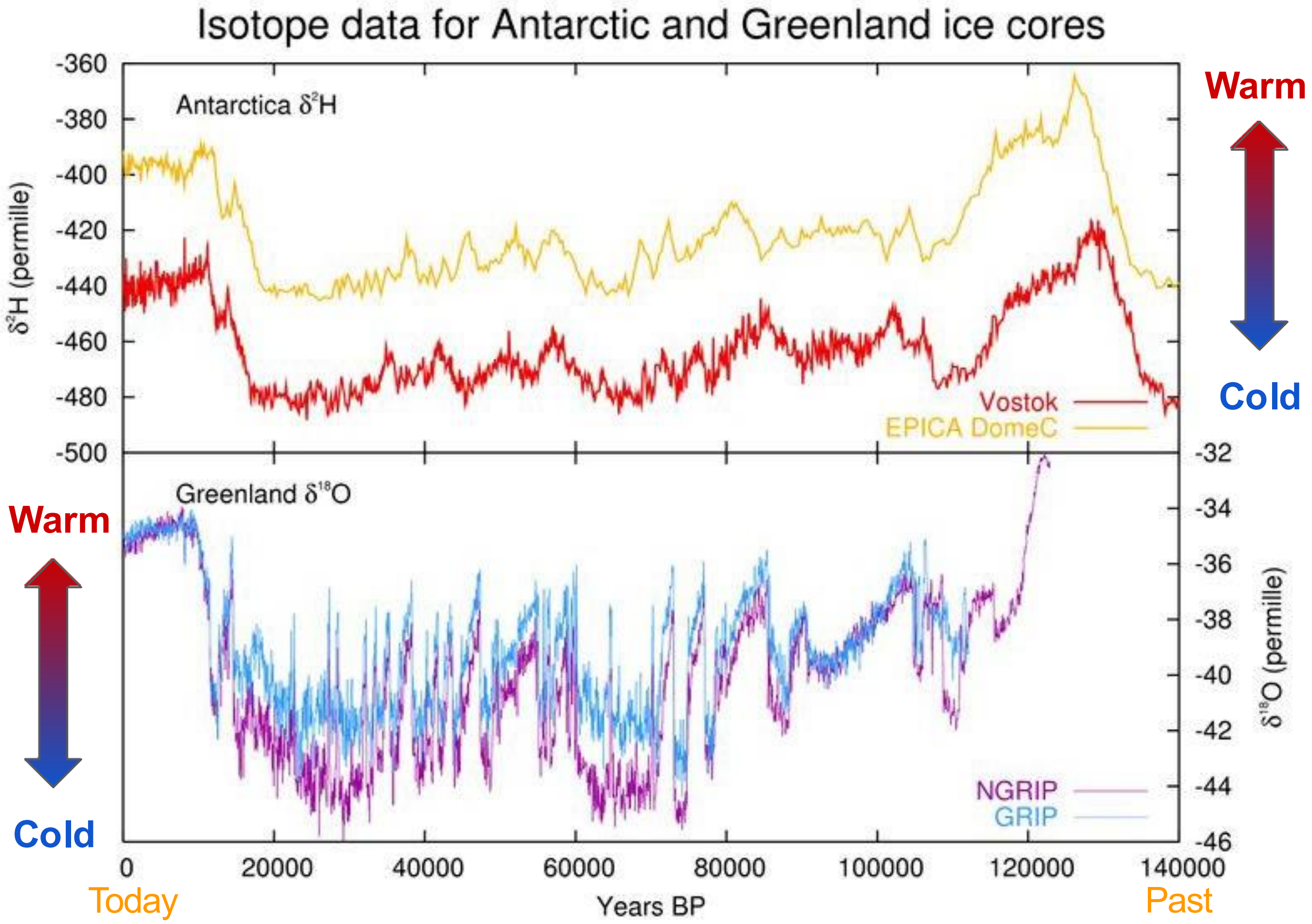


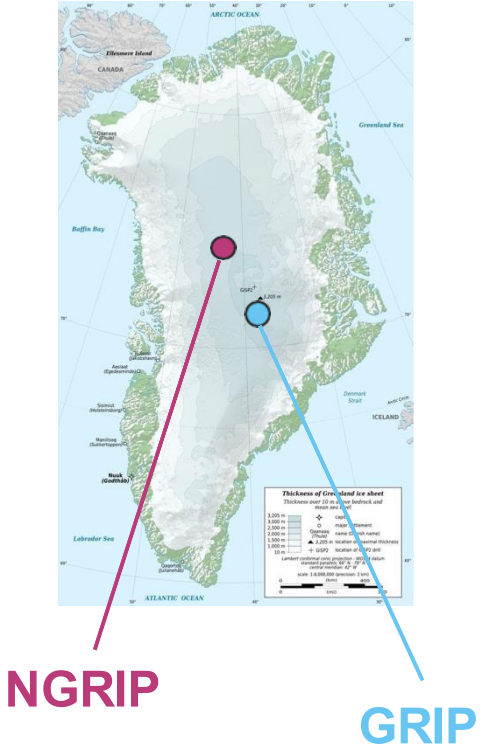




Antarctic and Greenland Ice Cores

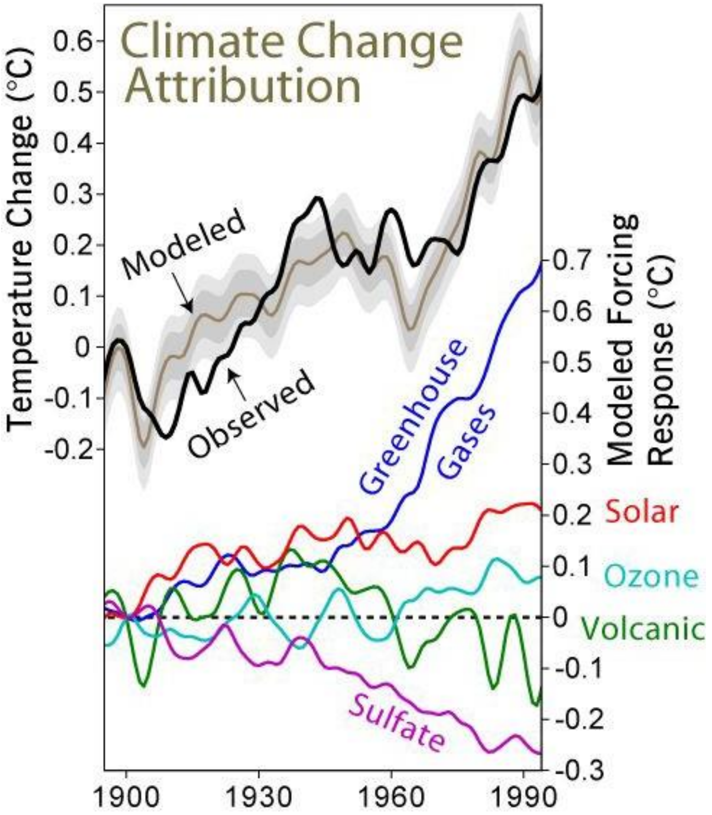






Proxy-Model Comparisons

Assess climate forcings



Compare proxy & model climate signals

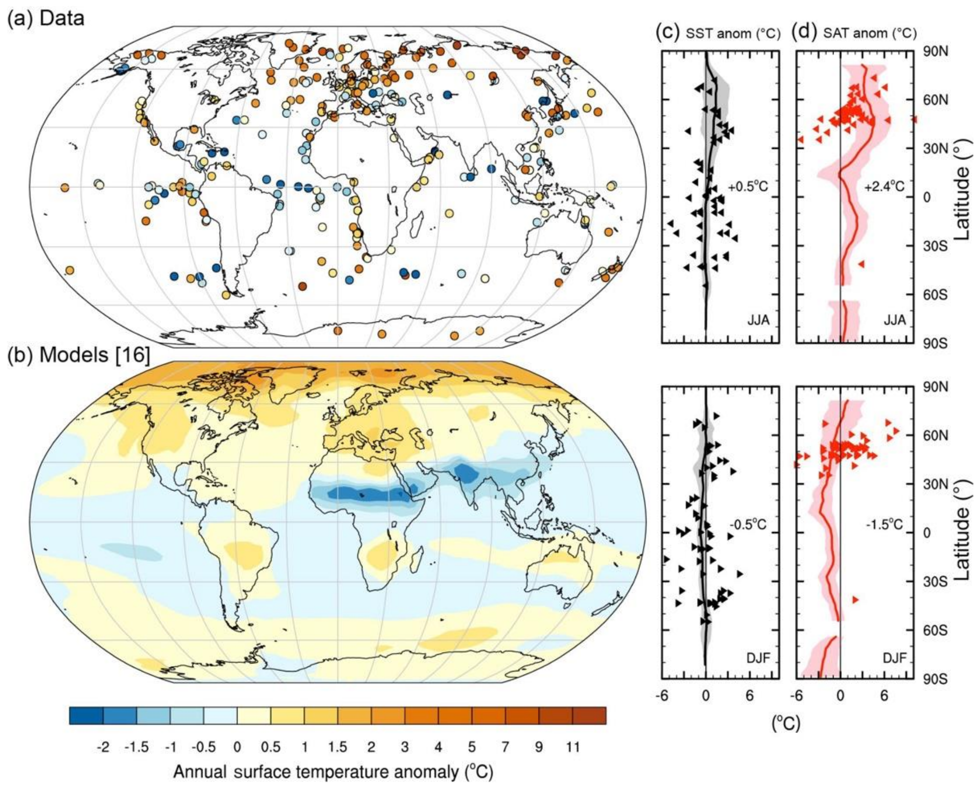
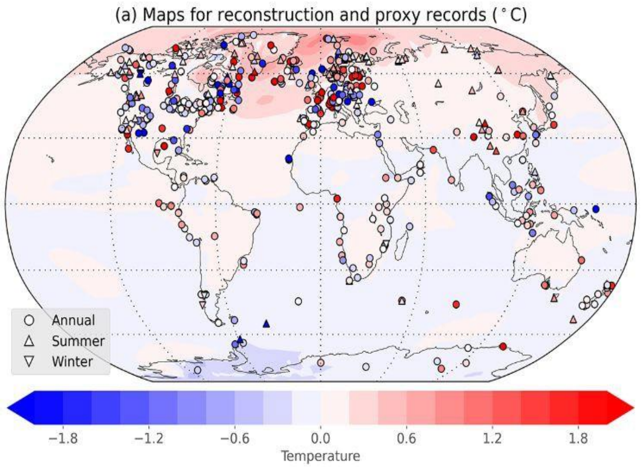
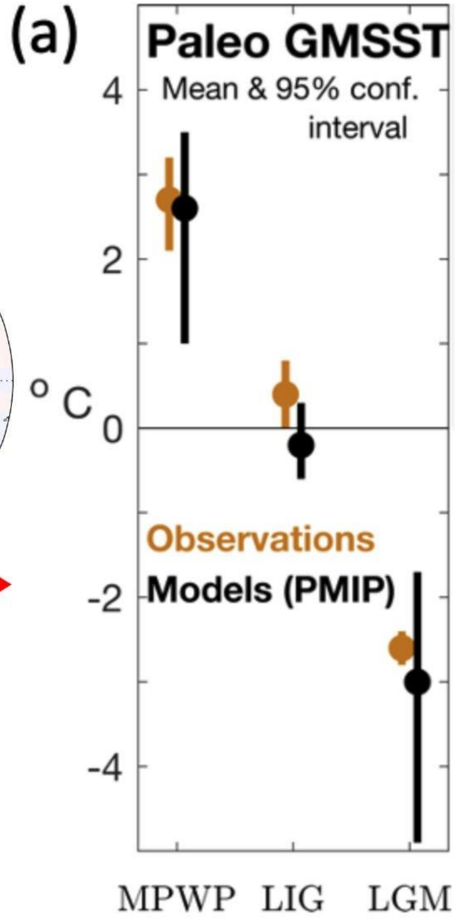


Figure 5.6 | Changes in surface temperature for the Last Interglacial (LIG) as reconstructed from data and simulated by an ensemble of climate model experiments in response to orbital and well-mixed greenhouse gas (WMGHG) forcings. (a) Proxy data syntheses of annual surface temperature anomalies as published by Turney and Jones (2010) and McKay et al. (2011). McKay et al., (2011) calculated an annual anomaly for each record as the average sea surface temperature (SST) of the 5-kyr period centred on the warmest temperature between 135 ka and 118 ka and then subtracting the average SST of the late Holocene (last 5 kyr). Turney and Jones (2010) calculated the annual temperature anomalies relative to 1961–1990 by averaging the LIG temperature estimates across the isotopic plateau in the marine and ice records and the period of maximum warmth in the terrestrial records (assuming globally synchronous terrestrial warmth). (b) Multi-model average of annual surface air temperature anomalies simulated for the LIG computed with respect to pre-industrial. The results for the LIG are obtained from 16 simulations for 128 to 125 ka conducted by 13 modelling groups (Lunt et al., 2013). (c) Seasonal SST anomalies. Multi-model zonal averages are shown as solid line with shaded bands indicating 2 standard deviations. Plotted values are the respective seasonal multi-mean global average. Symbols are individual proxy records of seasonal SST anomalies from McKay et al. (2011). (d) Seasonal terrestrial surface temperature anomalies (SAT). As in (c) but with symbols representing terrestrial proxy records as compiled from published literature (Table 5.A.5). Observed seasonal terrestrial anomalies larger than 10°C or less than –6°C are not shown. In (c) and (d) JJA denotes June – July – August and DJF December – January – February, respectively.

(Robert A. Rohde, CC BY-SA 3.0; Masson-Delmotte, V., M. et al., Information from Paleoclimate Archives. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change)





IPCC AR6 WG1 Figure 9.3a

Figure 9.3 | Sea surface temperature (SST) and its changes with time. (a) Time series of global mean SST anomaly relative to 1950–1980 climatology. Shown are paleoclimate reconstructions and PMIP models, observational reanalyses (HadISST) and multi-model means from the Coupled Model Intercomparison Project (CMIP) historical simulations, CMIP projections, and HighResMIP experiment. **(b)** Map of observed SST (1995–2014 climatology HadISST). **(c)** Historical SST changes from observations. **(d)** CMIP 2005–2100 SST change rate. **(e)** Bias of CMIP. **(f)** CMIP change rate. **(g)** 2005–2050 change rate for SSP5-8.5 for the CMIP ensemble. **(h)** Bias of HighResMIP (bottom left) over 1995–2014. **(i)** HighResMIP change rate for 1950–2014. **(j)** 2005–2050 change rate for SSP5-8.5 for the HighResMIP ensemble. No overlay indicates regions with high model agreement, where ≥80% of models agree on sign of change. Diagonal lines indicate regions with low model agreement, where <80% of models agree on sign of change (see Cross-Chapter Box Atlas.1 for more information). Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

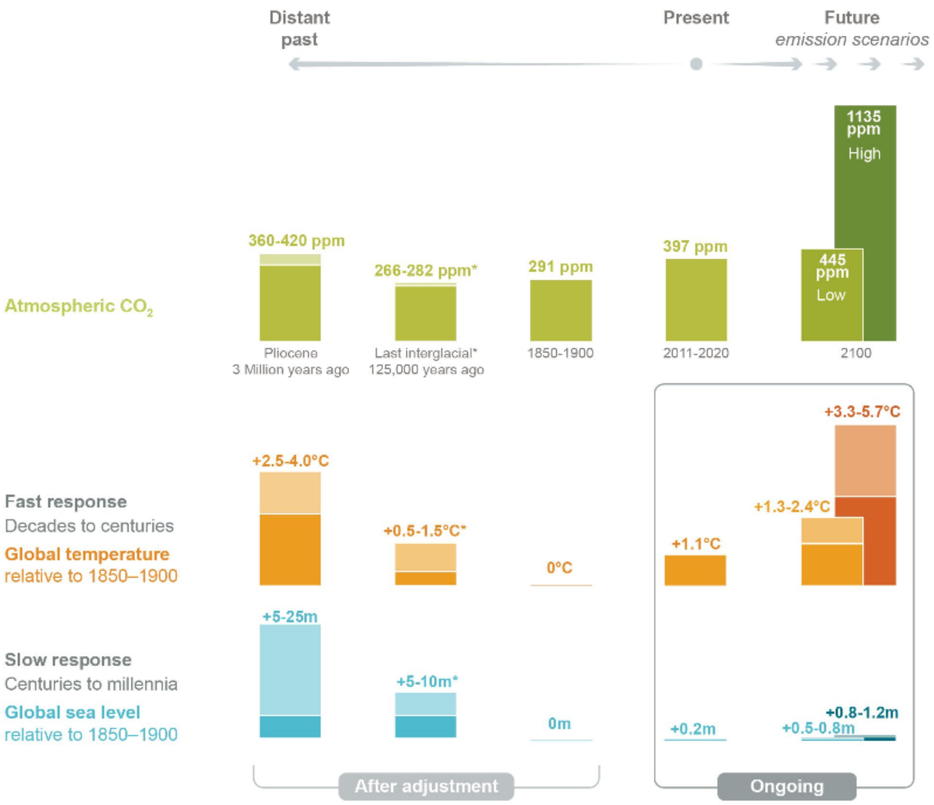
Paleoclimate observations of Earth's climate are critical to CMIP6 because they provide:

1. **Context:** How extreme are future projections?
2. **Validation:** Can PMIP (=PaleoMIP) models simulate extreme past climates? (e.g., ice age, sea level maxima, or long-term GHG forcing)

Paleoclimate insights into the future

FAQ 1.3: **What can the past tell us about the future?**

Past warm periods inform about the potential consequences of rising greenhouse gases in the atmosphere.



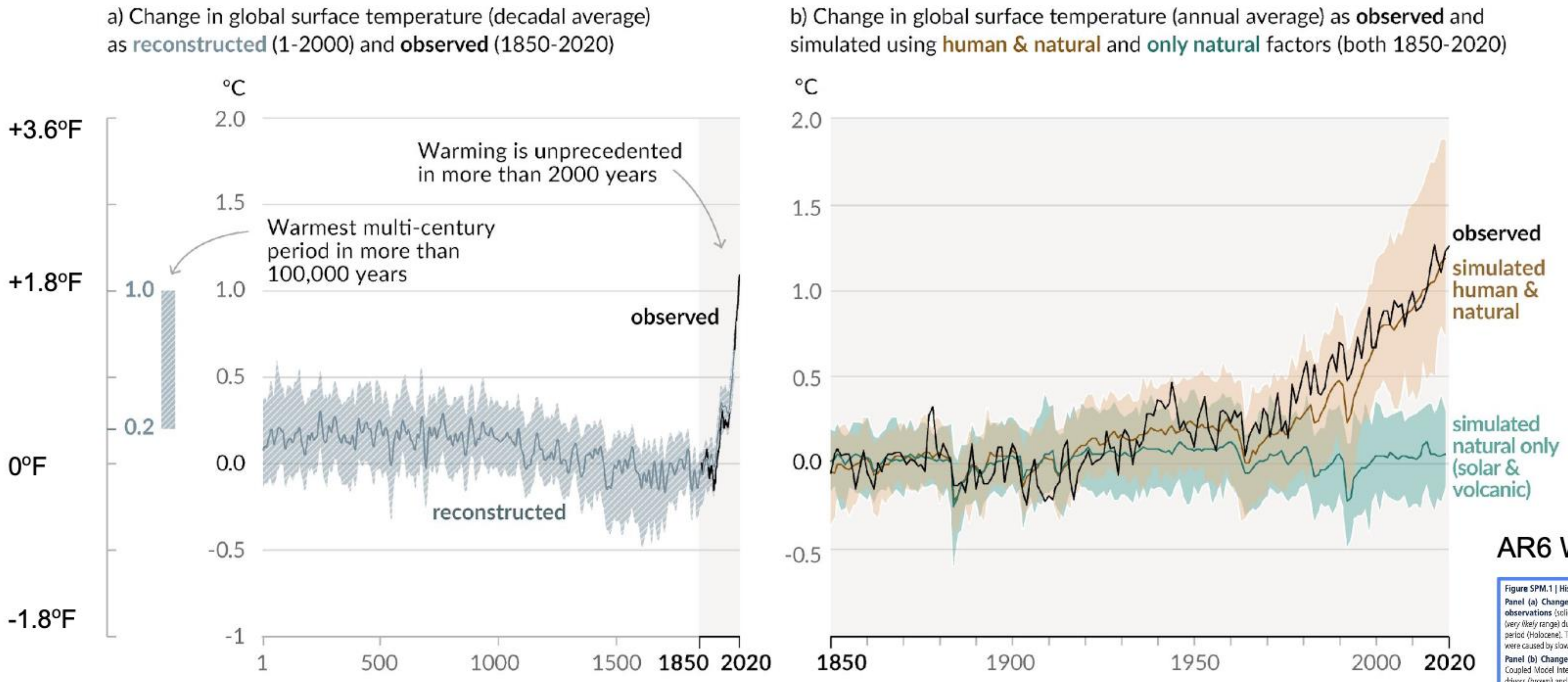
*Triggered by changes in the Earth's orbit, which redistributed incoming solar energy between seasons and latitudes

FAQ 1.3, Figure 1 | Comparison of past, present and future. Schematic of atmospheric carbon dioxide concentrations, global temperature, and global sea level during previous warm periods as compared to 1850–1900, present-day (2011–2020), and future (2100) climate change scenarios corresponding to low-emissions scenarios (SSP1-2.6; lighter colour bars) and very high-emissions scenarios (SSP5-8.5; darker colour bars).

- **Paleoclimates provide analogues for climate states with different CO2 levels**
- **Atmospheric CO2 during the Pliocene was similar to present day but was warmer and had higher sea levels because the present day hasn't yet adjusted to the carbon dioxide levels**
- **Paleoclimate records indicate the existence of tipping elements**
- **Past climate states can be used to test climate models**

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

Changes in global surface temperature relative to 1850-1900



AR6 WG1 Figure SPM.1

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

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

Panel (b) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model simulations (see Box SPM.1) of the temperature response to both human and natural drivers (brown) and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations. (See Figure SPM.2 for the assessed contributions to warming).

Future Uncertainty Terminology

Climate scientists often communicate complex data to a diverse audience

As a result, the IPCC uses specific terms for confidence level, e.g.,:

- **Likely range** (middle 66% of model projections; ignore bottom/top 17%)
- **Very likely range** (middle 90% of model projections; ignore bottom/top 5%)

For maps, **high model agreement** means ≥80% have the same sign of projected change

AR6 WG1 Figure SPM.2

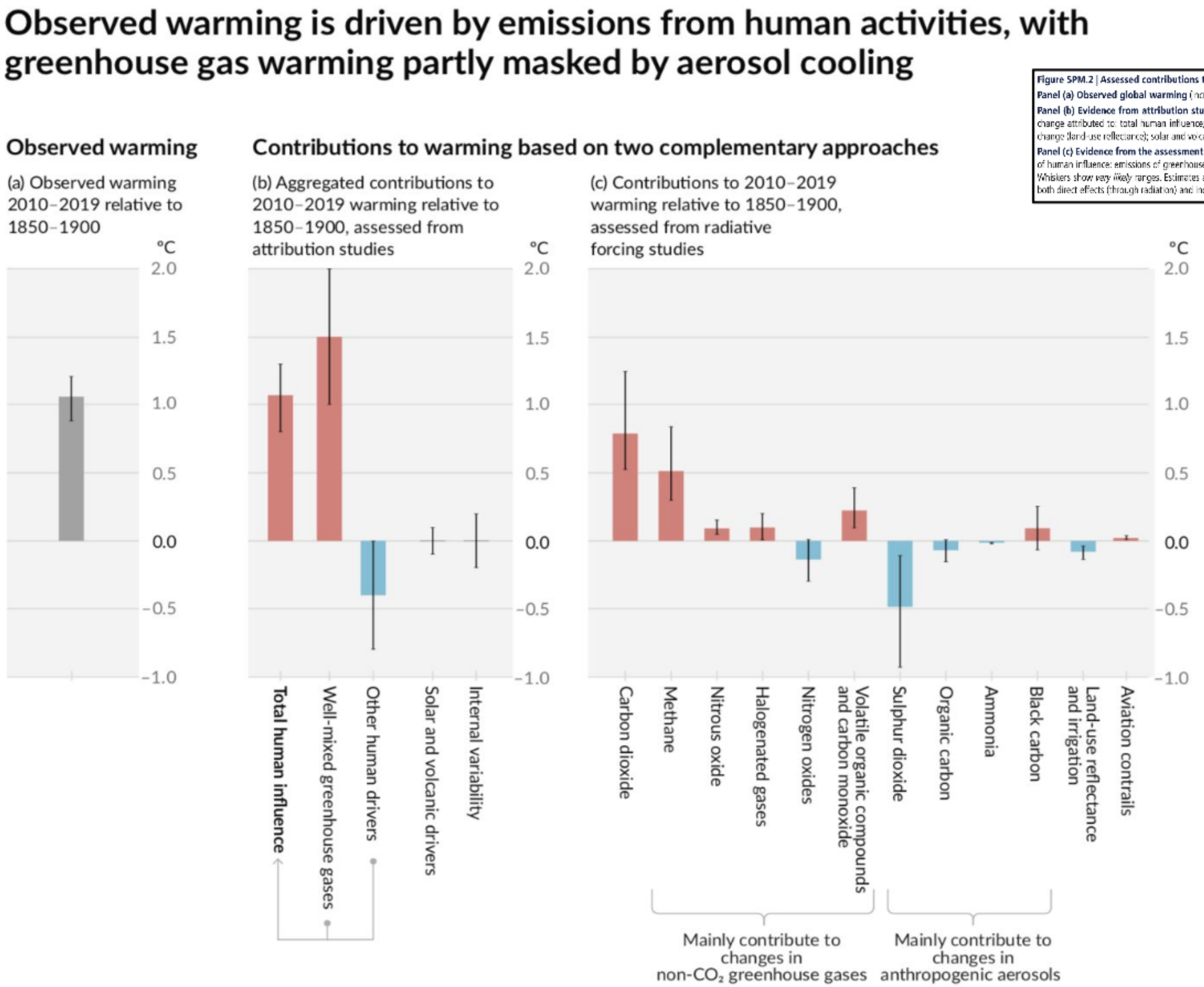


Figure SPM.2 | Assessed contributions to observed warming in 2010–2019 relative to 1850–1900

Panel (a) Observed global warming (increase in global surface temperature). Whiskers show the *very likely* range.

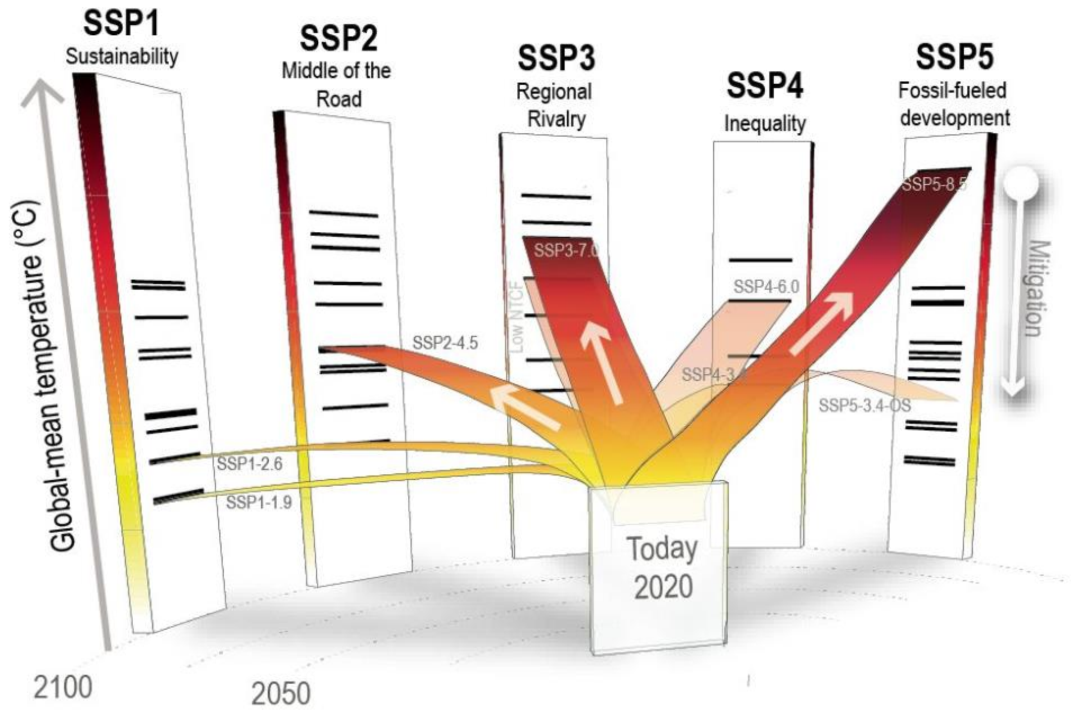
Panel (b) Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to: total human influence; changes in well-mixed greenhouse gas concentrations; other human drivers due to aerosols, ozone and land-use change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

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

Human influence is no longer assessed with a confidence level:

That means it is taken as a *FACT* according to IPCC procedure

How do we make projections of future climate?



SSP = Shared Socioeconomic Pathway

AR6 WG1 Cross-Chapter Box 1.4, Figure 1 (left panel)

Cross-Chapter Box 1.4, Figure 1 | The SSP scenarios used in this Report, their indicative temperature evolution and radiative forcing categorization, and the five socio-economic storylines upon which they are built. The core set of scenarios used in this report – i.e., SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 – is shown together with an additional four SSPs that are part of ScenarioMIP, as well as previous RCP scenarios. In the **left-hand panel**, the indicative temperature evolution is shown (adapted from Meinshausen et al., 2020). The black stripes on the respective scenario family panels on the left-hand side indicate a larger set of IAM-based SSP scenarios that span the scenario range more fully, but are not used in this report. The SSP–radiative forcing matrix is shown on the **right-hand panel**, with the SSP socio-economic narratives shown as columns and the indicative radiative forcing categorization by 2100 shown as rows. Note that the descriptive labels for the five SSP narratives refer mainly to the reference scenario futures without additional climate policies. For example, SSP5 can accommodate strong mitigation scenarios leading to net zero emissions; these do not match a 'fossil-fuelled development' label. Further details on data sources and processing are available in the chapter data table (Table 1.SM.1).

Future climate projections are complex with potential interactions between different parts of the system leading to feedbacks

To make quantitative projections of future climate, taking account of possible uncertainties, we need:

- **Scenarios of future forcing**
- **Climate models**

Coupled Model Intercomparison Project (CMIP)

- CMIP6 included over 23 Model Intercomparison Projects (MIP) and more than 70 different models
- As well as MIPs, there is a set of experiments characterising the models (Diagnostic, Evaluation and Characterization of Klima - DECK)
- To extend CMIP projections beyond 2100 and (in some cases) to the full range of scenarios, the model responses are sometimes emulated

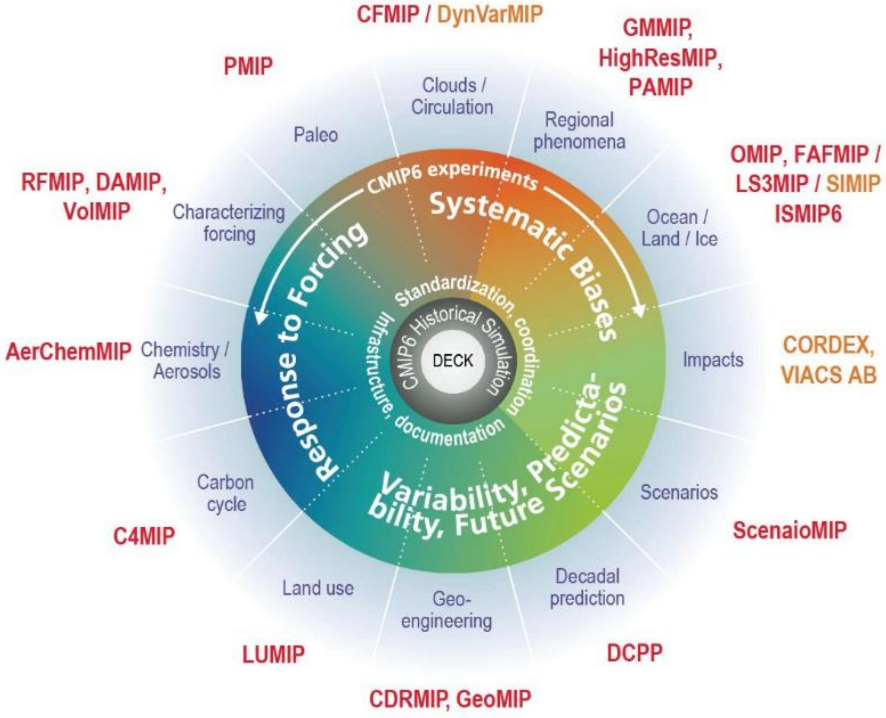


Figure 1.22 | Structure of CMIP6, the 6th phase of the Coupled Model Intercomparison Project. The centre shows the common DECK (Diagnostic, Evaluation and Characterization of Klima) and historical experiments that all participating models must perform. The outer circles show the topics covered by the endorsed (red) and other MIPs (orange). See Table 1.3 for explanation of the MIP acronyms. Figure is adapted from Eyring et al. (2016).

IPCC AR6 WG1 Figure 1.22

Brief history of model complexity

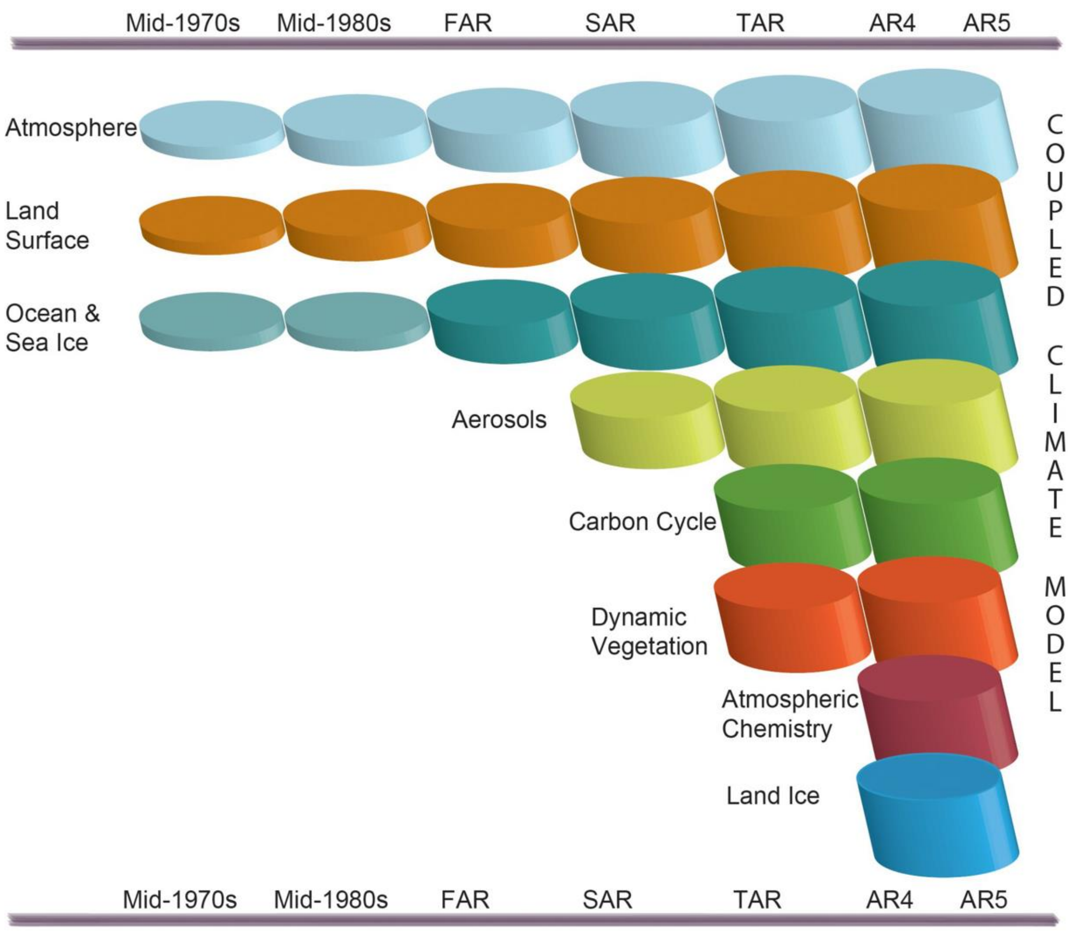
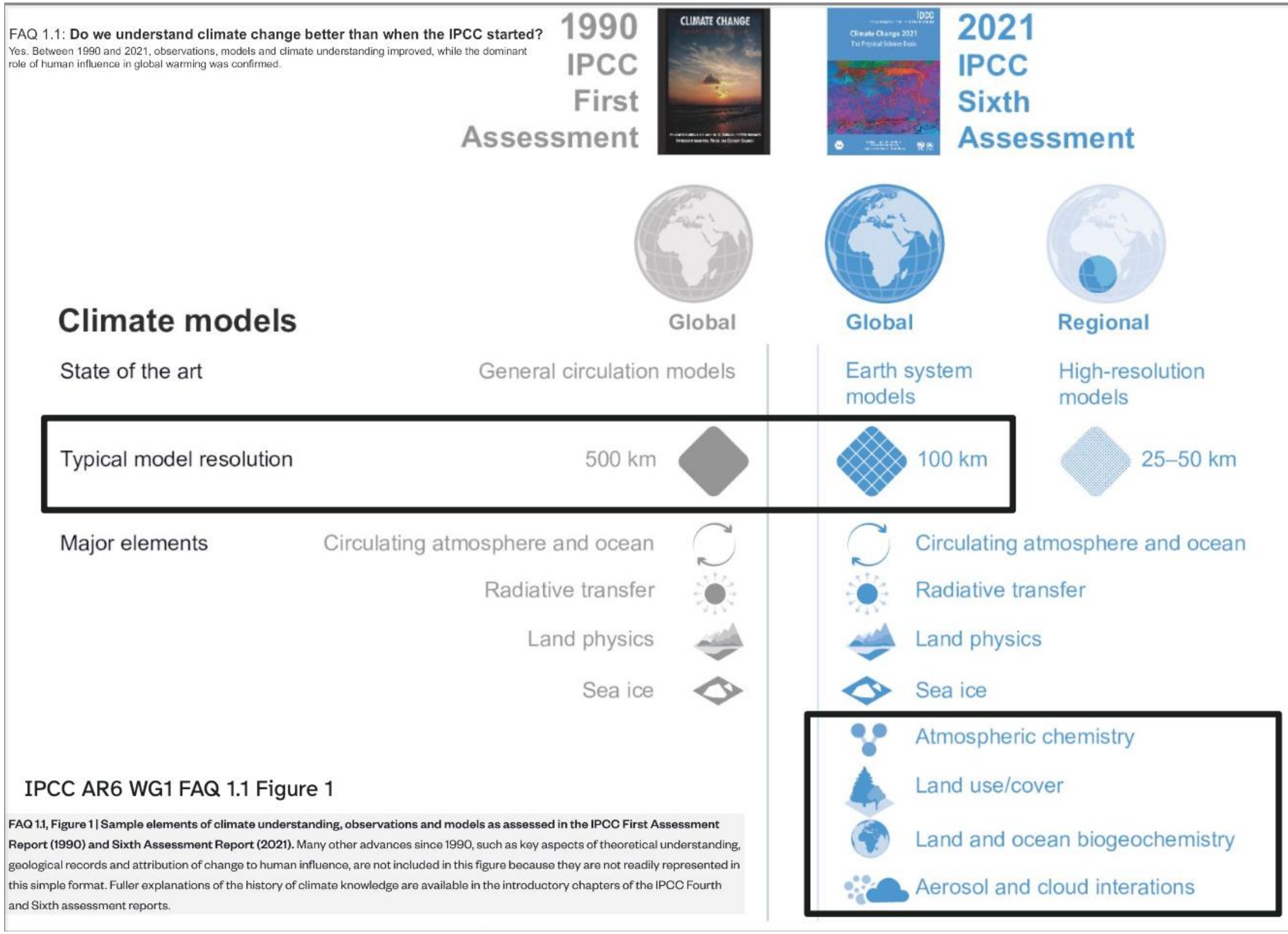


Figure 1.13 | The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resolution and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independent experiments can be considered as standard.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.



IPCC AR6 WG1 FAQ 1.1 Figure 1

FAQ 1.1, Figure 1 | Sample elements of climate understanding, observations and models as assessed in the IPCC First Assessment Report (1990) and Sixth Assessment Report (2021). Many other advances since 1990, such as key aspects of theoretical understanding, geological records and attribution of change to human influence, are not included in this figure because they are not readily represented in this simple format. Fuller explanations of the history of climate knowledge are available in the introductory chapters of the IPCC Fourth and Sixth assessment reports.

- **Resolution & complexity of climate models is increasing,**
- **But many important processes are still not resolved**

A discretized model world

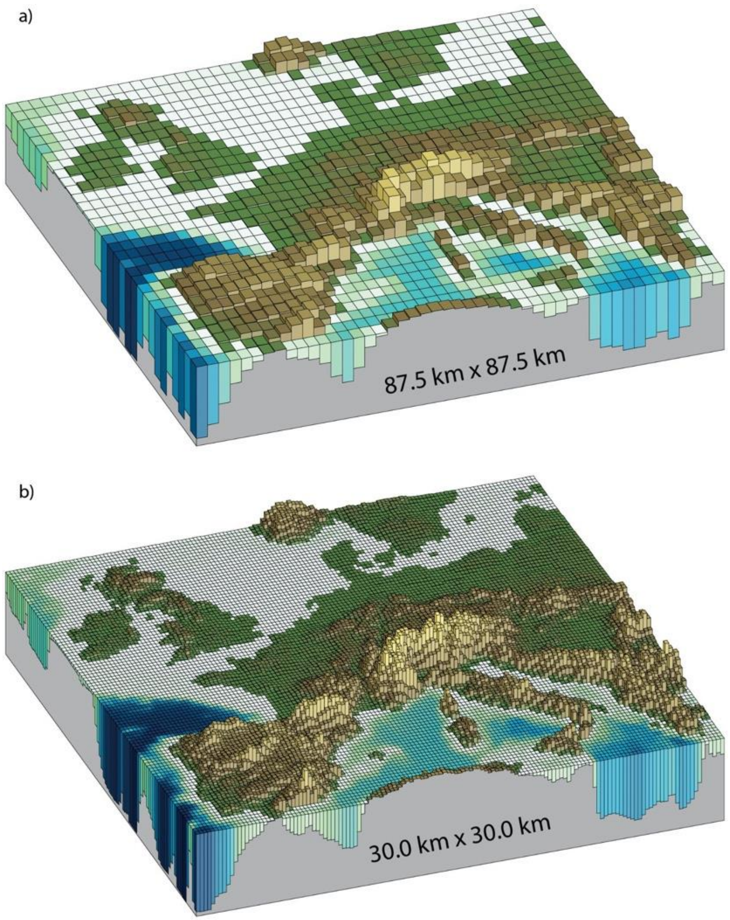


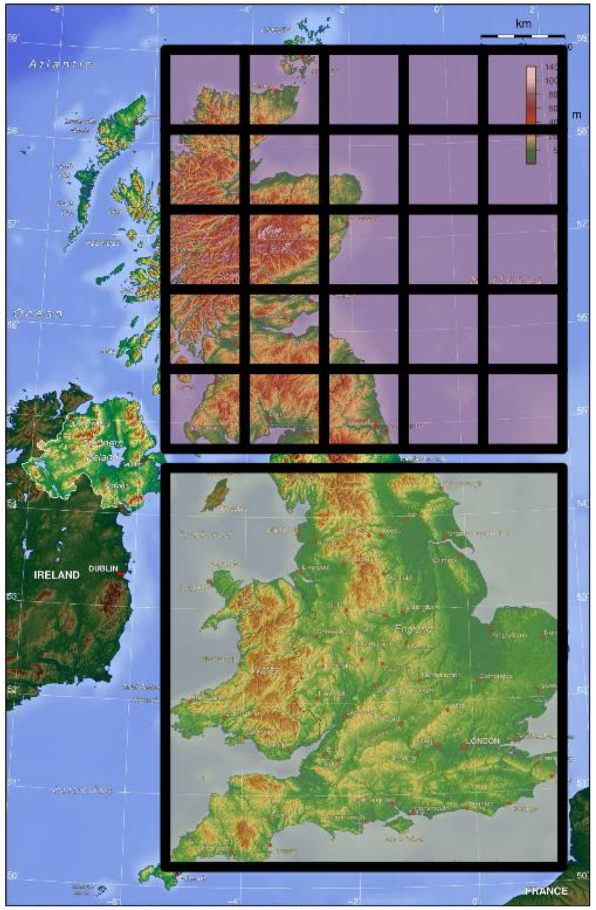
Figure 1.14 | Horizontal resolutions considered in today's higher resolution models and in the very high resolution models now being tested: (a) Illustration of the European topography at a resolution of 87.5 × 87.5 km; (b) same as (a) but for a resolution of 30.0 × 30.0 km.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

What’s smaller than 100km?

https://en.wikipedia.org/wiki/Geography_of_the_United_Kingdom

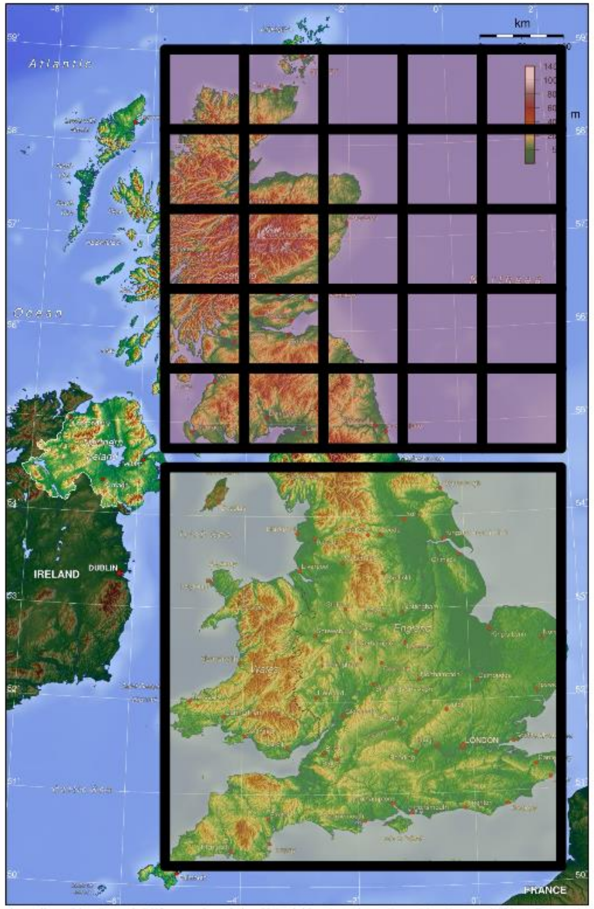
What's smaller than 100km?



https://en.wikipedia.org/wiki/Geography_of_the_United_Kingdom

New Models
(~100km)

Old Models
(~500km)



New Models (~100km)

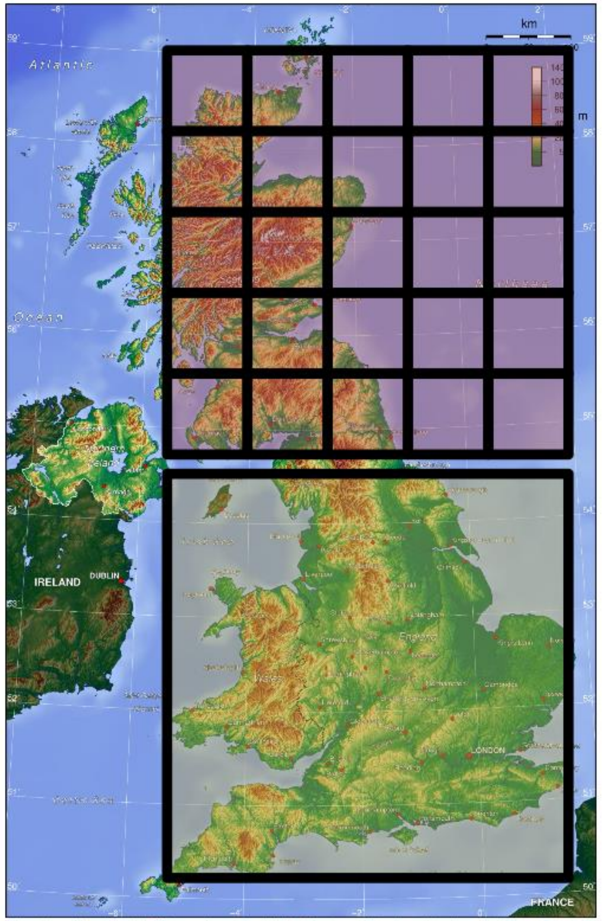
Old Models (~500km)

What's smaller than 100km?

Clouds (atmosphere) & surface conditions (land)

https://en.wikipedia.org/wiki/Geography_of_the_United_Kingdom ; https://en.wikipedia.org/wiki/New_Forest ; https://en.wikipedia.org/wiki/Iceberg ; https://en.wikipedia.org/wiki/Phytoplankton

What's smaller than 100km?



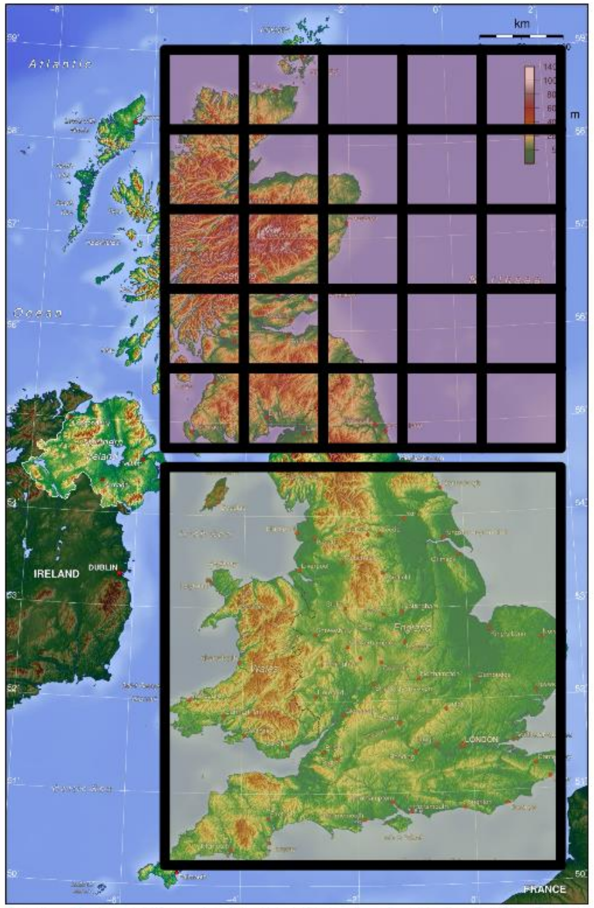
New Models (~100km)

Old Models (~500km)

Icebergs (cryosphere)

https://en.wikipedia.org/wiki/Geography_of_the_United_Kingdom ; https://en.wikipedia.org/wiki/New_Forest ; https://en.wikipedia.org/wiki/Iceberg ; https://en.wikipedia.org/wiki/Phytoplankton

What's smaller than 100km?



New Models
(~100km)

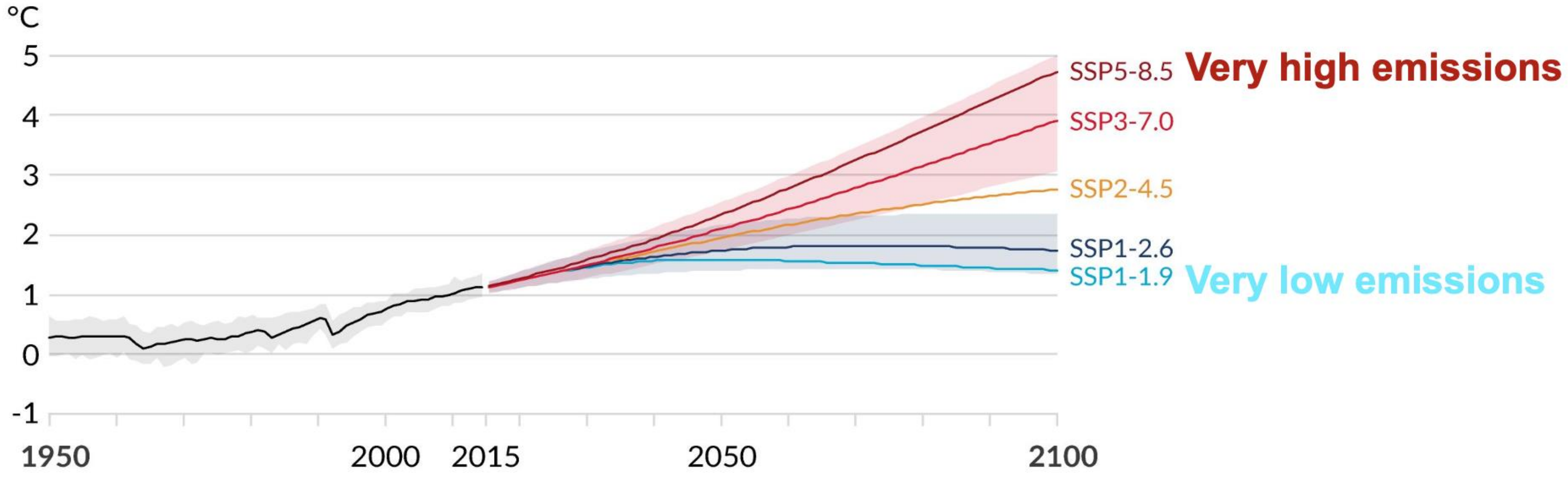
Old Models
(~500km)

Eddies (ocean) & phytoplankton (biology)

https://en.wikipedia.org/wiki/Geography_of_the_United_Kingdom ; https://en.wikipedia.org/wiki/New_Forest ; https://en.wikipedia.org/wiki/Iceberg ; https://en.wikipedia.org/wiki/Phytoplankton

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

a) Global surface temperature change relative to 1850-1900

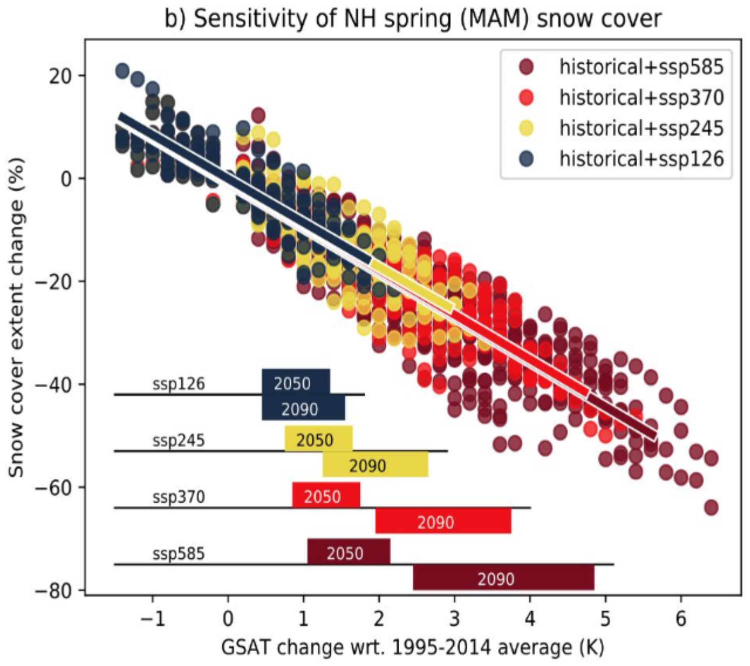


AR6 WG1 Figure SPM.8a

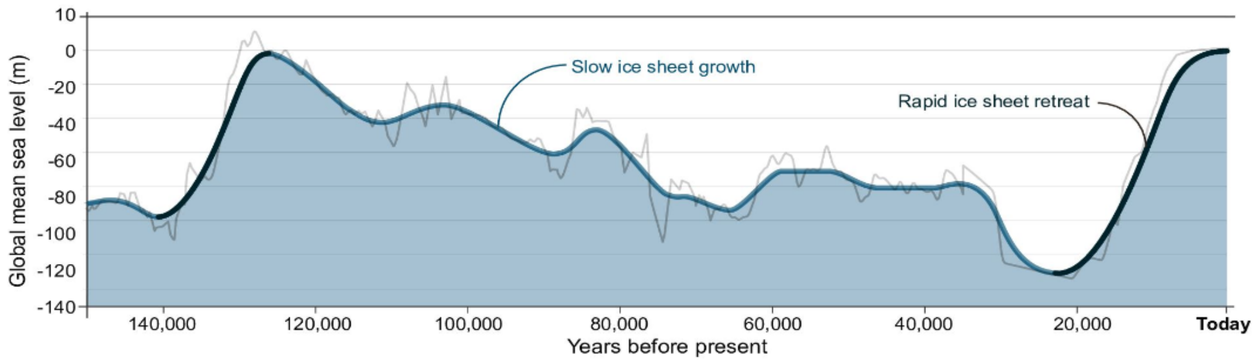
Figure SPM.8 | Selected indicators of global climate change under the five illustrative scenarios used in this Report

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

Fast & slow responses to temperature change



- **Some components respond proportionally to temperature change**

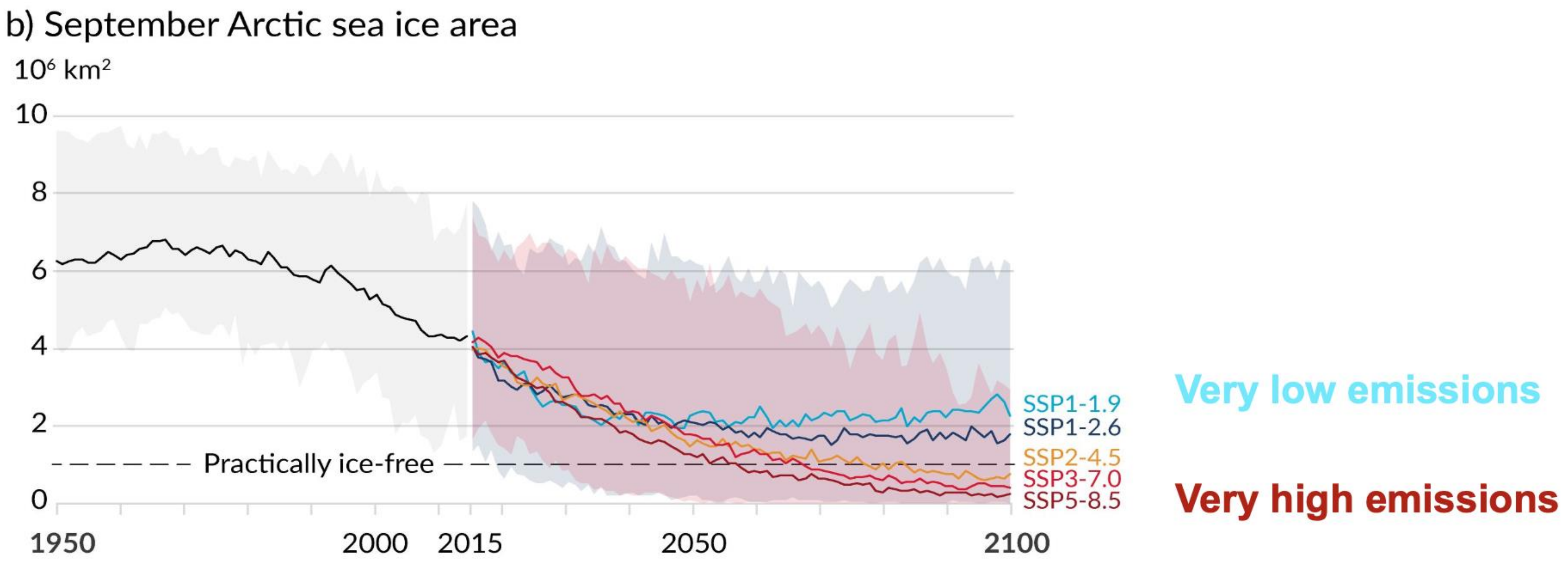


- **Ice sheets, deep ocean circulation respond slowly: irreversible, committed change underway (including sea level)**

Figure 9.24 | Simulated Coupled Model Intercomparison Project Phase 6 (CMIP6) and observed snow cover extent (SCE). (a) Simulated CMIP6 and observed (Mudryk et al., 2020) SCE (in millions of km^2) for 1981–2014. Boxes and whiskers with outliers represent monthly mean values for the individual CMIP6 models averaged over 1981–2014, with the red bar indicating the median of the CMIP6 multi-model ensemble for that period. The observed interannual distribution over the period is represented in green, with the yellow bar indicating the median. **(b)** Spring (March to May) Northern Hemisphere SCE against global surface air temperature (GSAT) (relative to the 1995–2014 average) for the CMIP6 Tier 1 scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), with linear regressions. Each data point is the mean for one CMIP6 simulation (first ensemble member for each available model) in the corresponding temperature bin. Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

FAQ 9.1, Figure 1 | Ice sheets growth and decay. (Top) Changes in ice-sheet volume modulate sea level variations. The grey line depicts data from a range of physical environmental sea level recorders such as coral reefs while the blue line is a smoothed version of it. **(Bottom left)** Example of destabilization mechanism in Antarctica. **(Bottom right)** Example of destabilization mechanism in Greenland.

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

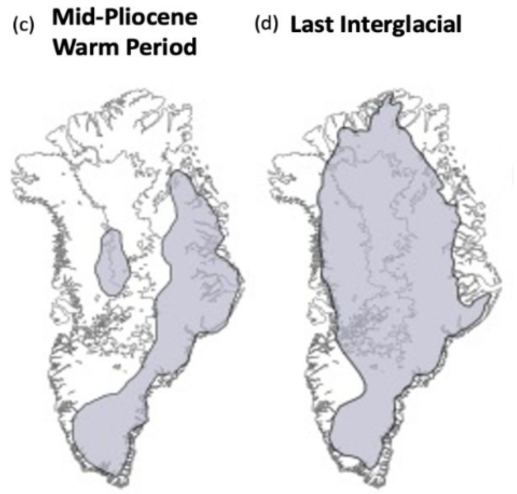


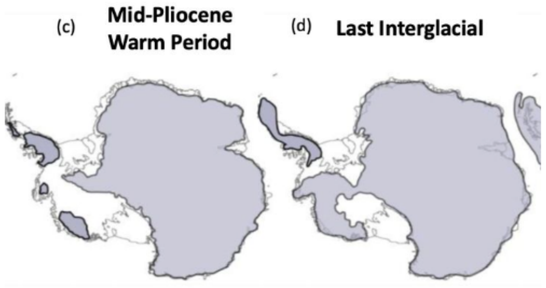
AR6 WG1 Figure SPM.8b

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

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

Tipping points in the ice sheets





AR6 WG1 Figure 9.17c-d, 9.18c-d

At sustained warming levels **between 2°C and 3°C, there is limited evidence that the Greenland and West Antarctic Ice Sheets will be lost** almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss increases with higher surface temperatures (*high confidence*).

At sustained warming levels **between 3°C and 5°C, near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet** is projected to occur irreversibly over multiple millennia (*medium confidence*); with substantial parts or all of Wilkes Subglacial Basin in East Antarctica lost over

Figure 9.17 | Greenland Ice Sheet cumulative mass change and equivalent sea level contribution. (a) A p-box (Section 9.6.3.2) based estimate of the range of values of paleo Greenland Ice Sheet mass and sea level equivalents relative to present day and the median over all central estimates (Simpson et al., 2009; Argus and Peltier, 2010; Colville et al., 2011; Dolan et al., 2011; Fyke et al., 2011; Robinson et al., 2011; Born and Nisancioglu, 2012; K.G. Miller et al., 2012; Dahl-Jensen et al., 2013; Helsen et al., 2013; Nick et al., 2013; Quiquet et al., 2013; Stone et al., 2013; Colleoni et al., 2014; Lecavalier et al., 2014; Robinson and Goelzer, 2014; Calov et al., 2015, 2018; Dutton et al., 2015; Koenig et al., 2015; Peltier et al., 2015; Stuhne and Peltier, 2015; Vizcaino et al., 2015; Goelzer et al., 2016; Khan et al., 2016; Yau et al., 2016; de Boer et al., 2017; Simms et al., 2019); **(b, left)** cumulative mass loss (and sea level equivalent) since 2015 from 1972 (Mouginot et al., 2019) and 1992 (Bamber et al., 2018b; The IMBIE Team, 2020), the estimated mass loss from 1840 (Box and Colgan, 2013; Kjeldsen et al., 2015) indicated with a shaded box, and projections from Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) to 2100 under RCP8.5/SSP5-8.5 and RCP2.6/SSP1-2.6 scenarios (thin lines from Goelzer et al. (2020); Edwards et al. (2021); Payne et al. (2021)) and ISMIP6 emulator under SSP5-8.5 and SSP1-2.6 to 2100 (shades and bold line; Edwards et al., 2021); **(b, right)** 17th–83rd and 5th–95th percentile ranges for ISMIP6 and ISMIP6 emulator at 2100. Schematic interpretations of individual reconstructions (Lecavalier et al., 2014; Goelzer et al., 2016; Berends et al., 2019) of the spatial extent of the Greenland Ice Sheet are shown for the: **(c)** mid-Pliocene Warm Period; **(d)** the Last Interglacial; and **(e)** the Last Glacial Maximum: grey shading shows extent of grounded ice. Maps of mean elevation changes **(f)** 2010–2017 derived from CryoSat 2 radar altimetry (Bamber et al., 2018b) and **(g)** ISMIP6 model mean (2093–2100) projected changes for the MIROC5 climate model under the RCP8.5 scenario (Goelzer et al., 2020). Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

Figure 9.18 | Antarctic Ice Sheet cumulative mass change and equivalent sea level contribution. (a) A p-box (Section 9.6.3.2) based estimate of the range of values of paleo Antarctic ice sheet mass and sea level equivalents relative to present day and the median over all central estimates (Bamber et al., 2009; Argus and Peltier, 2010; Dolan et al., 2011; Mackintosh et al., 2011; Golledge et al., 2012, 2013, 2014, 2015, 2017b; K.G. Miller et al., 2012; Whitehouse et al., 2012; Ivins et al., 2013; Argus et al., 2014; Briggs et al., 2014; Maris et al., 2014; de Boer et al., 2015, 2017; Dutton et al., 2015; Pollard et al., 2015; DeConto and Pollard, 2016; Gasson et al., 2016; Goelzer et al., 2016; Yan et al., 2016; Kopp et al., 2017; Simms et al., 2019); **(b left)** cumulative mass loss (and sea level equivalent) since 2015, with satellite observations shown from 1993 (Bamber et al., 2018a; The IMBIE Team, 2018; WCRP Global Sea Level Budget Group, 2018) and observations from 1979 (Rignot et al., 2019), and projections from Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) to 2100 under RCP8.5/SSP5-8.5 and RCP2.6/SSP1-2.6 scenarios (thin lines from Seroussi et al., 2020; Edwards et al., 2021; Payne et al., 2021) and ISMIP6 emulator under SSP5-8.5 and SSP1-2.6 to 2100 (shades and bold line; Edwards et al., 2021); **(b, right)** 17th–83rd, 5th–95th percentile ranges for ISMIP6, ISMIP6 emulator, and LARMIP-2 including surface mass balance (SMB) at 2100. **(c–e)** Schematic interpretations of individual reconstructions (Anderson et al., 2002; Bentley et al., 2014; de Boer et al., 2015; Goelzer et al., 2016) of the spatial extent of the Antarctic Ice Sheet are shown for the: **(c)** mid-Pliocene Warm Period, **(d)** Last Interglacial; and **(e)** Last Glacial Maximum (Fretwell et al., 2013): grey shading shows extent of grounded ice. **(f–g)** Maps of mean elevation changes **(f)** 1978–2017 derived from multi-mission satellite altimetry (Schröder et al., 2019) and **(g)** ISMIP6: 2061–2100 projected changes for an ensemble using the Norwegian Climate Center's Earth System Model (NorESM1-M) climate model under the RCP8.5 scenario (Seroussi et al., 2020). Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

Ice-Albedo Feedback

- **In a warming climate, more sea ice melts in the summer season**
- **Ice is effective at reflecting radiation back to space ('high albedo')**
- **The ocean surface is darker and absorbs more heat**
- **With less ice, the ocean warms and melts sea ice from the sides and below, reducing the ice cover further**

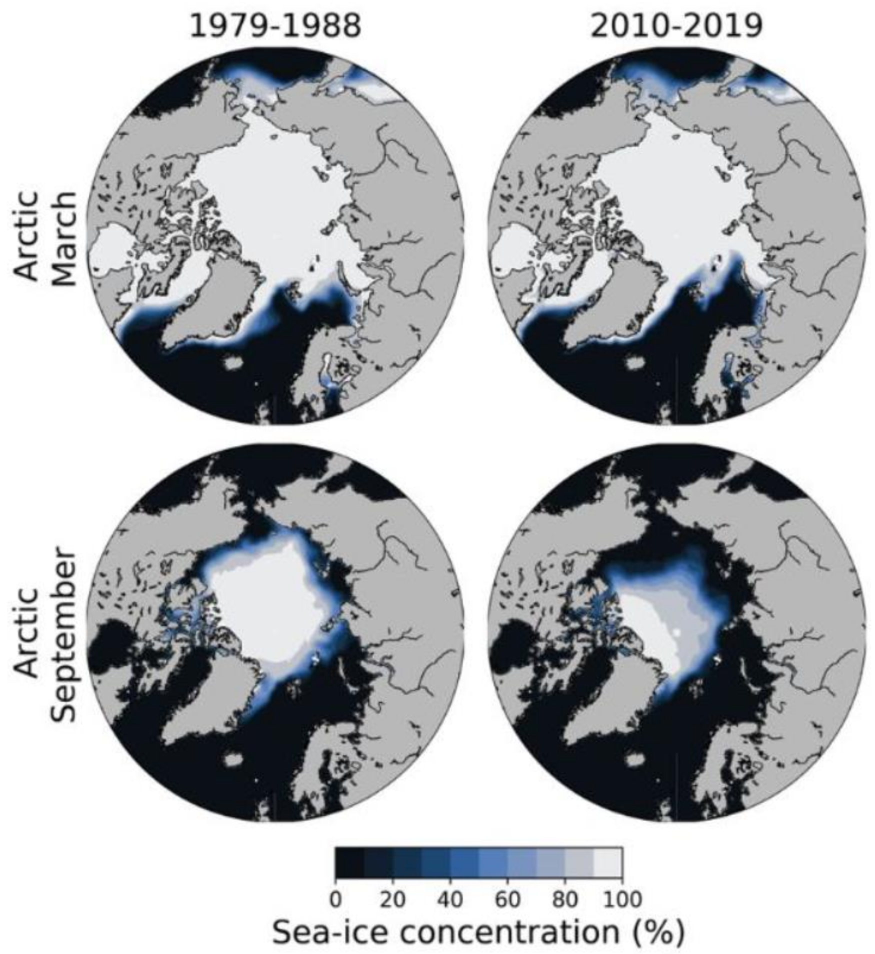
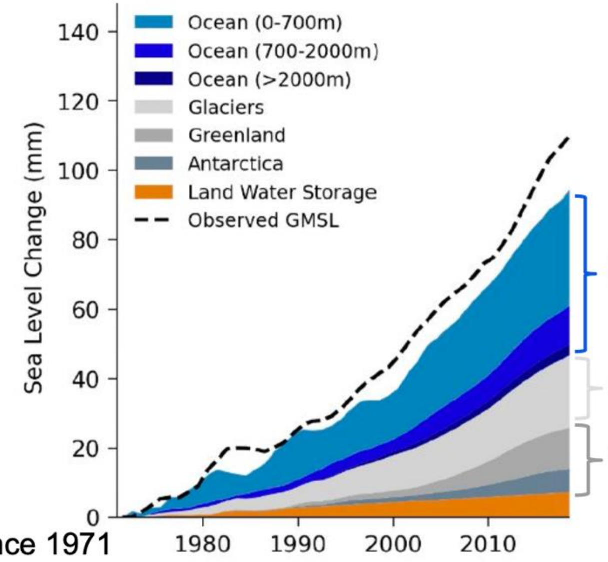


Figure 9.13 | Arctic sea ice historical records and Coupled Model Intercomparison Project Phase 6 (CMIP6) projections. (Left) Absolute anomaly of monthly-mean Arctic sea ice area during the period 1979 to 2019 relative to the average monthly-mean Arctic sea ice area during the period 1979 to 2008. **(Right)** Sea ice concentration in the Arctic for March and September, which usually are the months of maximum and minimum sea ice area, respectively. First column: Satellite-retrieved mean sea ice concentration during the decade 1979–1988. Second column: Satellite-retrieved mean sea ice concentration during the decade 2010–2019. Third column: Absolute change in sea ice concentration between these two decades, with grid lines indicating non-significant differences. Fourth column: Number of available CMIP6 models that simulate a mean sea ice concentration above 15 % for the decade 2045–2054. The average observational record of sea ice area is derived from the UHH sea ice area product (Doerr et al., 2021), based on the average sea ice concentration of OSISAF/CCI (OSI-450 for 1979–2015, OSI-430b for 2016–2019) (Lavergne et al., 2019), NASA Team (version 1, 1979–2019) (Cavalieri et al., 1996) and Bootstrap (version 3, 1979–2019) (Comiso, 2017) that is also used for the figure panels showing observed sea ice concentration. Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

AR6 WG1 Figure 9.13
1st and 2nd column of right panels

Heating of the climate system due to emissions of greenhouse gases is causing sea level rise due to ocean warming and the loss of land ice



since 1971

Ocean thermal expansion

Glaciers

Greenland & Antarctic ice sheets

x4

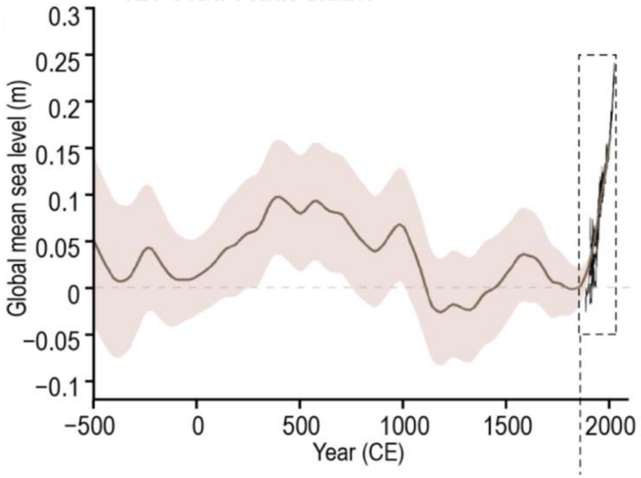
1990s to 2010s

Now dominant

Cross-Chapter 9.1, Figure 1 | Global Energy Inventory and Sea Level Budget. (a) Observed changes in the global energy inventory for 1971–2018 (shaded time series) with component contributions as indicated in the figure legend. Earth System Heating for the whole period and associated uncertainty is indicated to the right of the plot (red bar = central estimate; shading = *very likely* range); **(b)** Observed changes in components of global mean sea level for 1971–2018 (shaded time series) as indicated in the figure legend. Observed global mean sea level change from tide gauge reconstructions (1971–1993) and satellite altimeter measurements (1993–2018) is shown for comparison (dashed line) as a three-year running mean to reduce sampling noise. Closure of the global sea level budget for the whole period is indicated to the right of the plot (red bar = component sum central estimate; red shading = *very likely* range; black bar = total sea level central estimate; grey shading = *very likely* range). Full details of the datasets and methods used are available in Annex I. Further details on energy and sea level components are reported in Table 7.1 and Table 9.5.

AR6 WG1 Cross-Chapter Box 9.1, Figure 1 (right panel)

Global mean sea level rose faster since 1900 than over any prior century in at least the last 3000 years



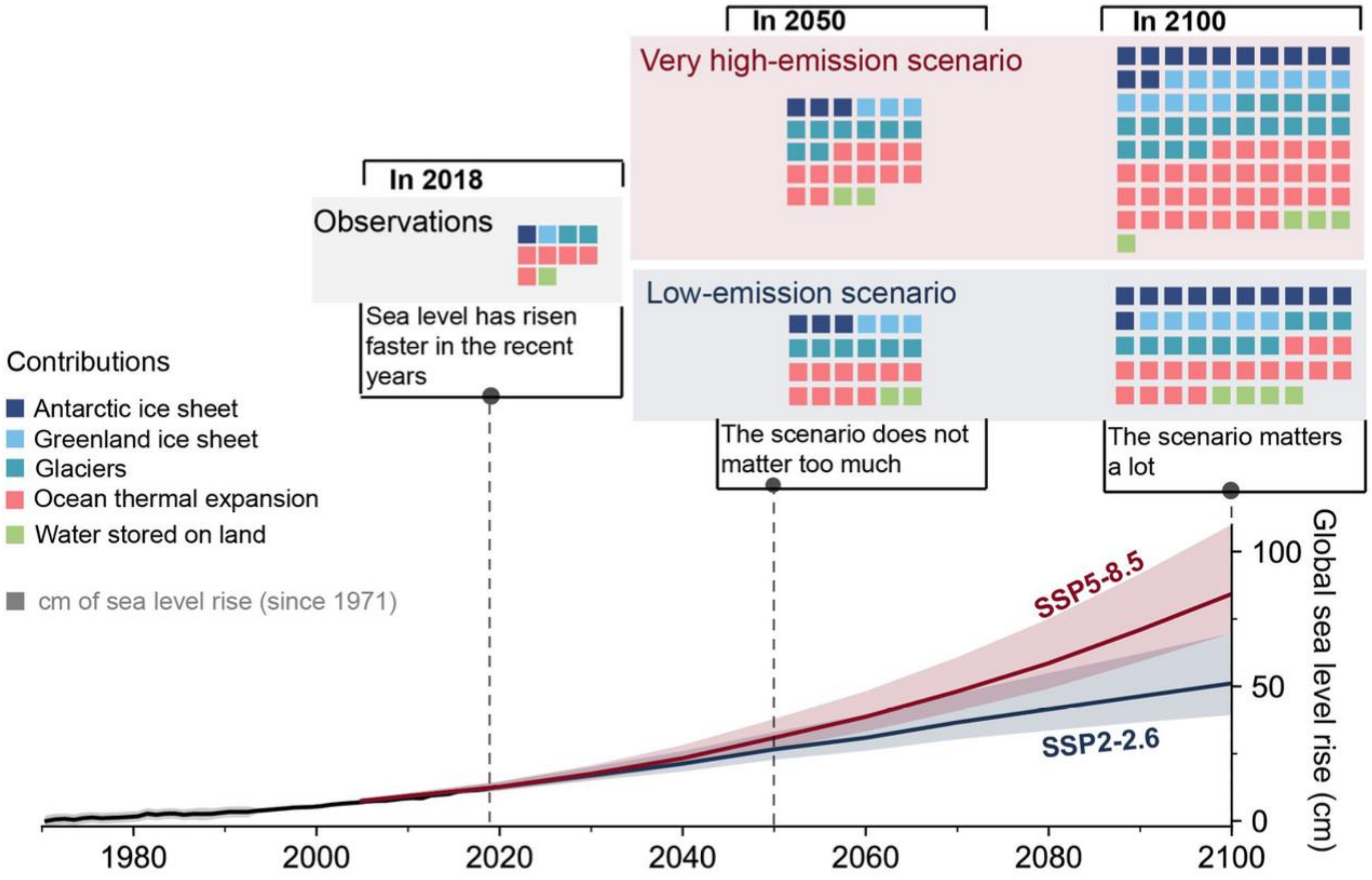
AR6 WG1
Figure 2.28

Figure 2.28 | Changes in global mean sea level. (a) Reconstruction of sea-level from ice core oxygen isotope analysis for the last 800 kyr. For target paleo periods (CCB2.1) and MIS11 the estimates based upon a broader range of sources are given as box whiskers. Note the much broader axis range (200 m) than for later panels (tenths of metres). **(b)** Reconstructions for the last 2500 years based upon a range of proxy sources with direct instrumental records superposed since the late 19th century. **(c)** Tide-gauge and, more latterly, altimeter-based estimates since 1850. The consensus estimate used in various calculations in Chapters 7 and 9 is shown in black. **(d)** The most recent period of record from tide-gauge and altimeter-based records. Further details on data sources and processing are available in the chapter data table (Table 2.SM.1).

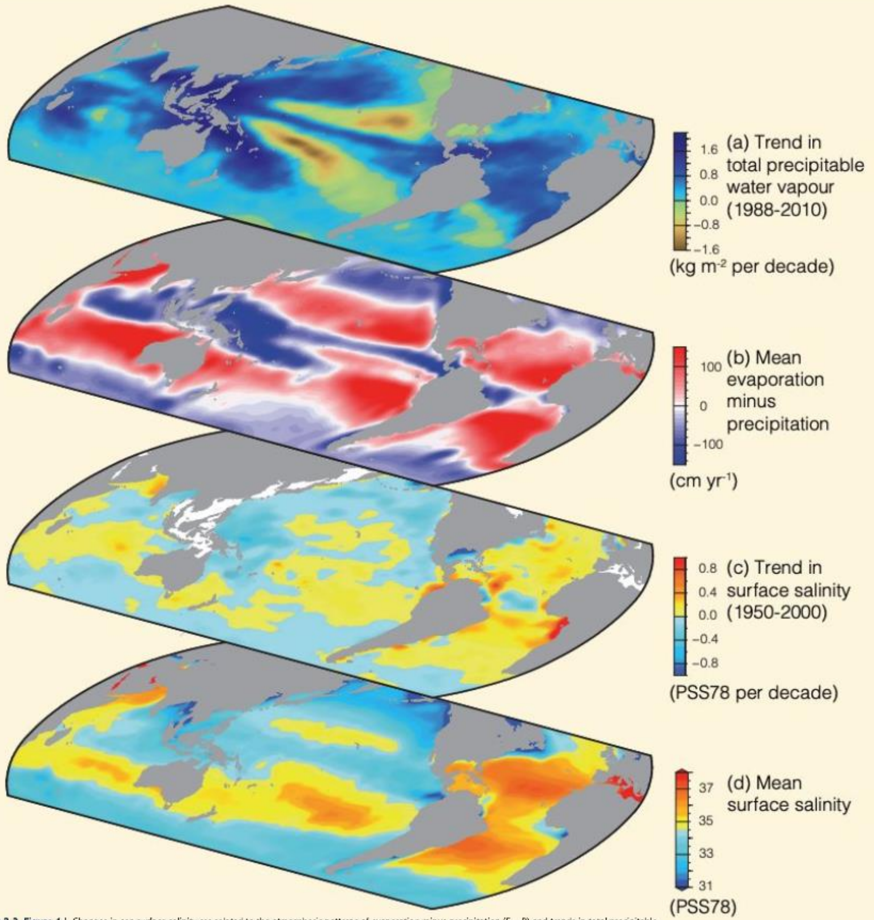
- **Global mean sea level increased by 20 [15 to 25] cm between 1901-2018**
- **The rate of global mean sea level rise is increasing**
- **The average rate of sea level rise was:**
  - **1.3 mm per year between 1901-1971**
  - **1.9 mm per year between 1971-2006,**
  - **3.7 mm per year between 2006-2018**
- **Human influence was *very likely* the main driver of these increases since at least 1971**

FAQ 9.2: **How much will sea level rise in the next few decades?**

Emissions scenarios influence little sea level rise of the coming decades but has a huge effect on sea level at the end of the century.



FAQ 9.2, Figure 1 | Observed and projected global mean sea level rise and the contributions from its major constituents.



FAQ 3.2, Figure 1 | Changes in sea surface salinity are related to the atmospheric patterns of evaporation minus precipitation (E – P) and trends in total precipitable water: (a) Linear trend (1988–2010) in total precipitable water (water vapor integrated from the Earth's surface up through the entire atmosphere) (kg m^{-2} per decade) from satellite observations (Special Sensor Microwave Imager) (after Wentz et al., 2007) (blues: wetter; yellows: drier). (b) The 1979–2005 climatological mean net E –P (cm yr^{-1}) from meteorological reanalysis (National Centers for Environmental Prediction/National Center for Atmospheric Research; Kalnay et al., 1996) (reds: net evaporation; blues: net precipitation). (c) Trend (1950–2000) in surface salinity (PSS78 per 50 years) (after Durack and Wijffels, 2010) (blues freshening; yellows-reds saltier). (d) The climatological-mean surface salinity (PSS78) (blues: <35; yellows–reds: >35).

AR5 WG1 FAQ3.2

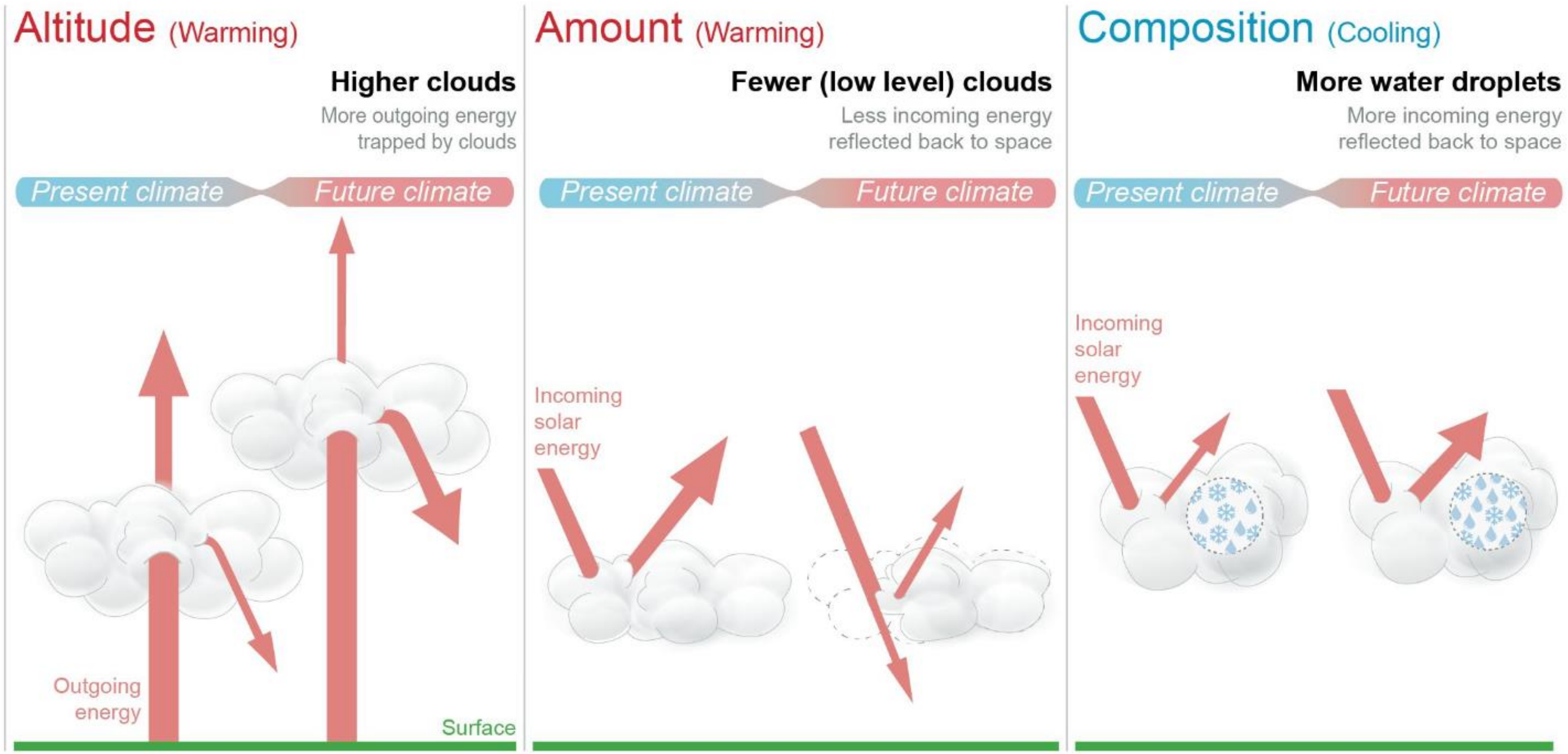
Water cycle

- The Earth's water cycle involves evaporation and precipitation at the Earth's surface
- As the planet warms, the water cycle is expected to intensify
- This is because the atmosphere can hold about 7% more water vapour for each degree Celsius of warming
- We also see this pattern is the ocean salinity

Cloud feedbacks

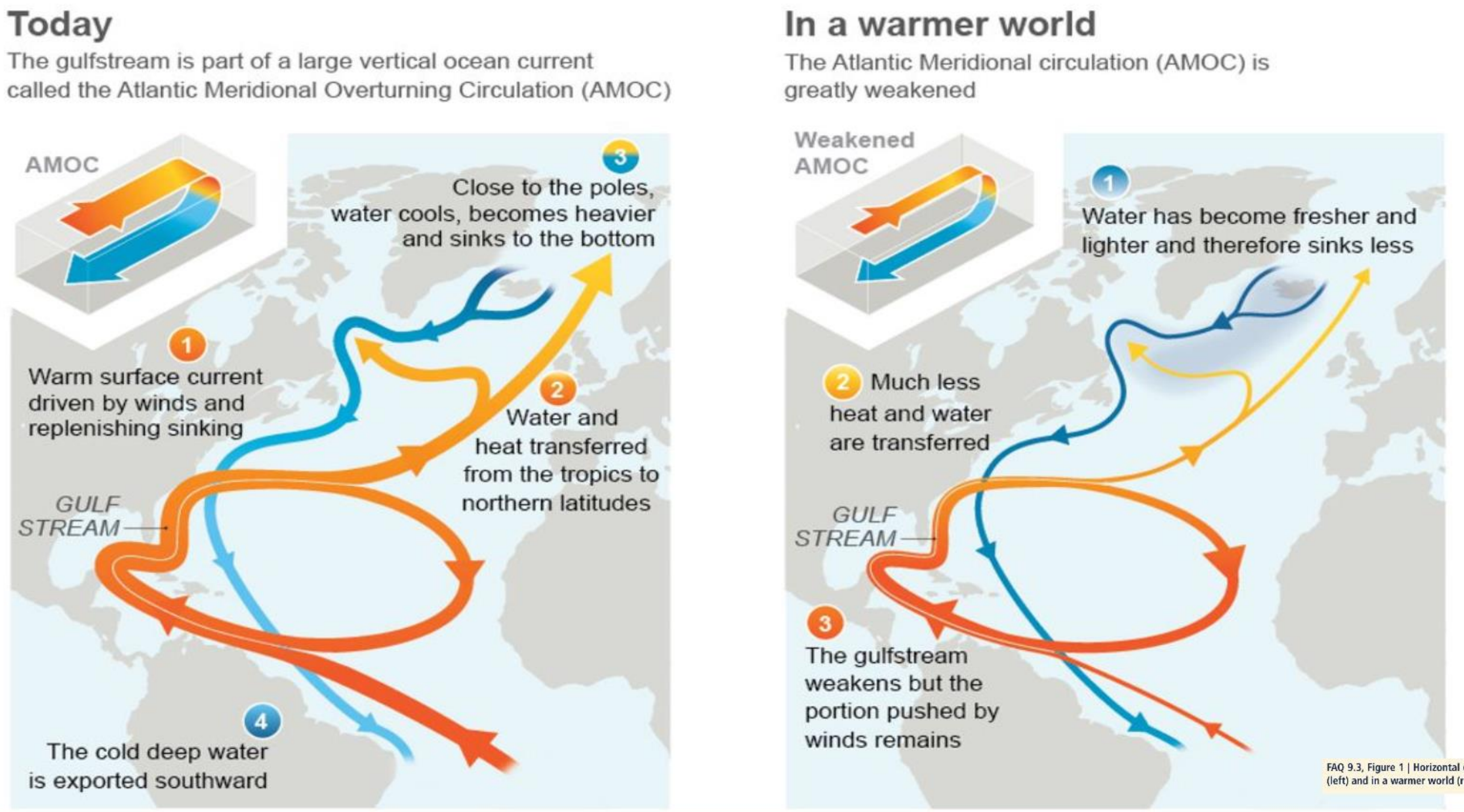
FAQ 7.2, Figure 1 | Interactions between clouds and the climate, today and in a warmer future. Global warming is expected to alter the altitude **(left)** and the amount **(centre)** of clouds, which will amplify warming. On the other hand, cloud composition will change **(right)**, offsetting some of the warming. Overall, clouds are expected to amplify future warming.

FAQ 7.2: **What is the role of clouds in a warming climate?**
Clouds affect and are affected by climate change. Overall, scientists expect clouds to **amplify future warming**.



FAQ9.3: **Will the Gulfstream shutdown?**

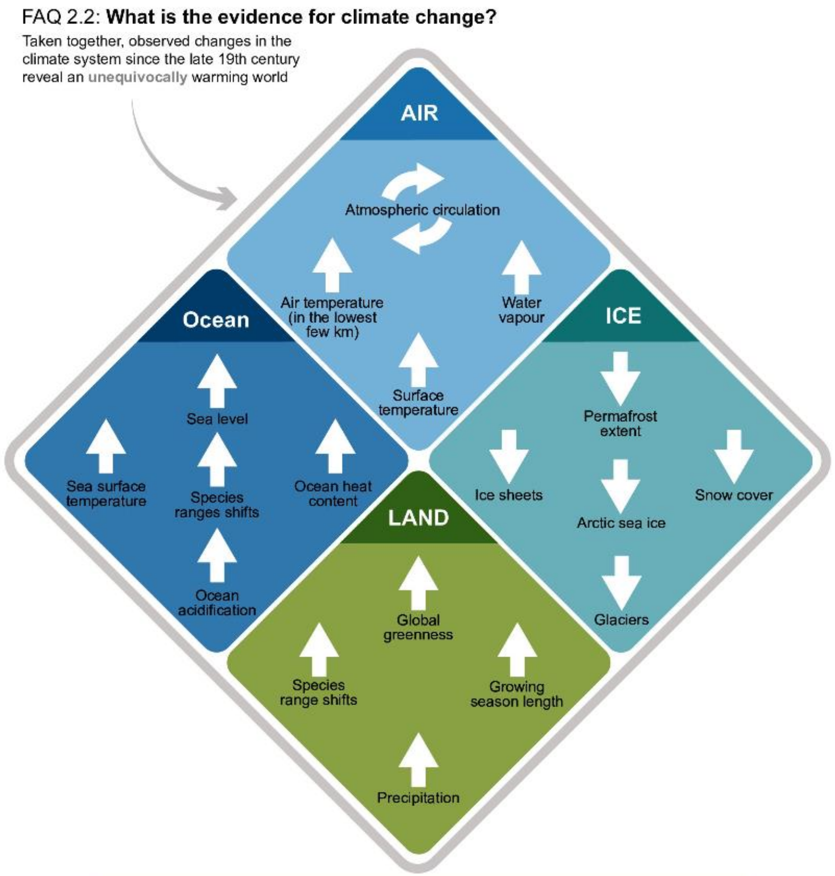
The warm current is expected to weaken but not cease, which will affect regional weather and sea level



FAQ 9.3, Figure 1 | Horizontal (gyre) and vertical (Atlantic Meridional Overturning Circulation, AMOC) circulations in the Atlantic today (left) and in a warmer world (right). The Gulf Stream is a warm current composed of both circulations.

Summary

- We have evidence from observations that climate has changed
- We understand many of the processes that are involved even if it is difficult to quantify their effects
- Scenarios of future climate forcing and complex climate models are needed to quantify future changes in climate and the uncertainties
- IPCC provides an assessment of past and future climate change



FAQ 2.2, Figure 1 | Synthesis of significant changes observed in the climate system over the past several decades. Upwards, downwards and circling arrows indicate increases, decreases and changes, respectively. Independent analyses of many components of the climate system that would be expected to change in a warming world exhibit trends consistent with warming. Note that this list is not comprehensive.

Climatematch Academy