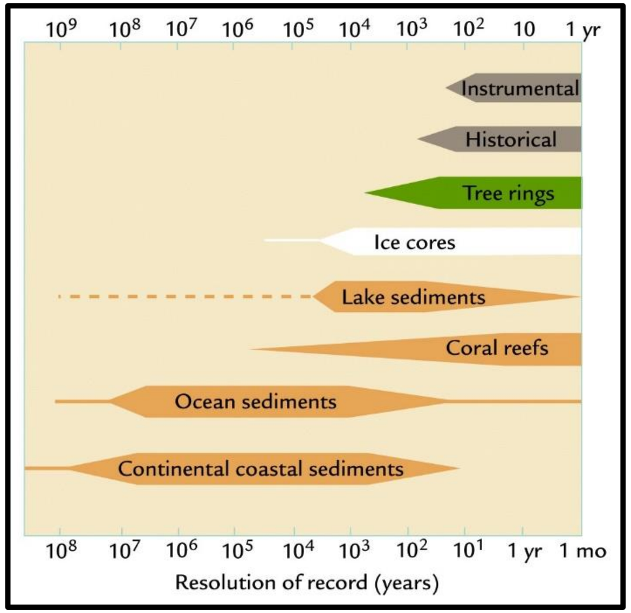
Go to: **responseware.eu**
Login: **enter as guest**
Session-ID: **env421**

Sustainability, climate and energy

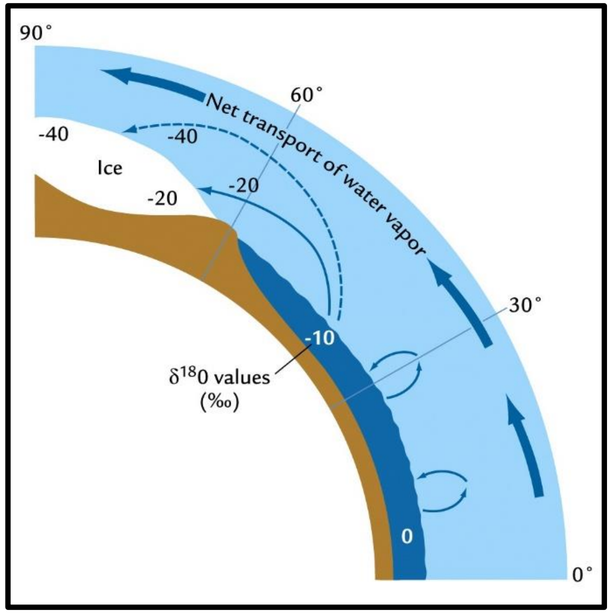
ENV-421
Jérôme Chappellaz, Jonas Schnidrig

Recap from last lecture

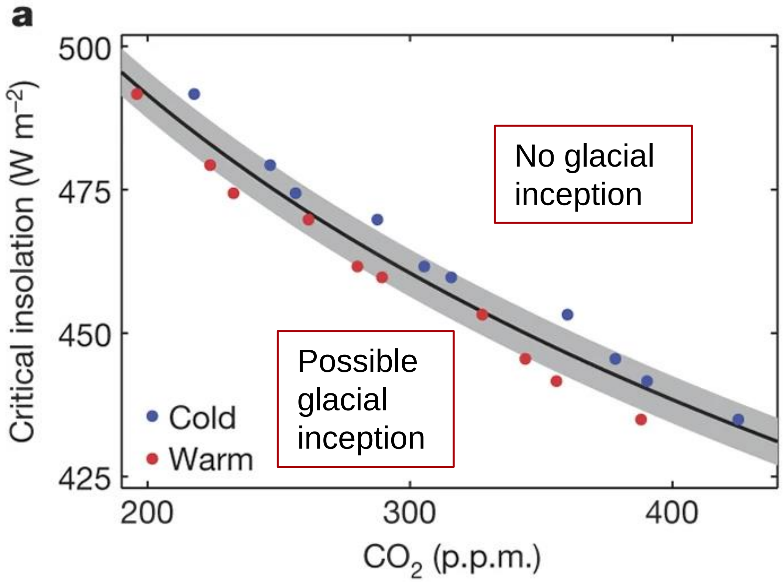
Climate proxies



Isotopic tracers

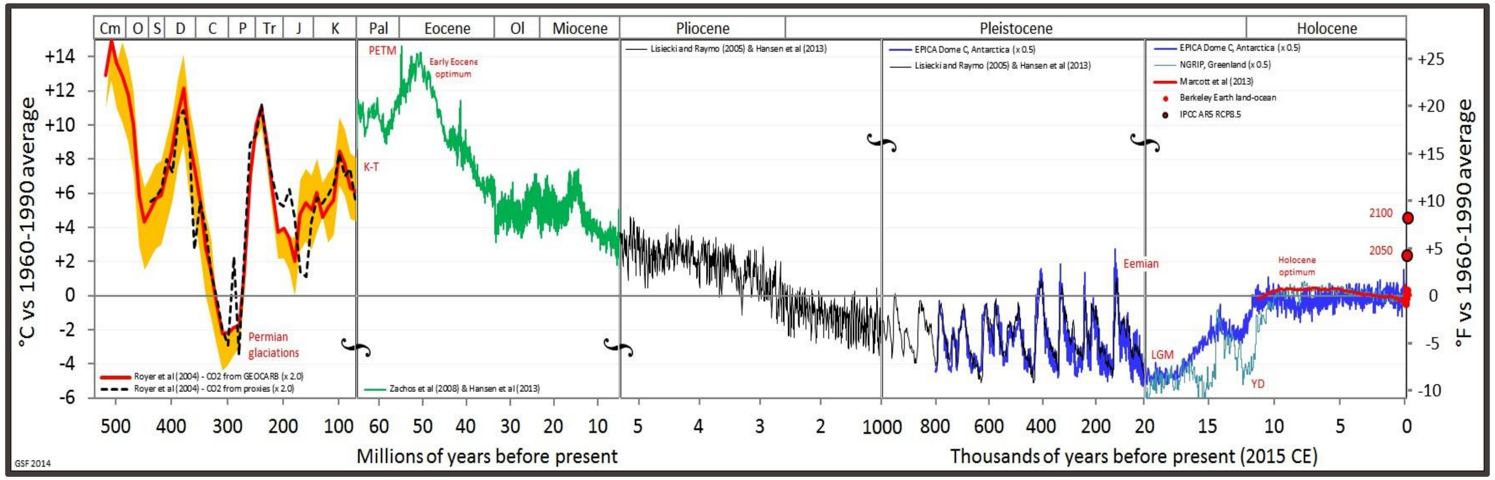


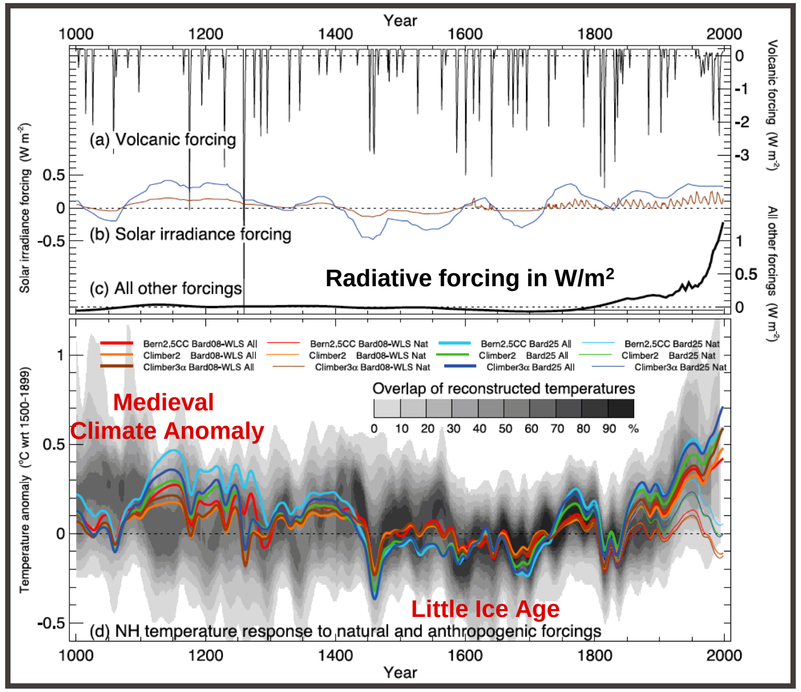
IPCC AR6 and Last Glacial Maximum:
Likely ECS range of **2.5 to 4.0°C**



CO_2 and insolation combined to generate glacial-interglacial cycles

Tectonics, volcanism, CO_2, orbital forcing





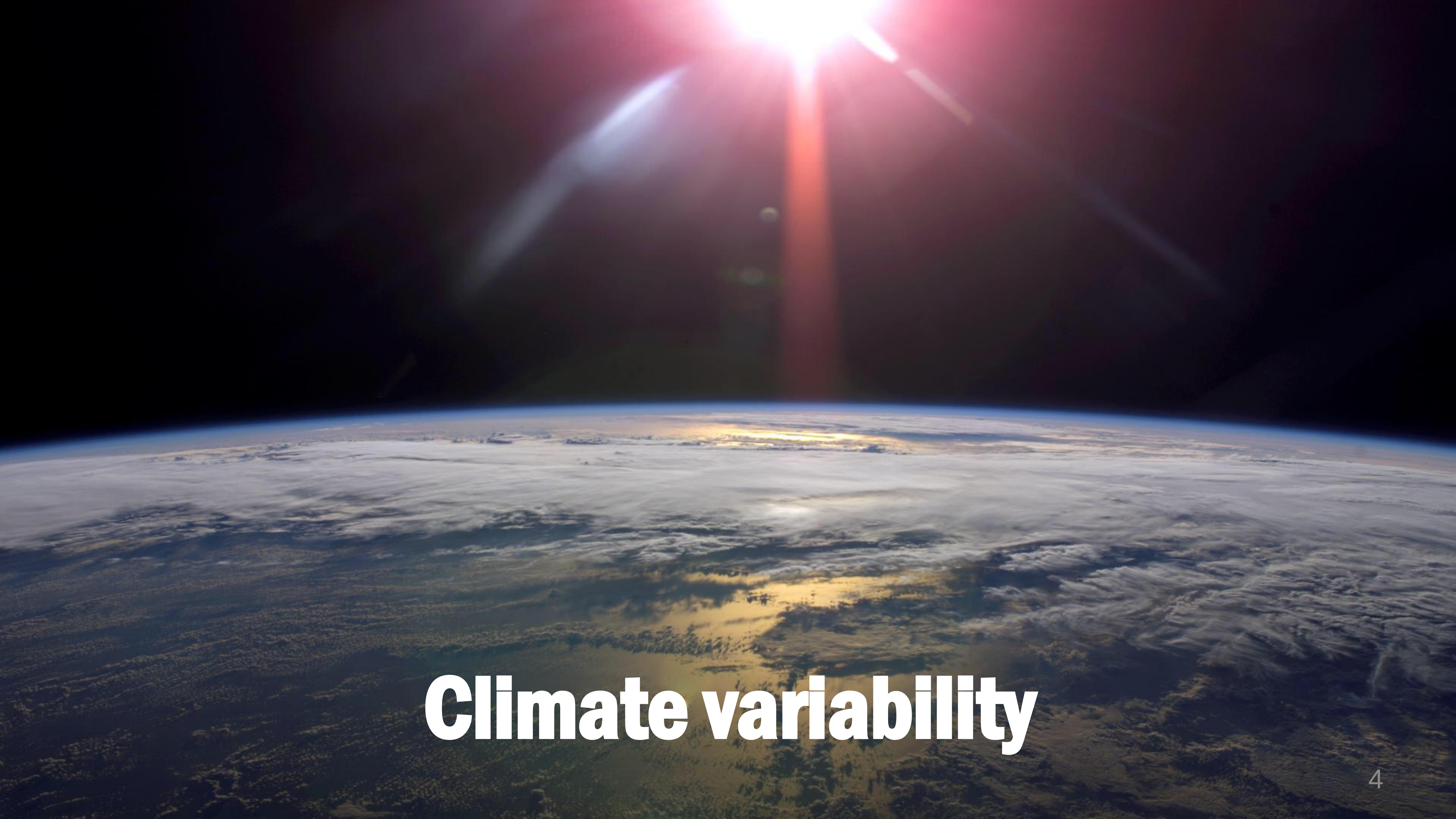
Last 1000 years: mostly volcanic & solar forcing.

General outline

No.	Date	Topics	Remarks
1.	18.02.2025	Introduction to the climate system. Earth energy balance. Greenhouse gases and aerosols	
2.	25.02.2025	Introduction to energy systems. Energy balance fundamentals	
3.	04.03.2025	Radiative forcing. Feedback mechanisms. Climate sensitivity	
4.	11.03.2025	Overview of energy technologies	
5.	18.03.2025	Climate archives: geological to millennial time scales	Conf. Michael Sigl + QCM evaluation (graded)
6.	25.03.2025	**Climate variability. Climate change scenarios. Carbon cycle feedbacks.**	
7.	01.04.2025	Technologies' impacts	Conf. Alexis Quentin
8.	08.04.2025	Tipping points. Extreme events. Regional climate change	
9.	15.04.2025	Climate change impacts on renewable energy systems. Impact of RES on climate	J. Castella (Watted) : PowerPlay game
10.	29.04.2025	Field visit : floating solar platform + dam (Romande Energie)	
11.	06.05.2025	Intro to systemic approach on local scale climate/energy engineering	Start of group work
12.	13.05.2025	Group work on chosen case study	
13.	20.05.2025	Group work on chosen case study	
14.	27.05.2025	Presentation of group reports	Reports are graded

Basics (1–9)
Applications (9–14)

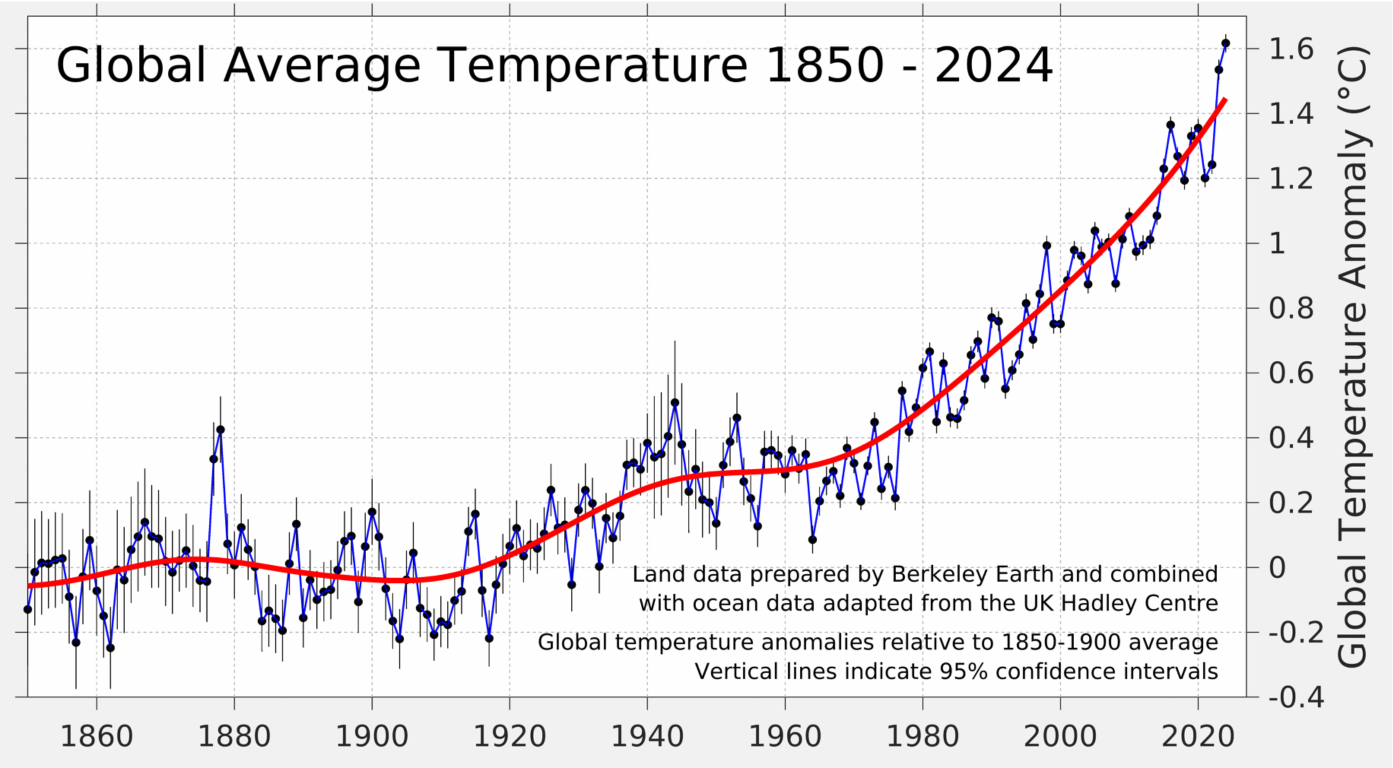
Exam session between 16.06.2025 and 05.07.2025



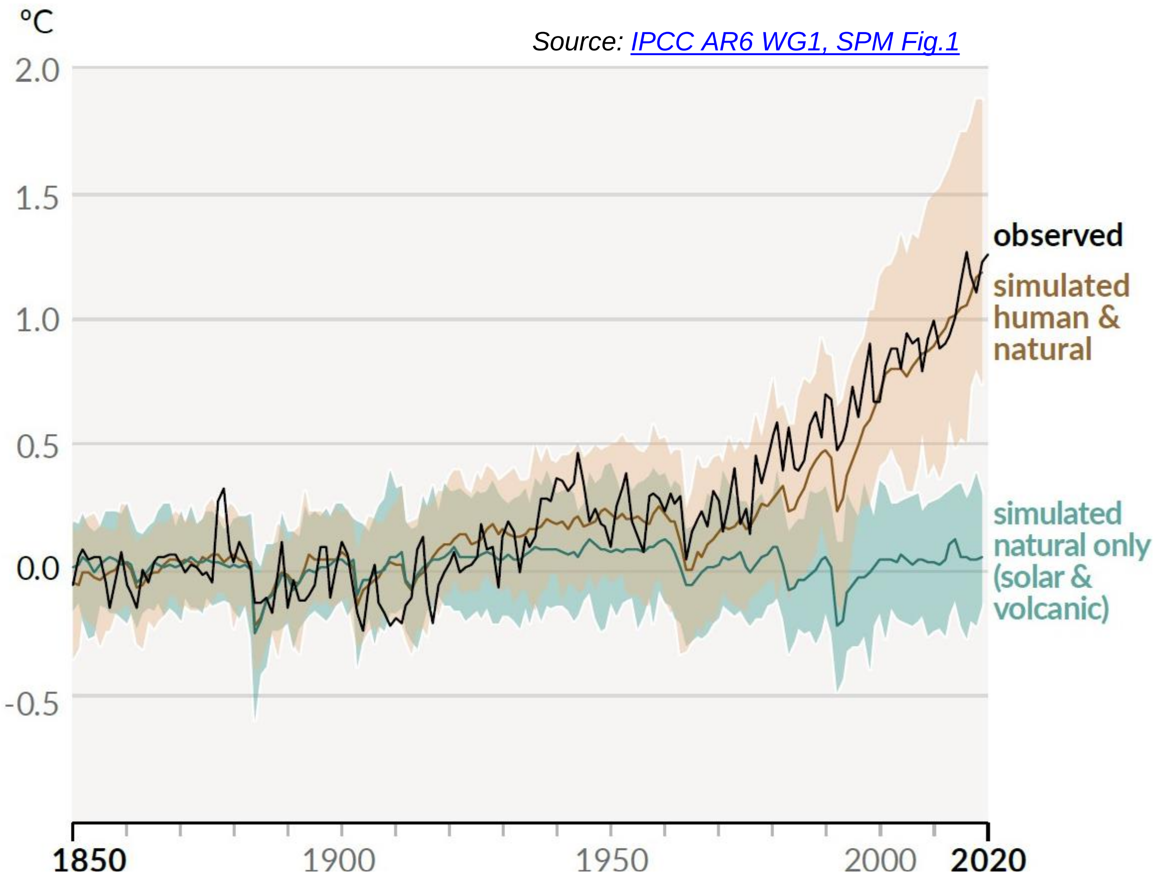
Climate variability

What is anthropogenic ? What is natural variability ?

Source: Berkeley annual temperature report for 2024



Source: IPCC AR6 WG1, SPM Fig.1



- Climate change since preindustrial time is a combination of anthropogenic forcing and natural variations.
- Climate models need to correctly represent natural climate variability:
  - It gives fate in the models.
  - It allows to anticipate potential changes of the variability under a warmer world.

- Climate and energy: renewable energy systems can also be affected by natural climate variability.

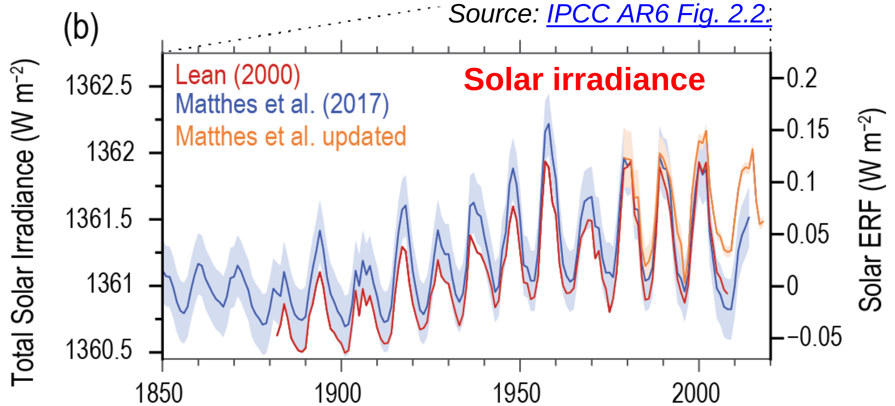
What can cause natural climate variability ?

- Natural climate variability due to **external forcing**.
  - Can be periodic or erratic.
  - Do not depend on the climate state.

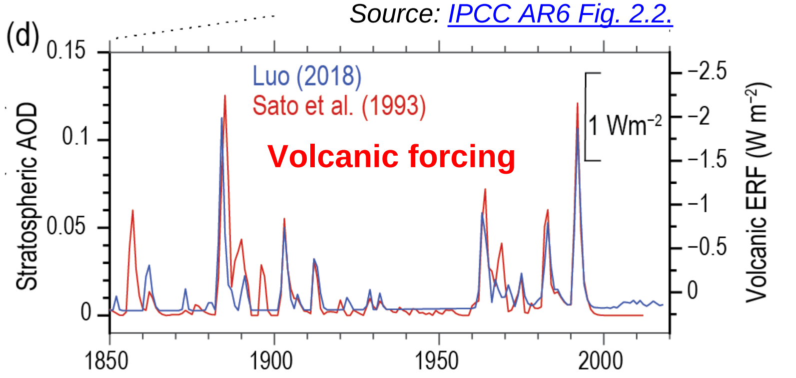
- **Internal climate variability** related with patterns / modes.

- We'll see examples with the next slides.

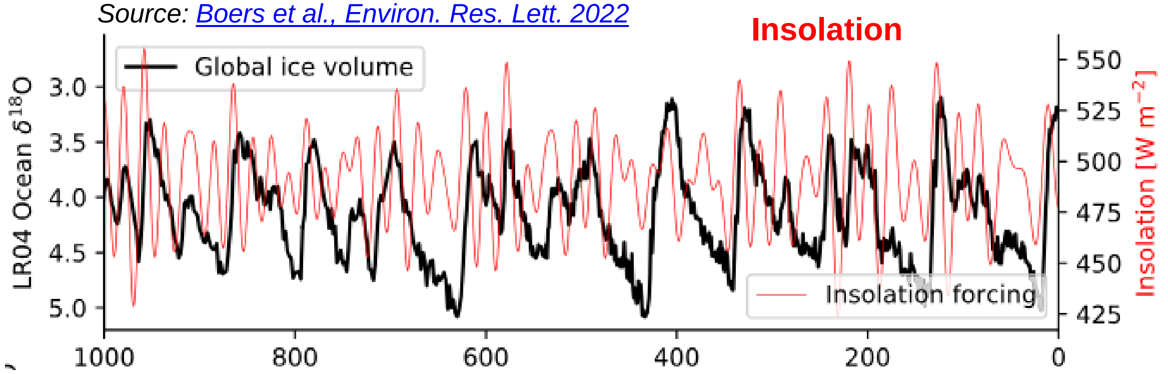
Source: IPCC AR6 Fig. 2.2.



Source: IPCC AR6 Fig. 2.2.

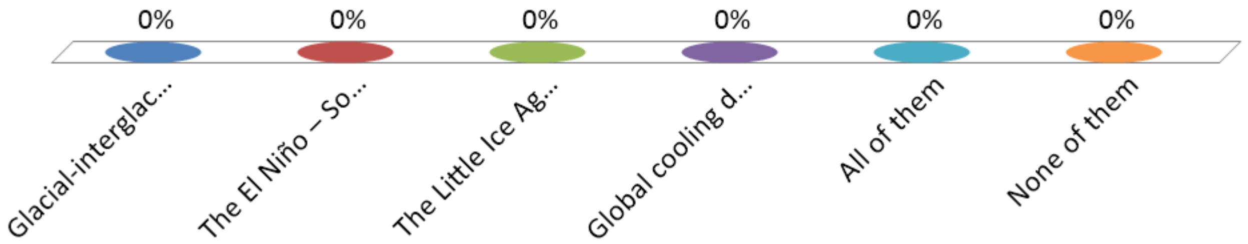


Source: Boers et al., Environ. Res. Lett. 2022



Which climatic phenomenon is internal variability ?

A. Glacial-interglacial cycles
B. The El Niño – Southern Oscillation (ENSO)
C. The Little Ice Age (from ~1300 to ~1850)
D. Global cooling due to the Tambora eruption
E. All of them
F. None of them



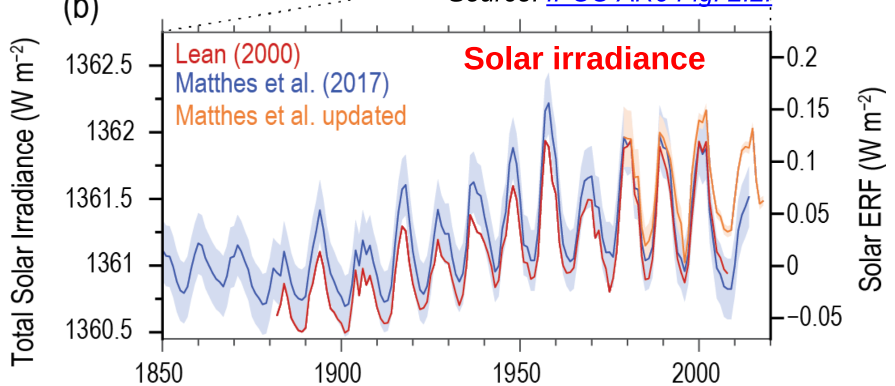
What can cause natural climate variability ?

- Natural climate variability due to **external forcing**.
  - Can be periodic or erratic.
  - Do not depend on the climate state.

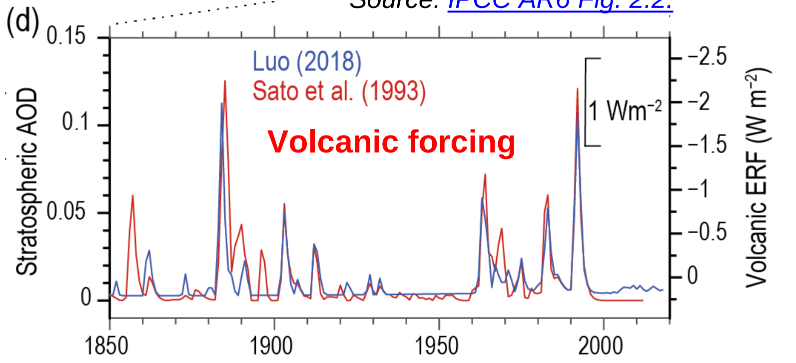
- **Internal climate variability** related with patterns / modes.

- We'll see examples with the next slides.

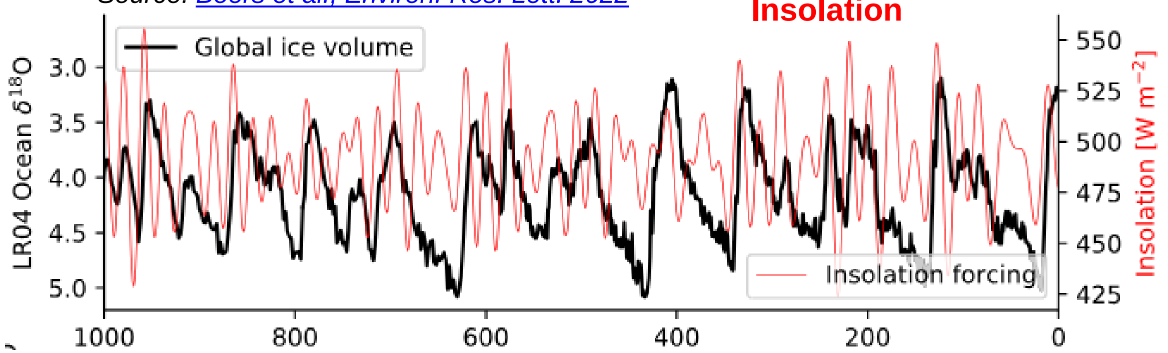
Source: IPCC AR6 Fig. 2.2.



Source: IPCC AR6 Fig. 2.2.



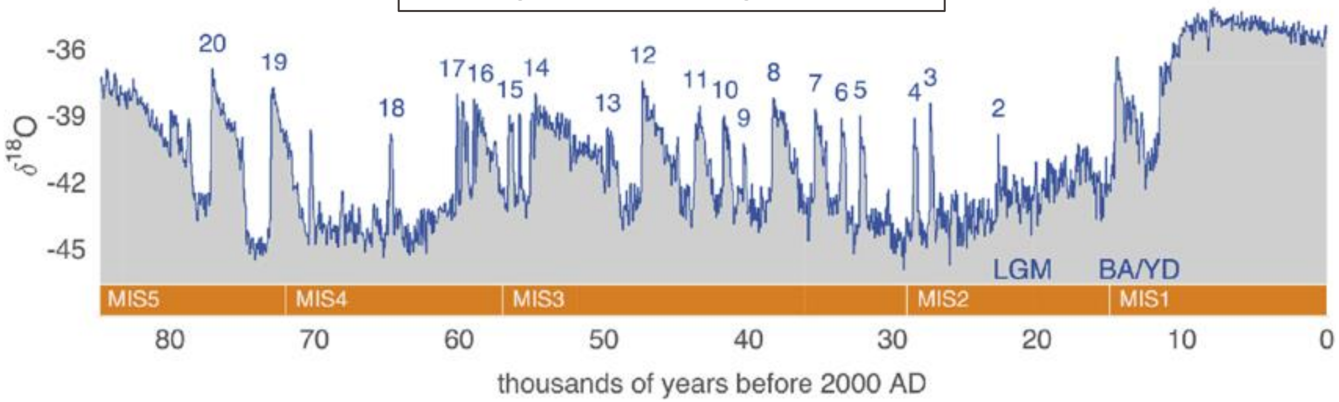
Source: Boers et al., Environ. Res. Lett. 2022



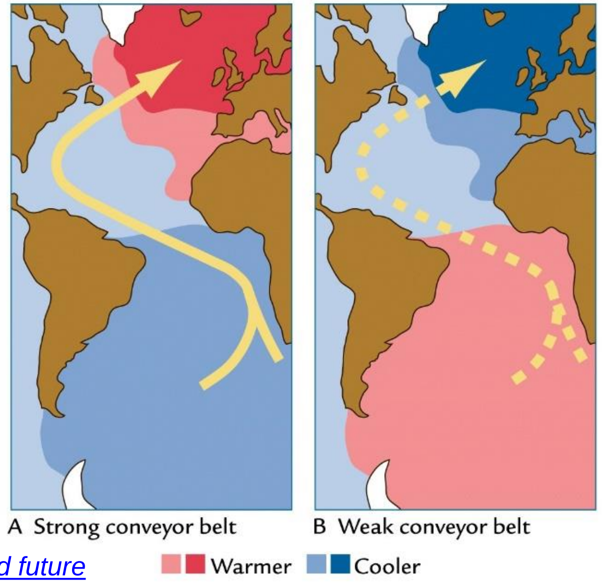
Modes of climate variability

- Climate variability can have «modes» : recurrent patterns in space (from regions to whole Earth) and time (seasons to multi-decadal).
- Generated by dynamics of:
  - Ice sheets (coupled to ocean circulation).

Dansgaard/Oeschger events



Source: Li and Born, Quat. Sci. Rev. 2019



Dansgaard/Oeschger events during the last glaciation:

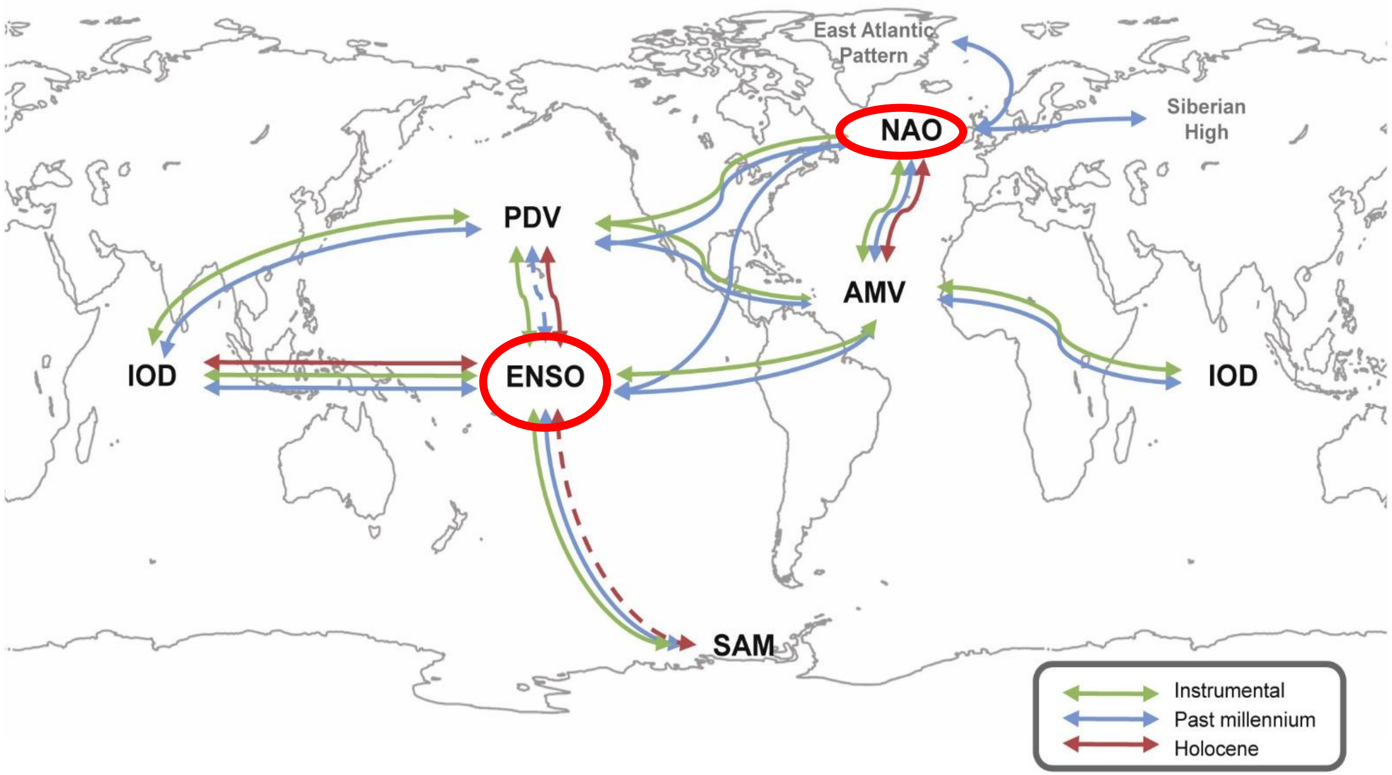
- Coupling between boreal ice sheet dynamics and Atlantic Meridional Overturning Circulation (AMOC)
- Seesaw effect between both hemispheres (opposite cooling and warming trends)

Source: Ruddiman, Earth's climate, past and future

Modes of climate variability

- Climate variability can have «modes» : recurrent patterns in space (from regions to whole Earth) and time (seasons to multi-decadal).

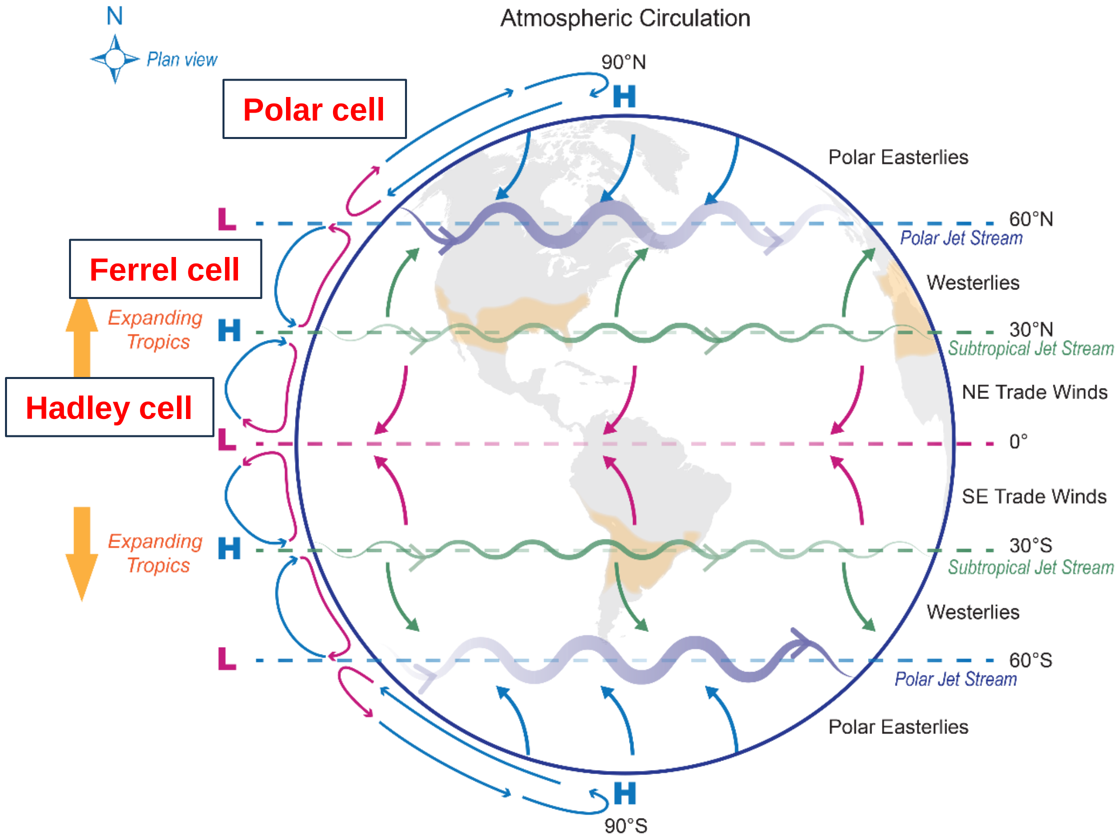
- Generated by dynamics of:
    - Ice sheets (coupled to ocean circulation).
    - Atmospheric circulation.
    - Ocean circulation.
    - Coupling between ocean and atmosphere.

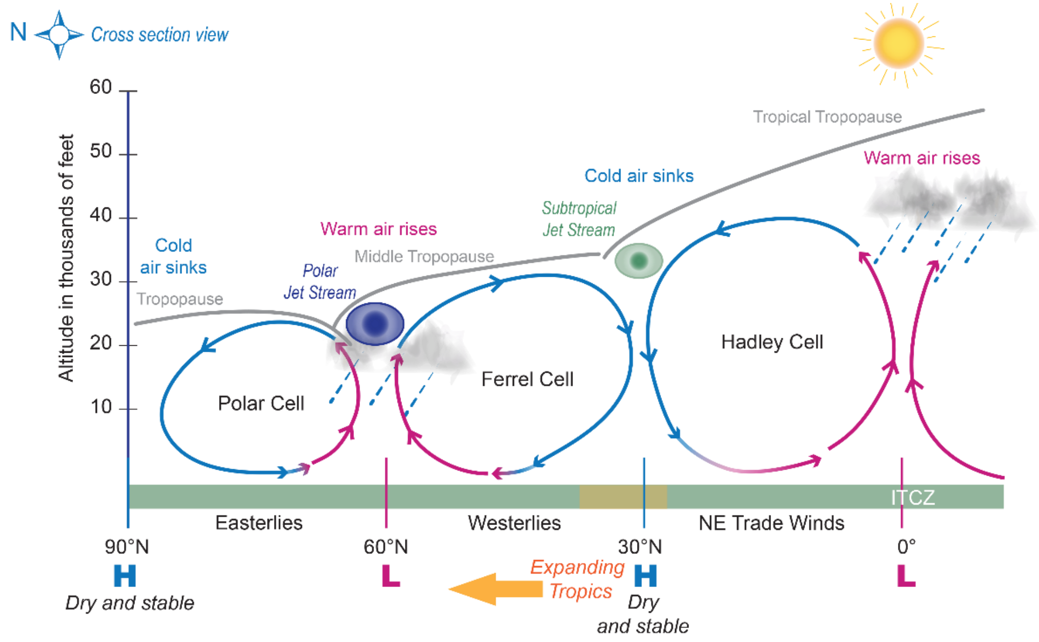


- Modes of climate variability can combine and lead to **"teleconnections"**, relating climate change between remote regions (through atmospheric or oceanic processes).

- IOD: Indian Ocean Dipole
- PDV: Pacific Decadal Variability
- ENSO: El Niño - Southern Oscillation
- SAM: Southern Annular Mode
- NAO: North Atlantic Oscillation
- AMV: Atlantic Multidecadal Variability

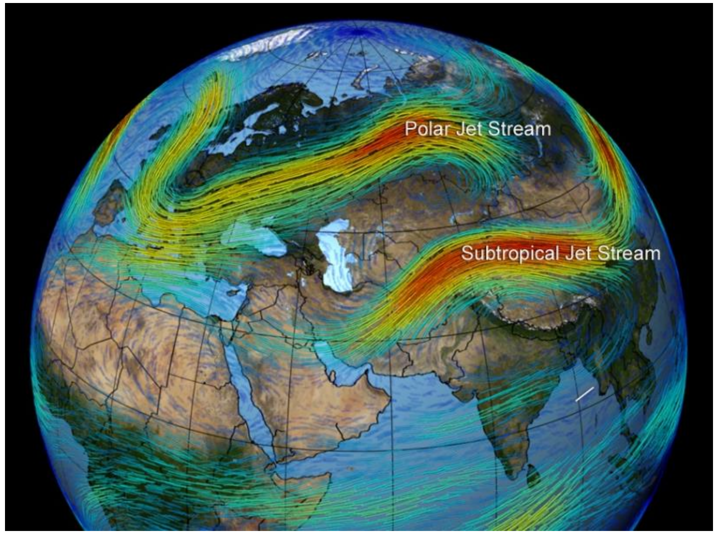
Global circulation patterns





Polar jet stream:

- Fluctuates between 40 and 60°N
- Altitude of 9 to 12 km
- Speed of up to 400 km/h

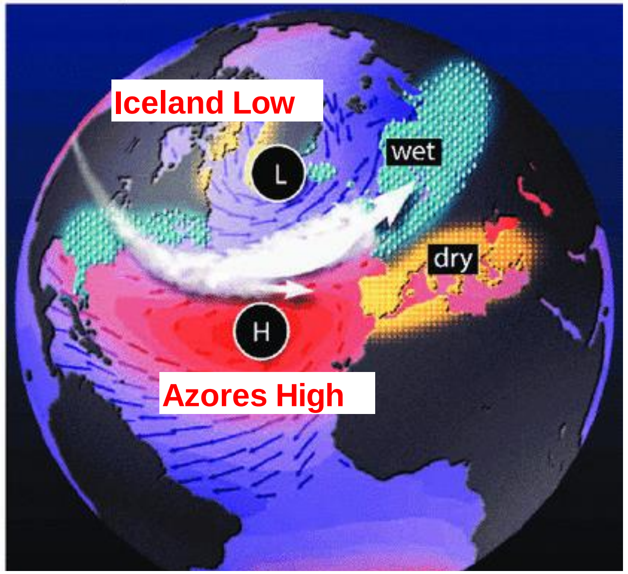


Source: NASA scientific visualization studio

Source: CSSR Report, Chapter 5

Atmospheric pattern: North Atlantic Oscillation (NAO)

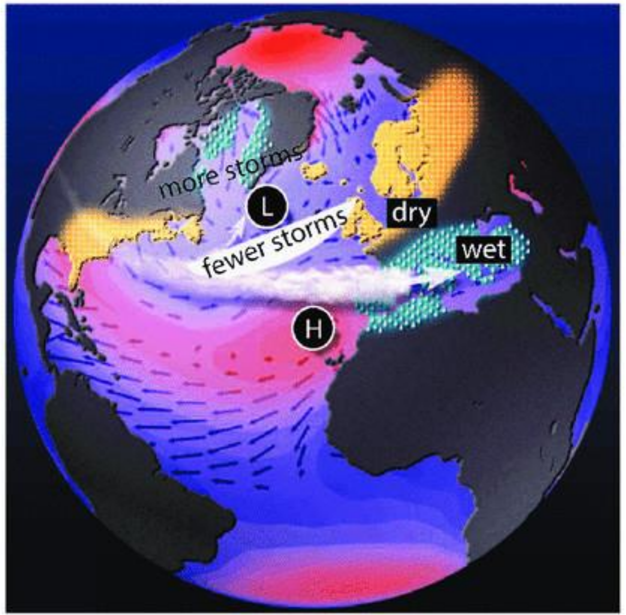
b) NAO positive-mode



+

a) NAO negative-mode

Source: University of Miami

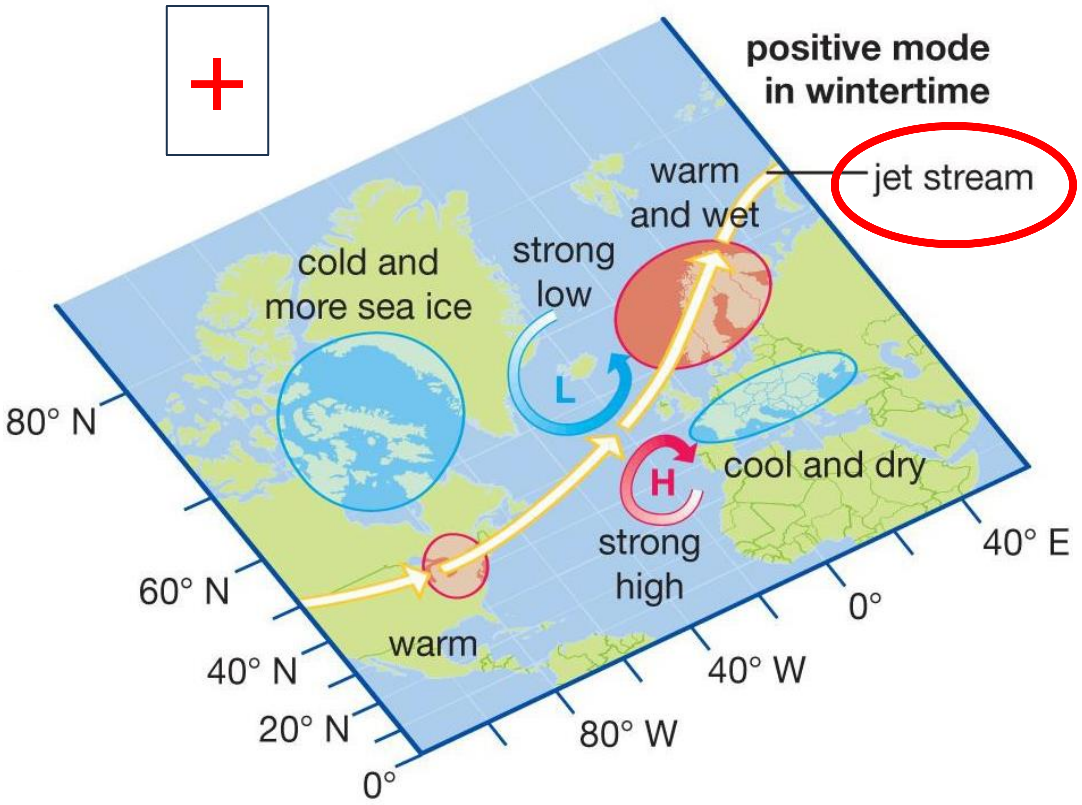


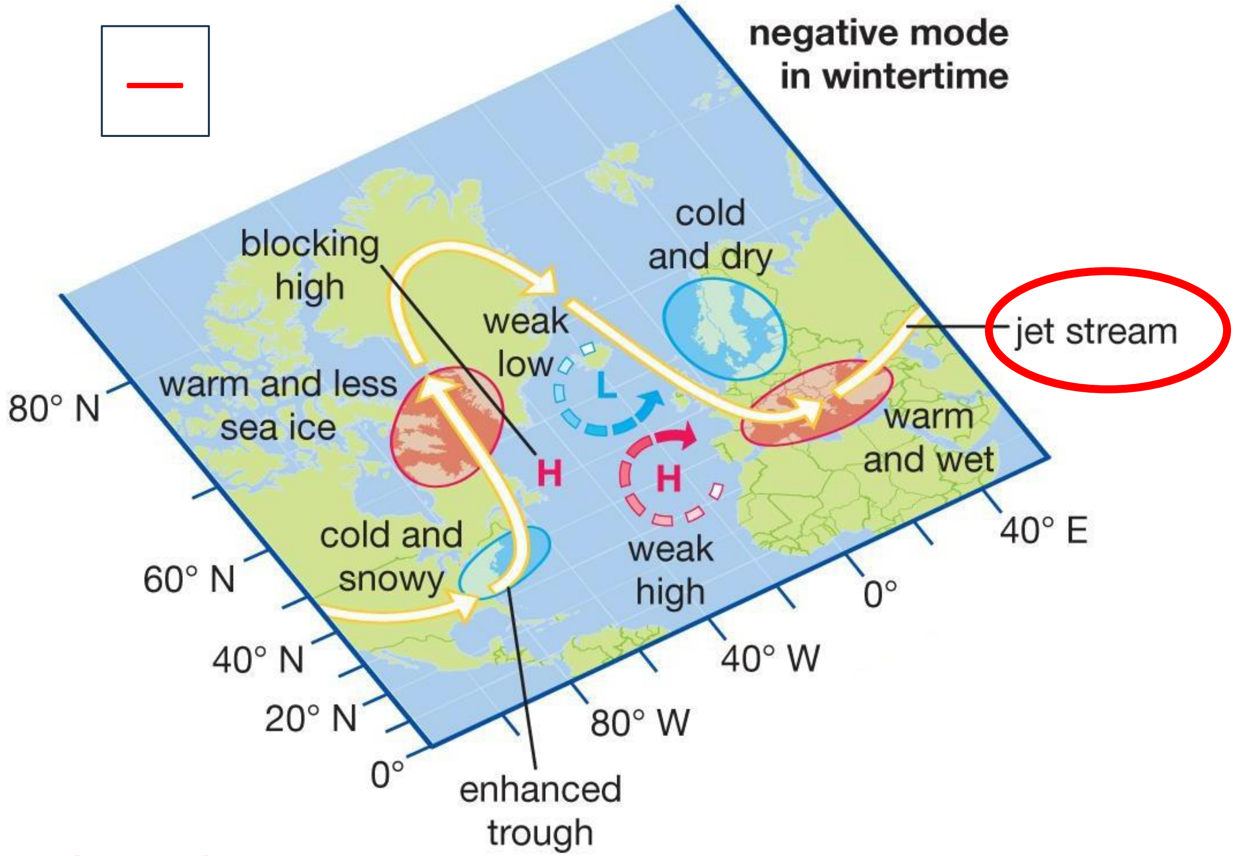
—

- NAO is the main mode of climate variability over Europe and North Atlantic. It is mostly pronounced in **winter**.
- NAO affects temperature, precipitation, winds, including their extremes.
- NAO varies from **intra-seasonal to multidecadal timescales.**
- Causes of NAO: mostly atmospheric variability, reflecting gradients of atmospheric pressure.
- NAO is **either Positive (strong pressure gradient) or Negative (weaker pressure gradient)** *.
- NAO is stochastic by nature. But it can be forced by changing strength of the polar vortex, of stratospheric temperatures, of sea surface temperatures.
- Planetary waves such as the Rossby waves *(arising from the Coriolis effect and affected by land-ocean temperature contrasts and mountain ranges)*, propagating from the troposphere to the stratosphere, play an important rôle in NAO mode.

* *Pressure gradient from weather stations of Stykkishólmur, Iceland and Gibraltar or Lisbon (Portugal) or Ponta Delgada (Azores)*

Atmospheric pattern: North Atlantic Oscillation (NAO)





Positive mode:

- Polar jet stream is stronger and more zonal.
- Westerly winds intensify over northern Europe, making it relatively warm, wet and stormy.
- Southern Europe experiences relatively cold and dry conditions.

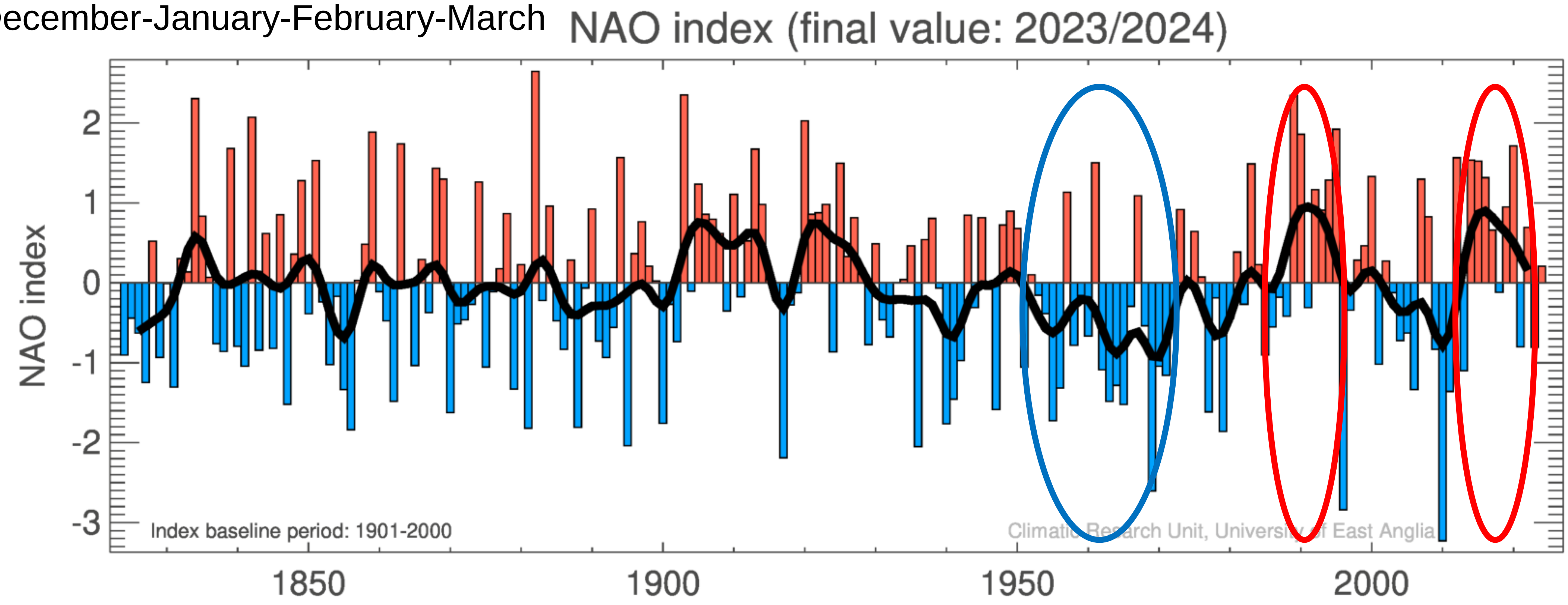
Negative mode:

- Polar jet stream weakens and becomes more meridional (meanders), allowing Arctic air intrusions.
- Westerlies weaken and shift southward toward the Mediterranean region.
- Northern Europe becomes colder and drier.
- Southern Europe receives more precipitation and experiences milder conditions.

Source: [Encyclopaedia Britannica 2012]

NAO Index

December-January-February-March



- Winter (December through March) index of NAO based on the difference of normalized sea level pressure (SLP) between Gibraltar and Stykkishólmur, Iceland since 1821.
- Index calculated as :

$$NAO = \frac{(SLP_{Gibraltar} - SLP_{Iceland}) - \mu}{\sigma}$$

μ = Long-term mean of P difference

σ = Std dev. of the P difference

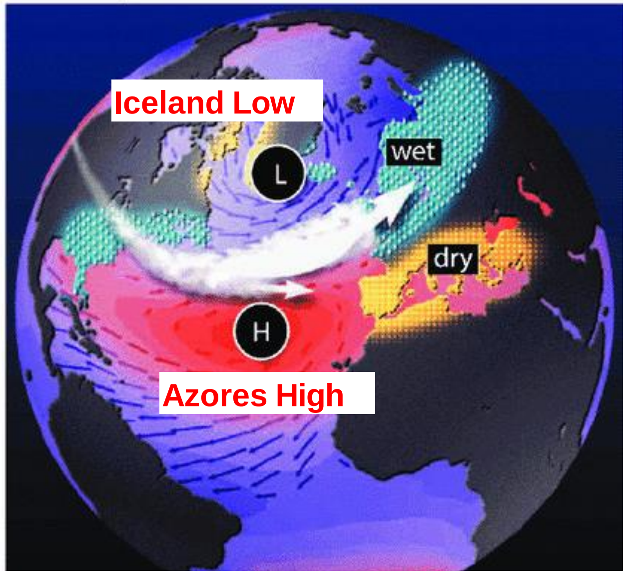
- Normalization (dimensionless number) ensures compatibility over different time periods.

Source: Climate Research Unit, Univ. East Anglia

Atmospheric pattern: North Atlantic Oscillation (NAO)

- NAO is the main mode of climate variability over Europe and North Atlantic. It is mostly pronounced in **winter**.
- NAO affects temperature, precipitation, winds, including their extremes.

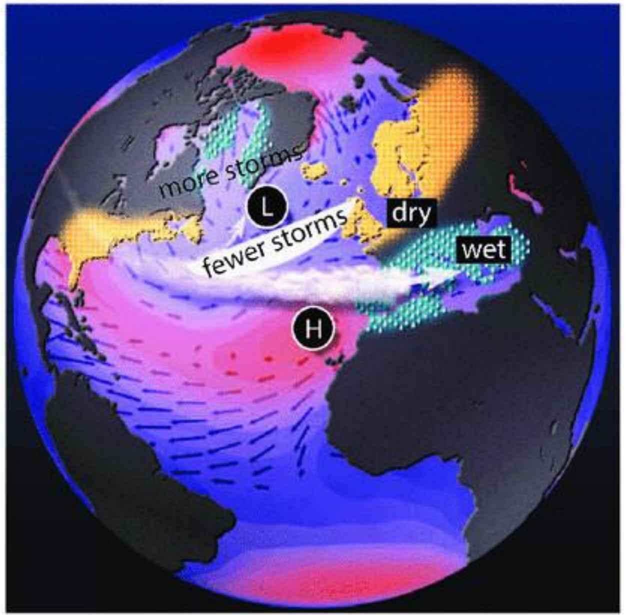
b) NAO positive-mode



+

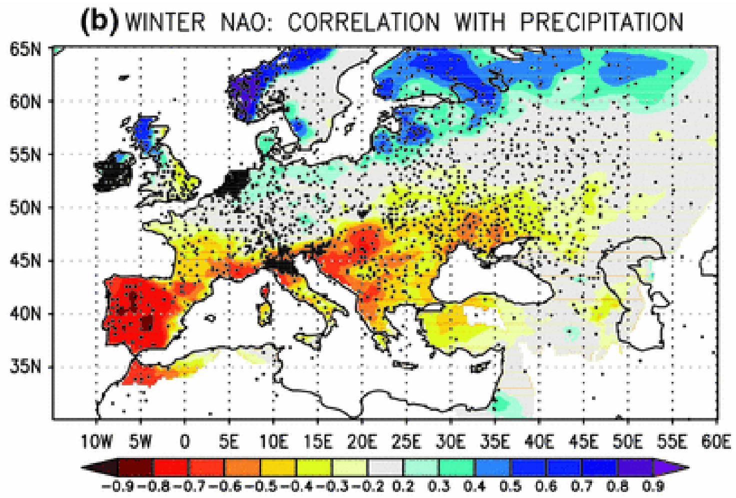
a) NAO negative-mode

Source: University of Miami



−

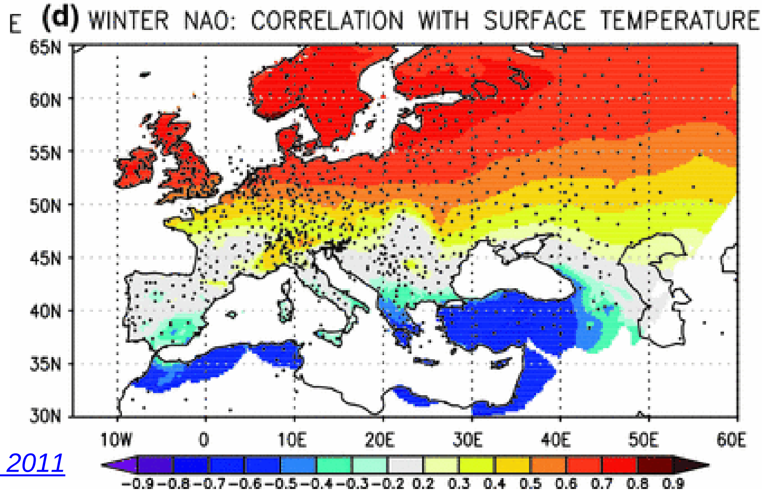
+



Winter Precipitation

From 1950 to 2010

Blue: *wet or cold*
Red: *dry or warm*



Winter Temperature

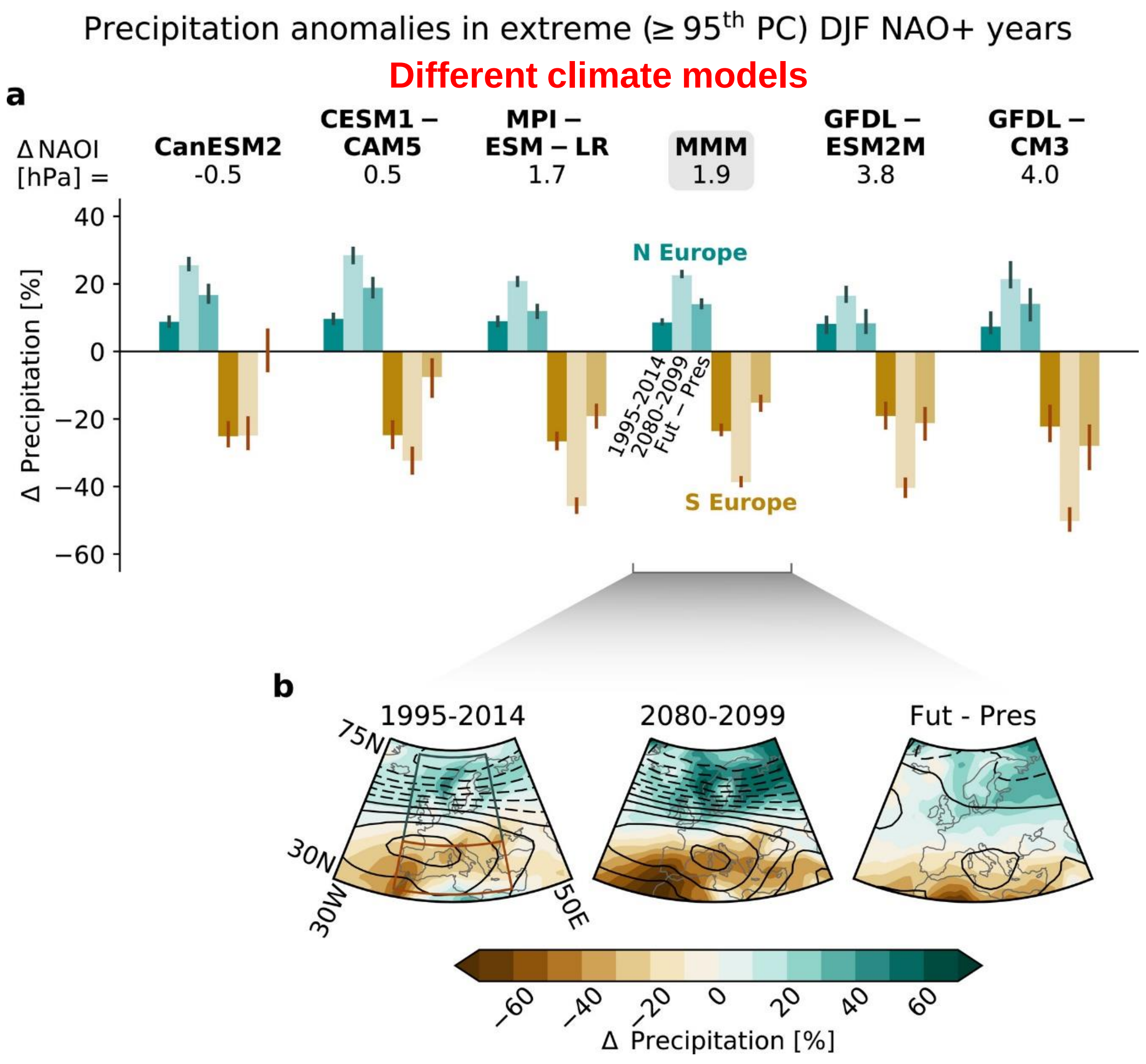
Source: Bladé et al., Climate Dynamics 2011

What about the future of NAO ?

- Most climate models project an increase in the winter NAO index (more NAO positive mode).
  - Increased winter precipitation in northern Europe
  - Decrease in southern Europe.
  - Increase of extremes.

- It comes on top of a general trend simulated by the models.

- Extreme NAO+ events (exceeding the 95th percentile) would lead to stronger deficits in precipitation in southern Europe (up to half of precipitation changes), compared with the relative increase of precipitation in northern Europe.



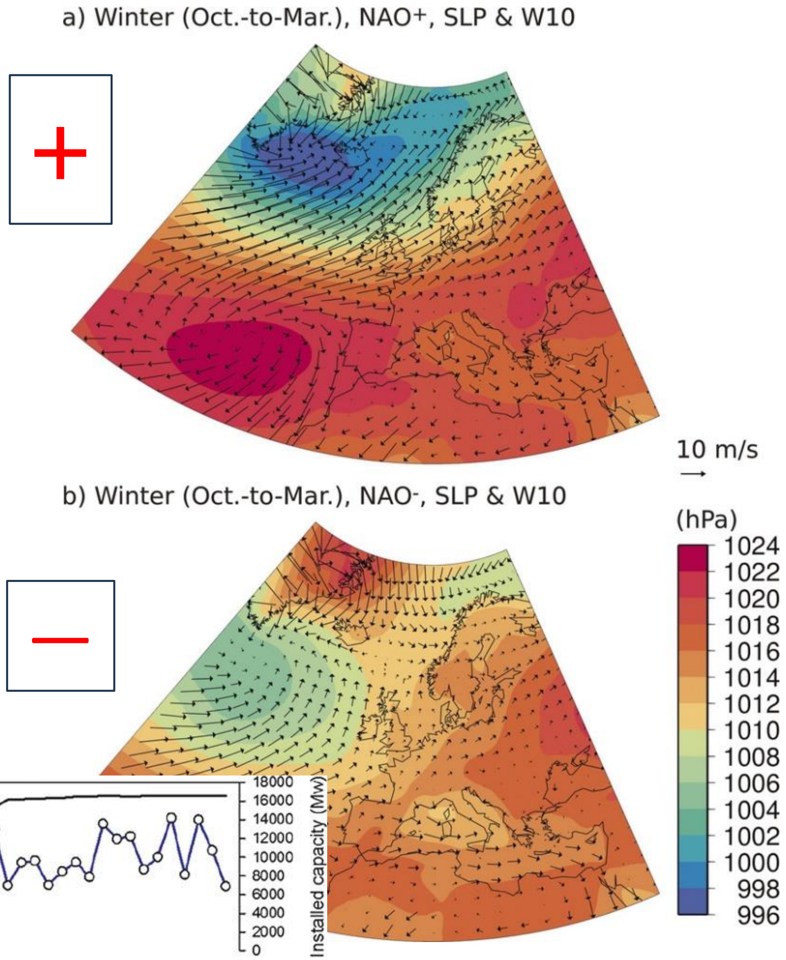
Source: Kenna and Maycock, Geophys. Res. Lett. 2022

What impact on renewable energy ?

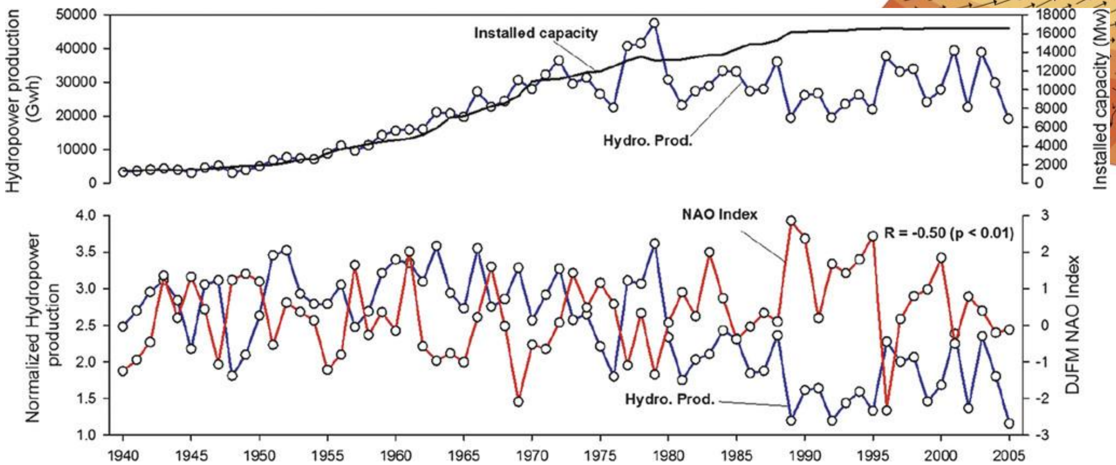
- The NAO mode of variability impacts temperature, irradiance, precipitation and wind.
    - ➢ Impacts on solar power, wind power and hydropower.

- NAO+ mode tends to reduce precipitation in southern Europe. **Strongest effects on hydropower in Spain and Portugal.**

- <u>Example of Spain</u>:
    - ➢ Large increase in installed capacities since the 1940s.
    - ➢ But normalized power production is inversely correlated with winter NAO index (-0.50).
    - ➢ Estimates of reduction of hydropower by 4 to 8% under NAO+ conditions.



Hydropower in Spain



Source: [Jerez et al., J. Applied Meteor. and Climatol., 2013]

El Niño Southern Oscillation (ENSO)

- The El Niño Southern Oscillation (ENSO) is a **coupled ocean-atmosphere** climate variability mode.

- ENSO refers to a large-scale alternation between anomalously warm **(El Niño)** and cool **(La Niña)** central/eastern equatorial Pacific sea surface temperature (SST), coinciding with changes of precipitation and winds.

- ENSO is the **dominant mode of tropical climate variability on interannual timescales** and its effects teleconnect with many other regions of the world.

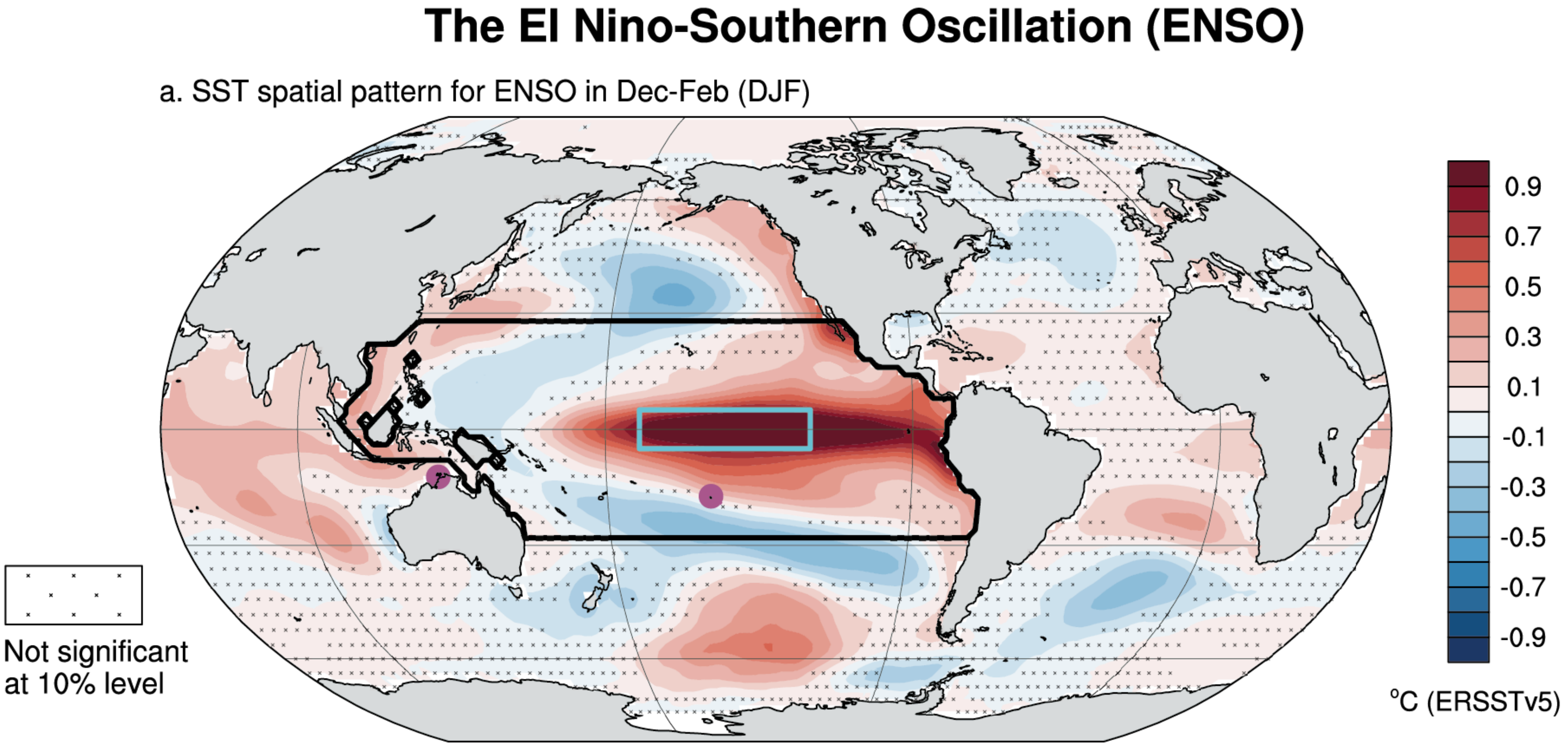
- ENSO remains **the main modulator of global surface temperature anomalies at interannual timescales.** It is the primary predictor of climate variability on seasonal to interannual timescales.

Source: Weather Underground

Lima (Peru) - Mars 2017

Source: The Happy Nomad

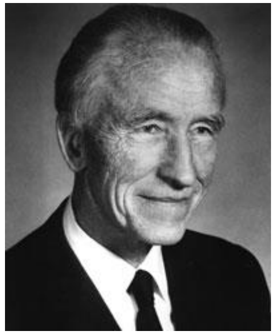
Sea surface temperature anomaly during El Niño



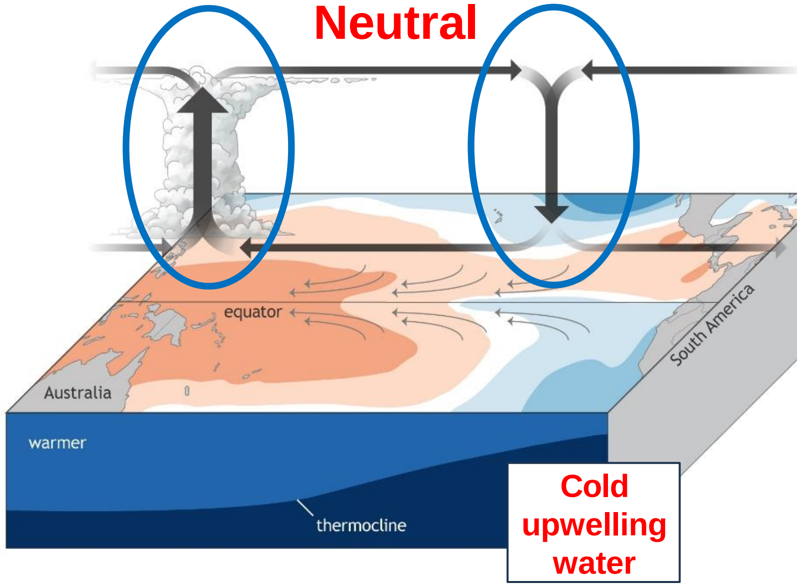
Unusally warm water off the western coast of South America.

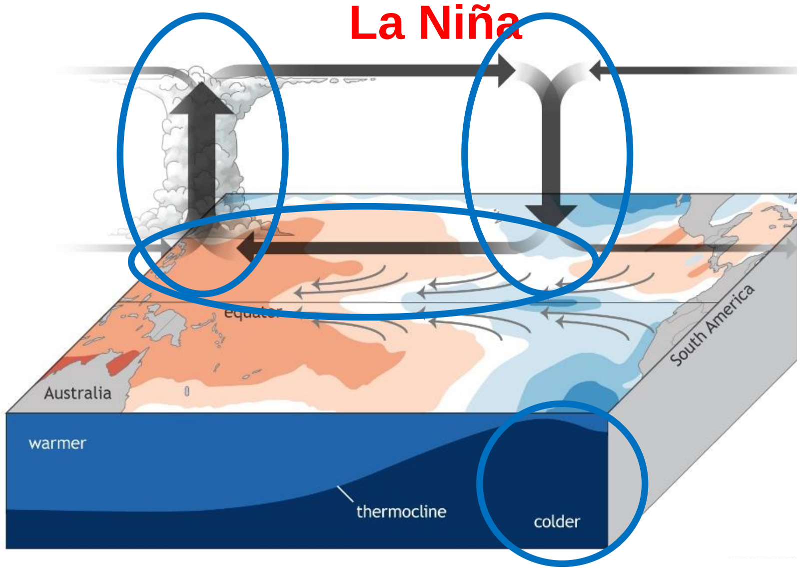
Source: IPCC AR6 WG1 Annex IV Fig. 3

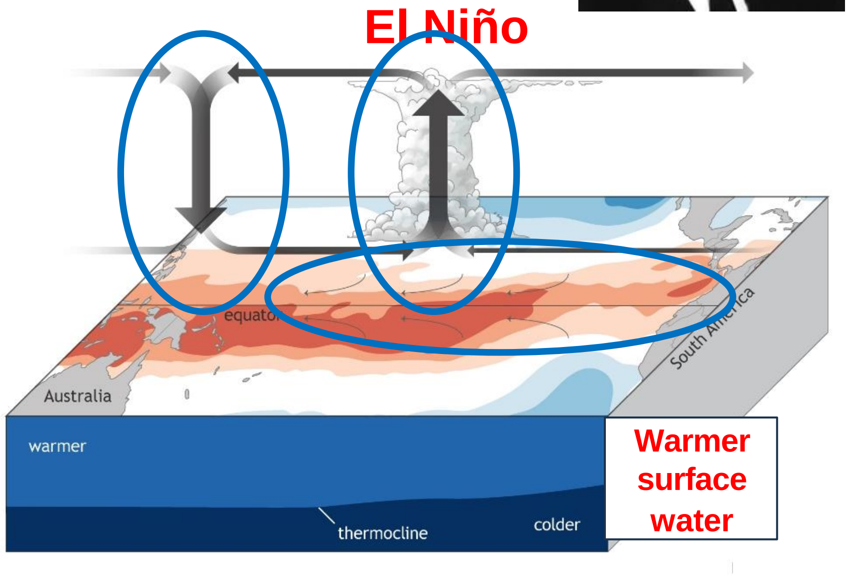
How ENSO works ?



El Niño or La Niña exists because of ocean-atmosphere coupling across the tropical Pacific ocean:
the Bjerknes feedback (+).







- Equatorial trade winds push warm surface waters westward.
- Warm and moist air uplifts over Western Pacific.
  - Subsidence eastward.
  - Upwelling of cold deep water along the coast of Equator.

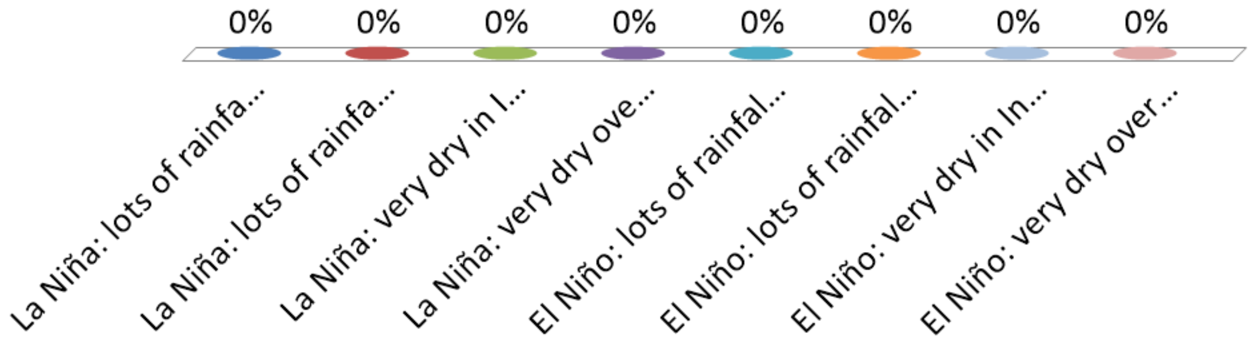
- Equatorial trade winds become stronger and push more warm surface waters westward.
- Stronger air uplifts over Western Pacific.
  - Stronger subsidence eastward.
  - Stronger upwelling of cold deep water along the coast of Equator.

- Equatorial trade winds weaken.
- Warming of central and eastern Pacific surface waters.
- Warm / moist air uplifts over central Pacific.
  - Subsidence westward.
  - No more upwelling of cold deep water along the coast of Equator.

Source: *NOAA Climate*

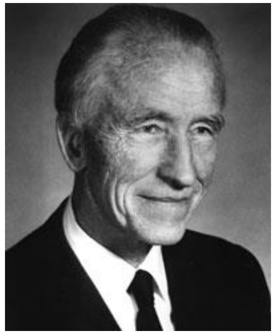
El Niño and La Niña: what impact on precipitation on each side of the Pacific ?

A. La Niña: lots of rainfall over Indonesia
B. La Niña: lots of rainfall over Peru
C. La Niña: very dry in Indonesia
D. La Niña: very dry over Peru
E. El Niño: lots of rainfall over Indonesia
F. El Niño: lots of rainfall over Peru
G. El Niño: very dry in Indonesia
H. El Niño: very dry over Peru



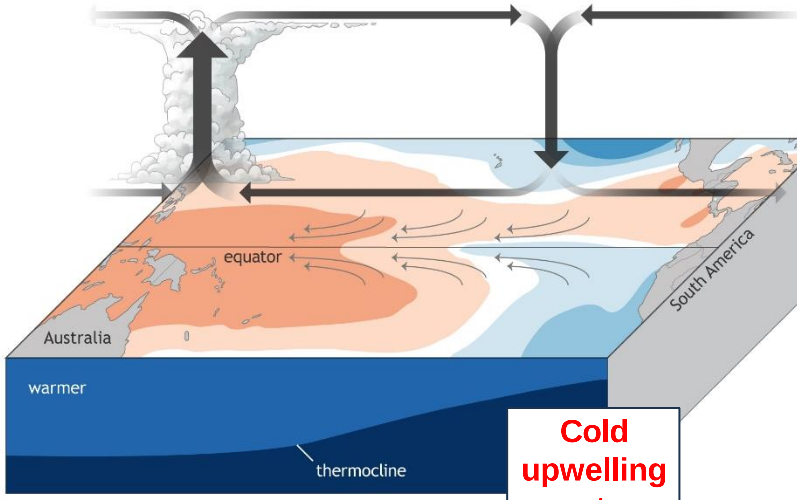
How ENSO works ?

Jakob Bjerknes
Norwegian
meteorologist



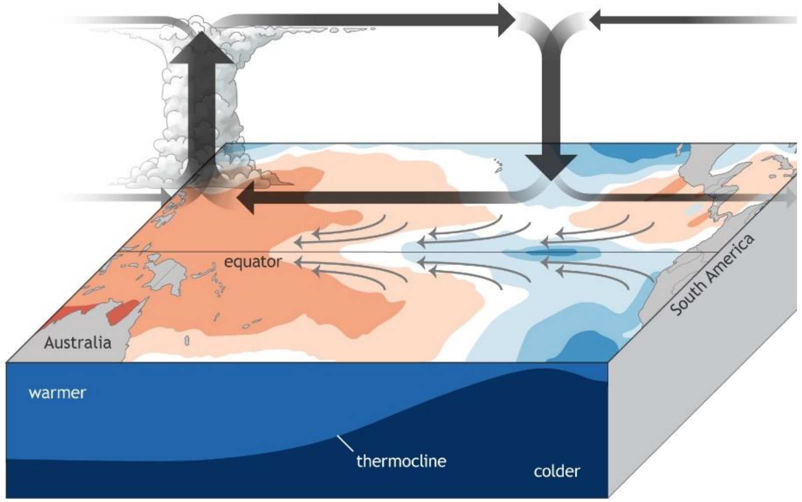
El Niño or La Niña exists because of ocean-atmosphere coupling across the tropical Pacific ocean:
the Bjerknes feedback (+).

Neutral



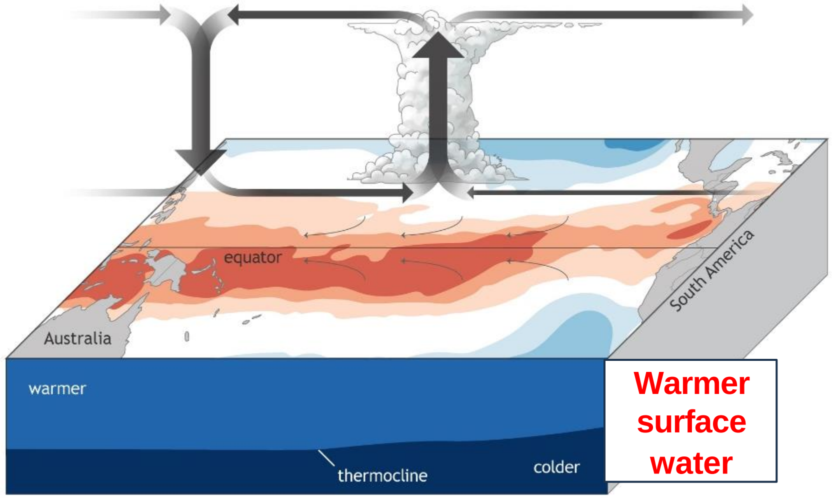
- Equatorial trade winds push warm surface waters westward.
- Warm and moist air uplifts over Western Pacific.
  - ➢ Subsidence eastward.
  - ➢ Upwelling of cold deep water along the coast of Equator.

La Niña



- Equatorial trade winds become stronger and push more warm surface waters westward.
- Stronger air uplifts over Western Pacific.
  - ➢ Stronger subsidence eastward.
  - ➢ Stronger upwelling of cold deep water along the coast of Equator.

El Niño

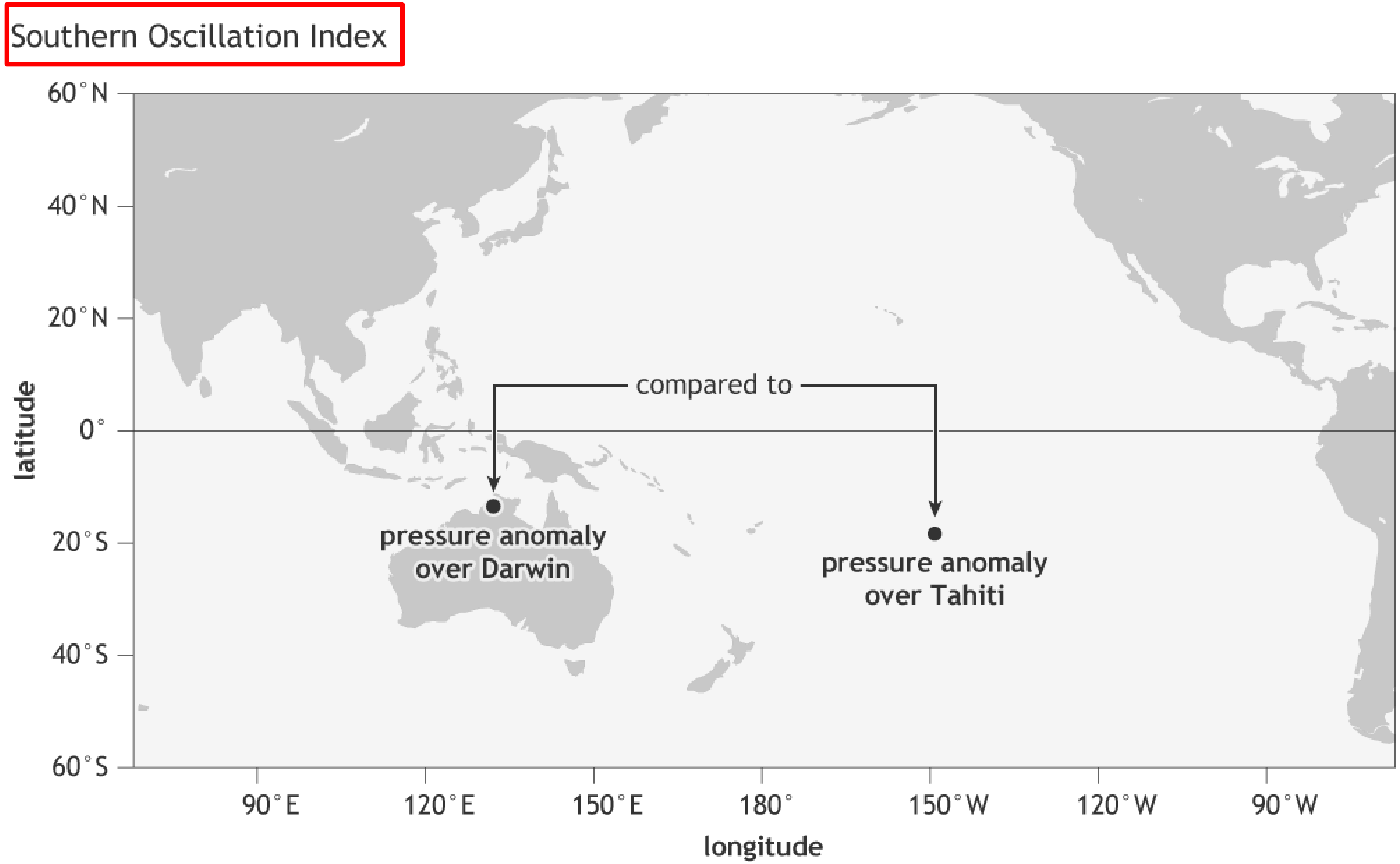


- Equatorial trade winds weaken.
- Warming of central and eastern Pacific surface waters.
- Warm / moist air uplifts over central Pacific.
  - ➢ Subsidence westward.
  - ➢ No more upwelling of cold deep water along the coast of Equator.

Source: NOAA Climate

How is it «measured» ?

Sea level pressure anomaly (Southern Oscillation)

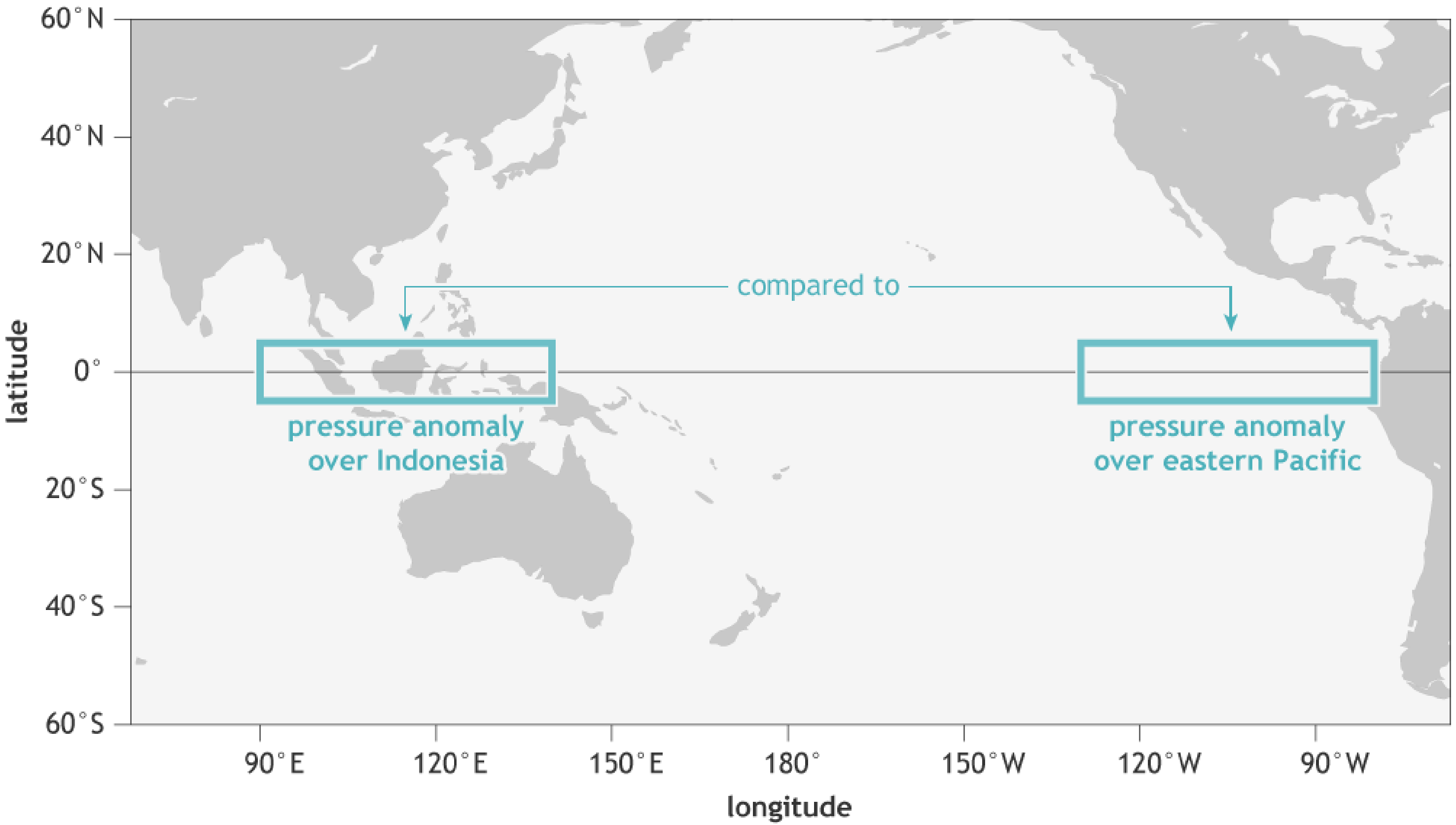


Source: [NOAA Climate]

How is it «measured» ?

Equatorial Southern Oscillation Index

Sea level pressure anomaly (Southern Oscillation)



Source: NOAA Climate

- Equatorial Southern Oscillation Index based on the difference of normalized sea level pressure (SLP) between equatorial eastern Pacific and Indonesia.
- Index calculated as :

$$EQ\_SOI = \frac{(SLP_{EastPacific} - SLP_{Indonesia}) - \mu}{\sigma}$$

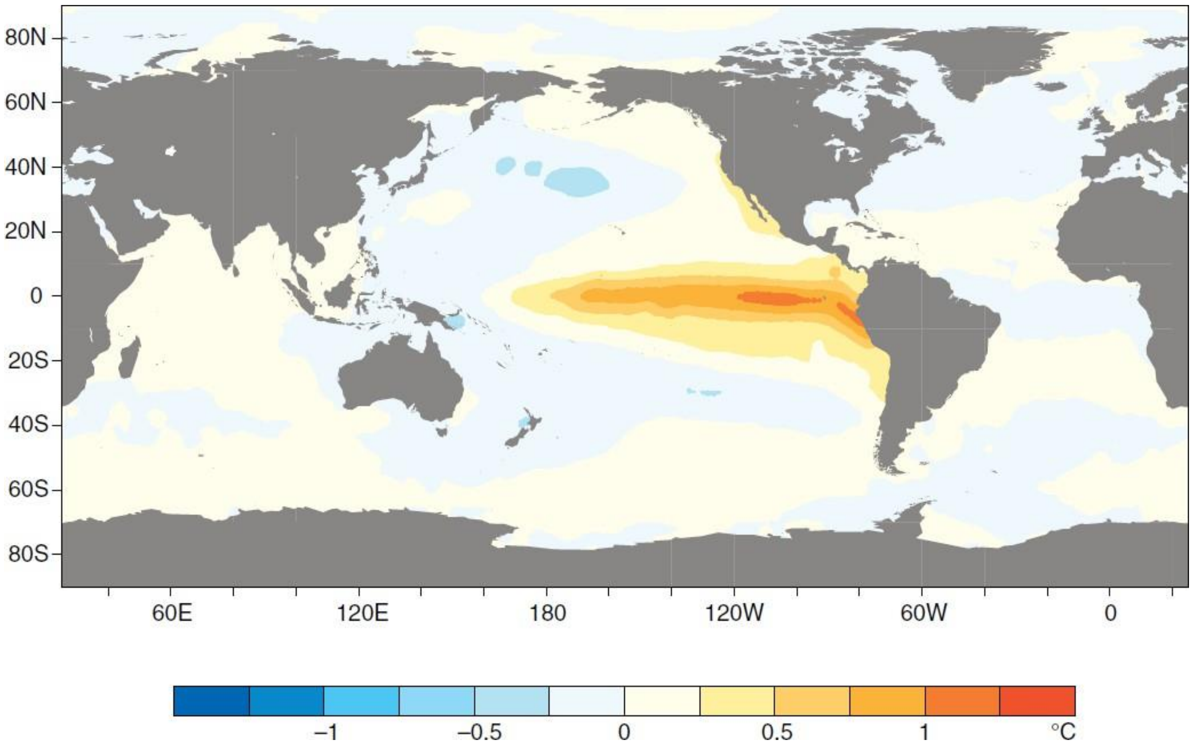
μ = Long-term mean of P difference

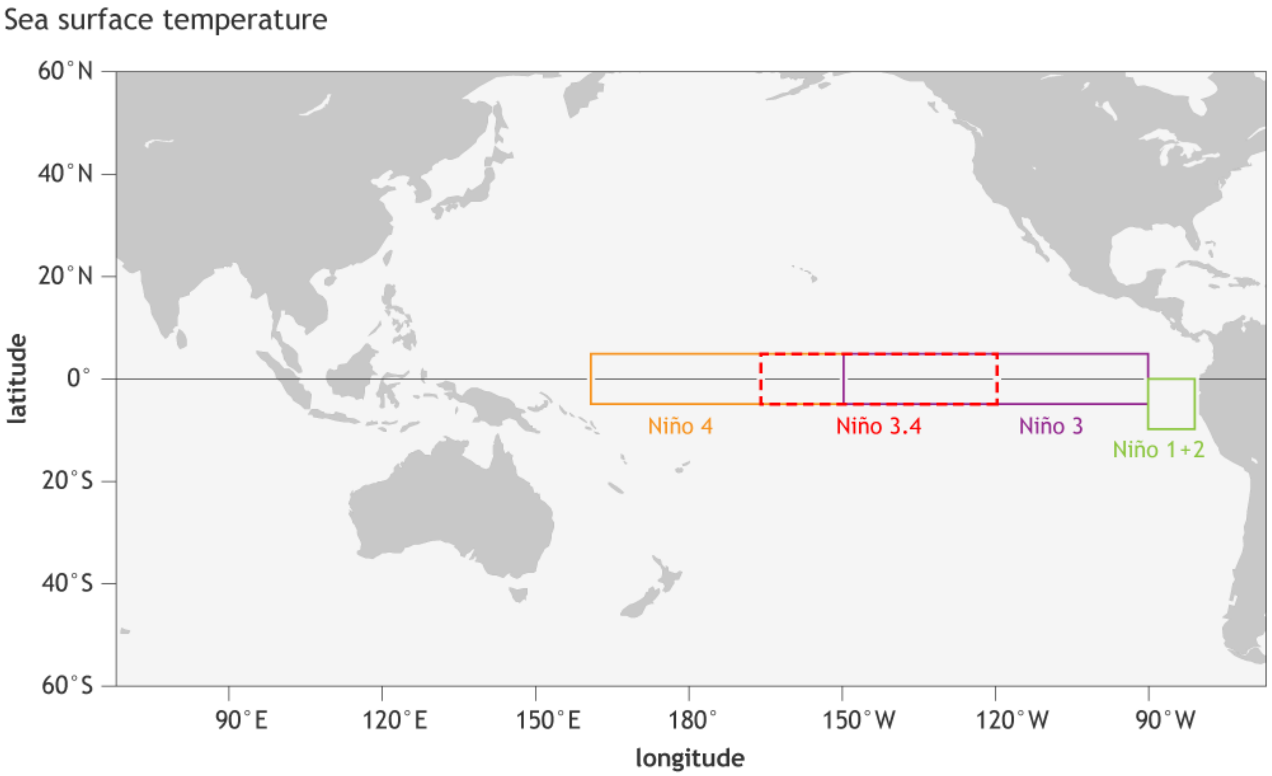
σ = Std dev. of the P difference

- . Goes back only to 1949. The SOI «Darwin-Tahiti» goes back to the late 1800s.

How is it «measured» ?

Sea surface temperature pressure anomaly

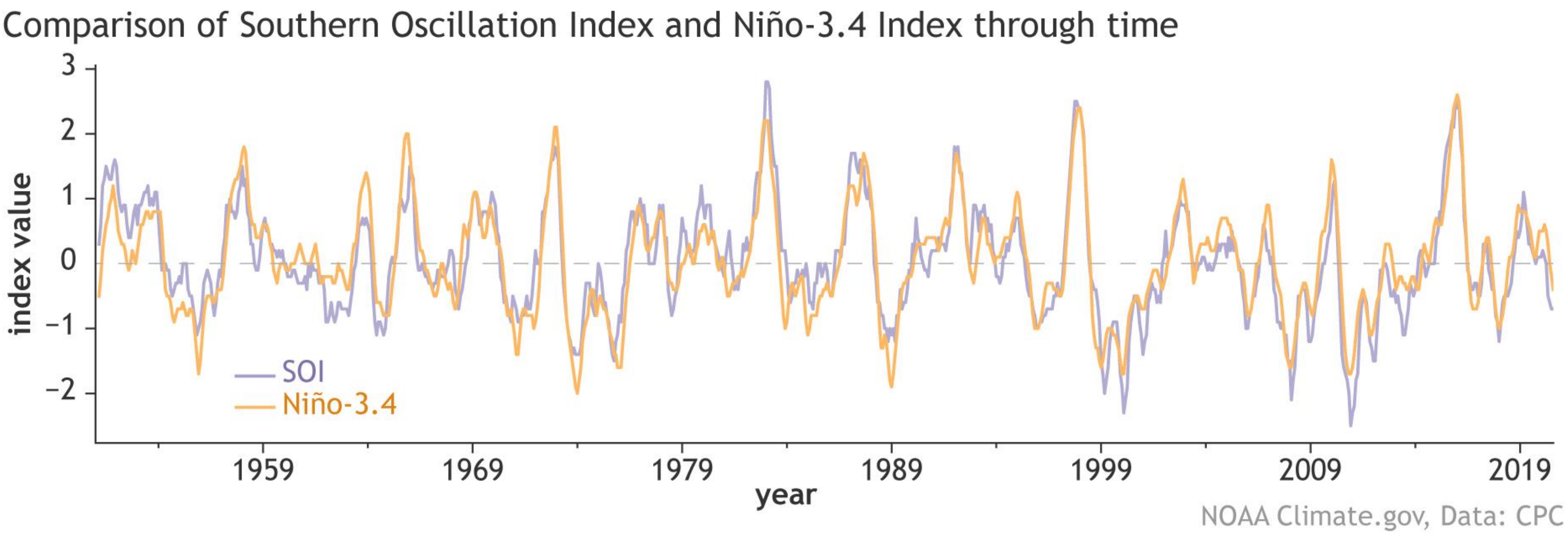


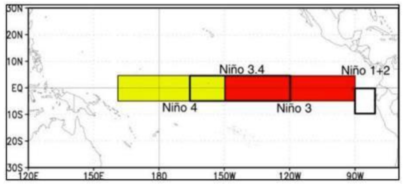


- Niño 3.4 is the commonly used region to classify El Niño/La Niña conditions.
- Threshold: El Niño if SST anomaly ≥ +0.5°C for 5 consecutive overlapping 3-month seasons.

Source: NOAA Climate

Strong coupling between atmosphere and ocean

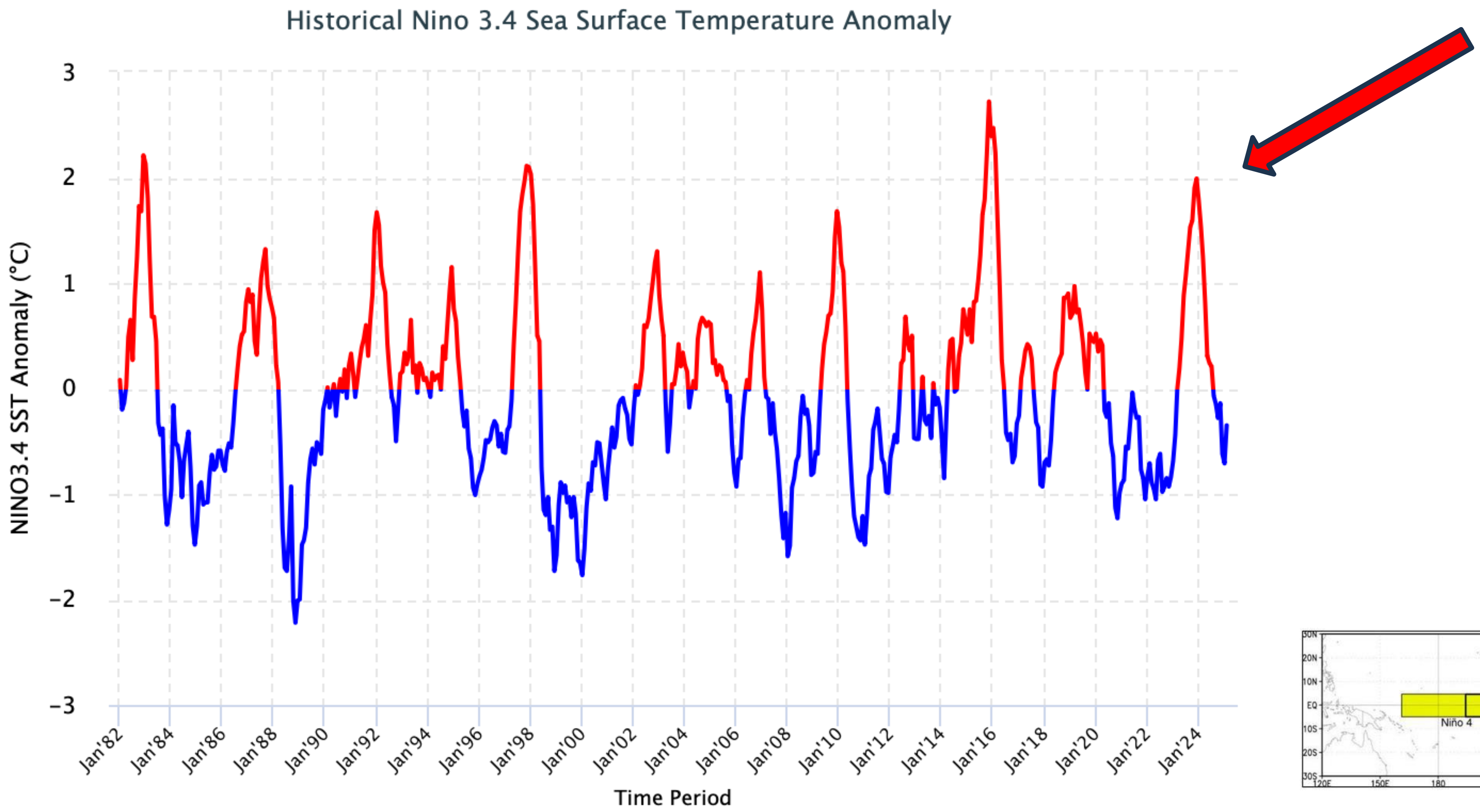


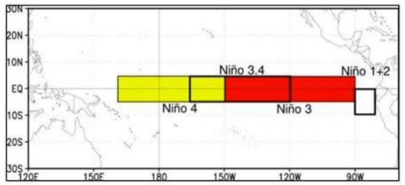


- SOI: sea level pressure difference
- Niño 3.4: sea surface temperature in east-central equatorial Pacific ocean
- Correlation $R = 0.9$!

Source: NOAA Climate

Most recent trend





- Niño 3.4: sea surface temperature in east-central equatorial Pacific ocean
- 2024: 5th most powerful El Nino event in recorded history.
- The 2024 El Niño may have contributed +0.16°C to the +1.55°C warming above pre-industrial times.

Source: NOAA Climate

Forecast: La Niña or neutral for 2025

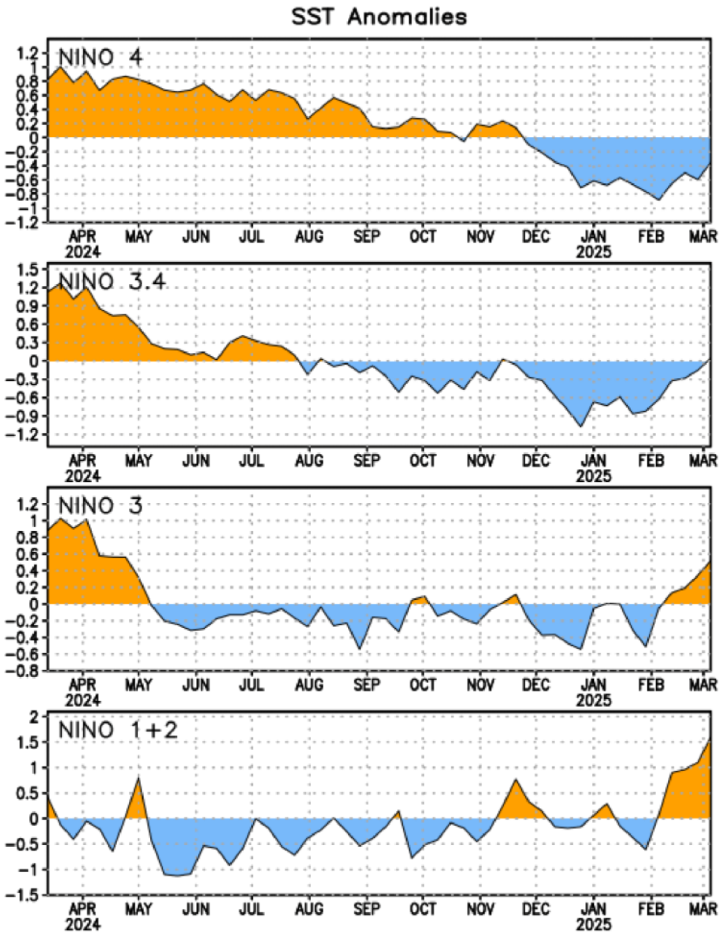
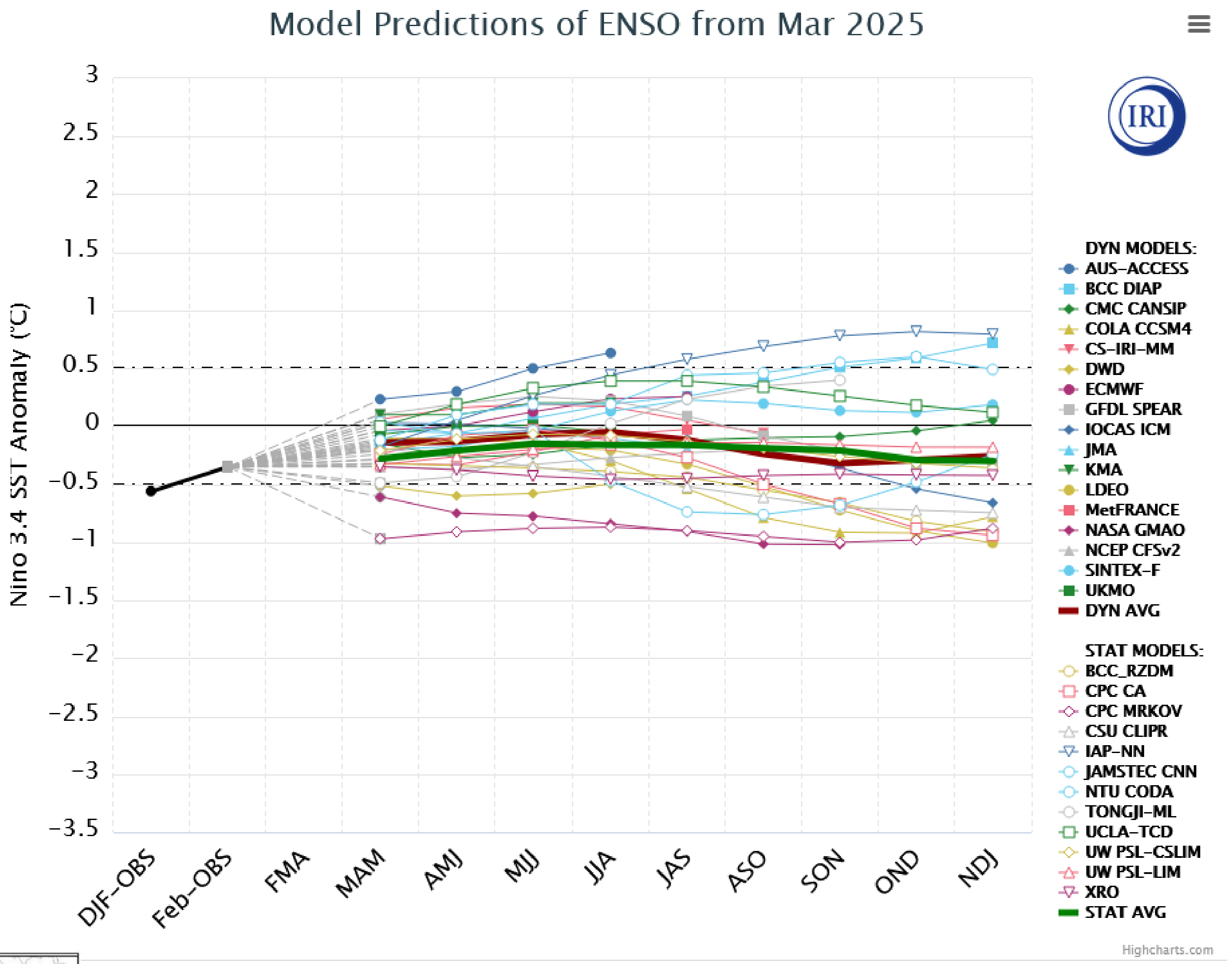
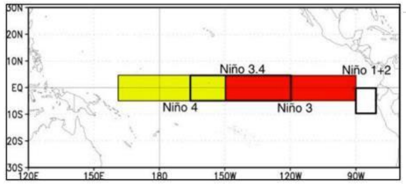


Figure 2. Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño regions [Niño-1+2 (0°-10°S, 90°W-80°W), Niño-3 (5°N-5°S, 150°W-90°W), Niño-3.4 (5°N-5°S, 170°W-120°W), Niño-4 (5ºN-5ºS, 150ºW-160ºE)]. SST anomalies are departures from the 1991-2020 base period weekly means.

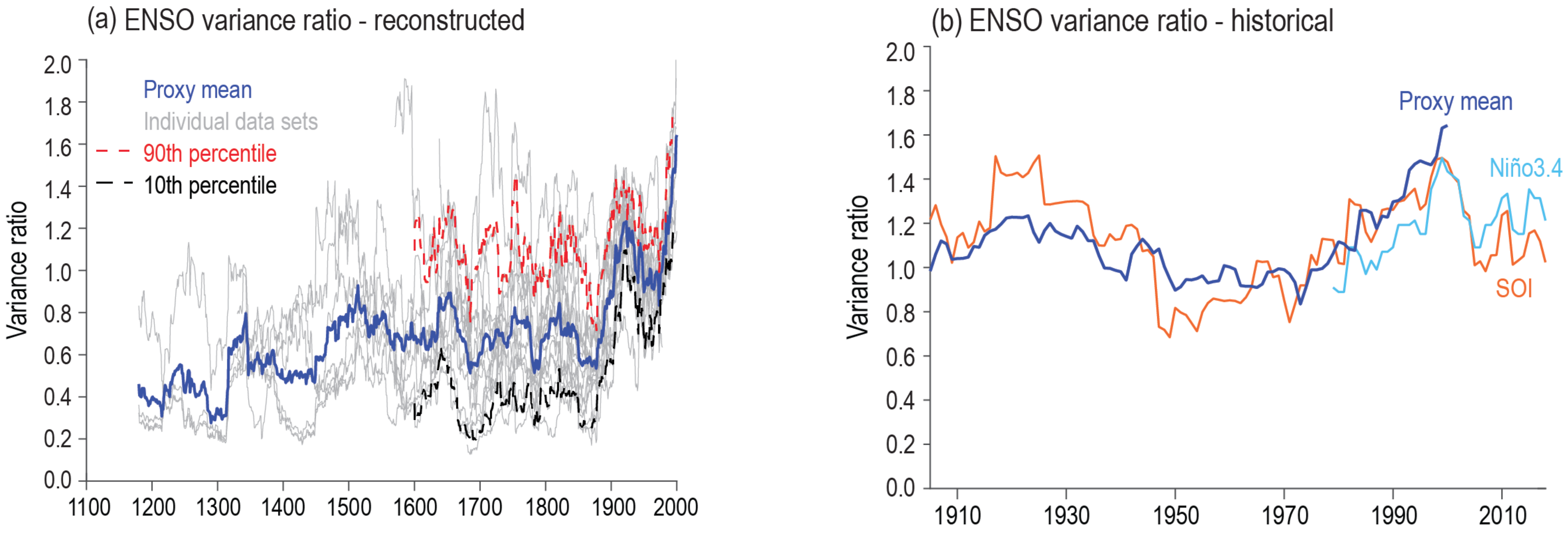




Source: [NOAA Climate Prediction Center]

What about the past ?

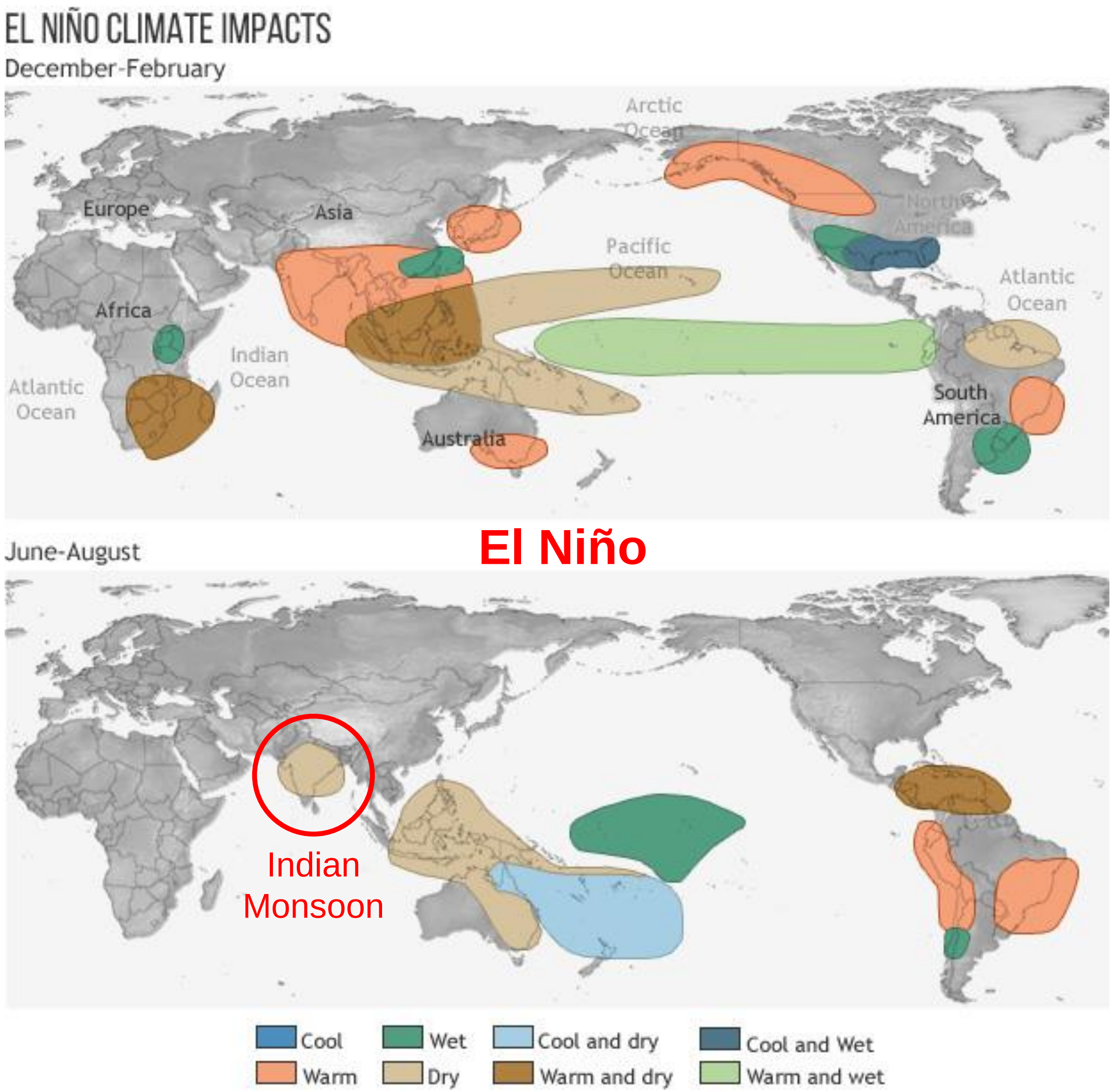
$$\text{Variance Ratio} = \frac{\text{ENSO variance in a given period}}{\text{ENSO variance in reference period}}$$

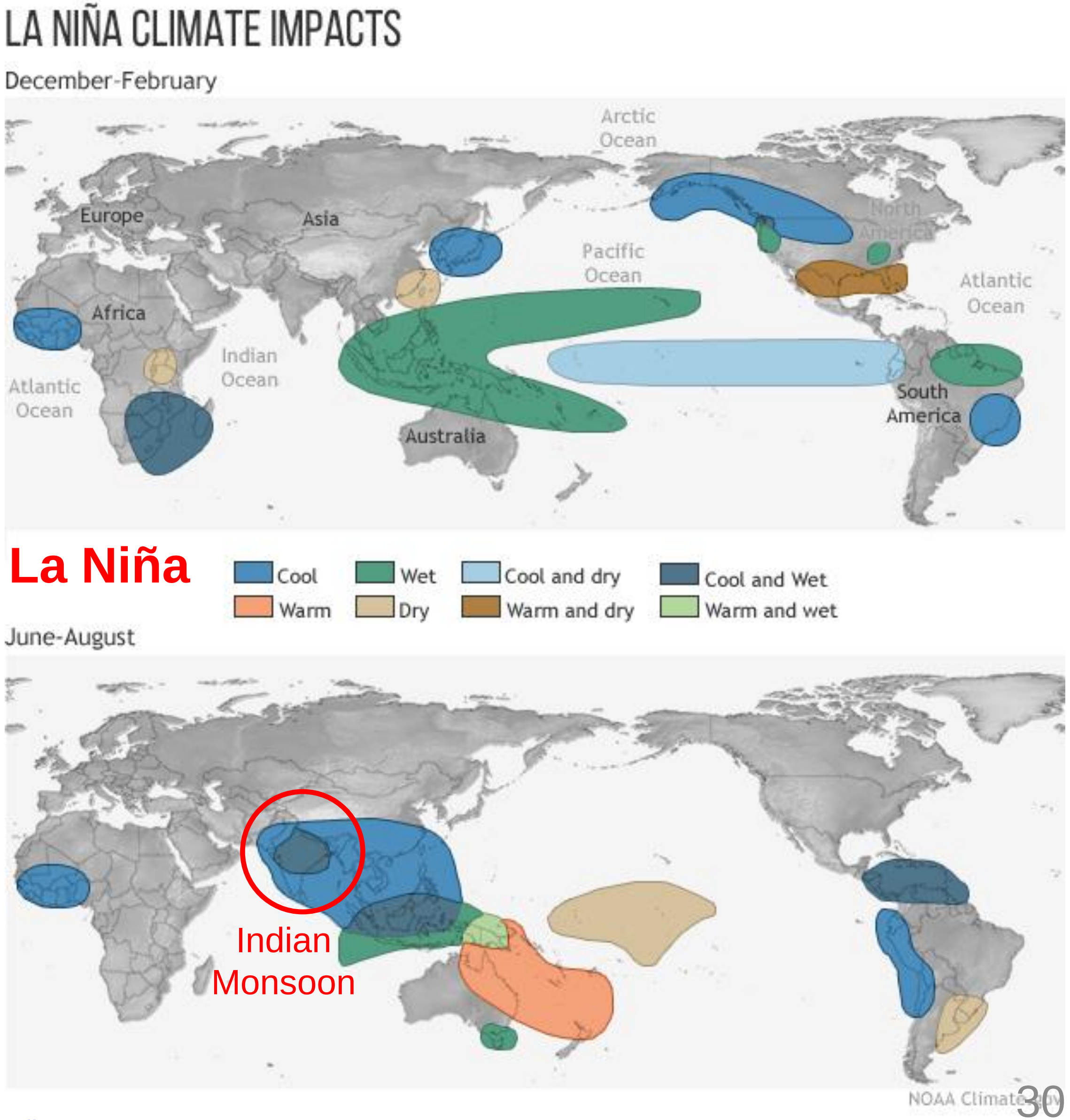


- Reconstruction from **corals** *(sea surface temperature)*, **tree rings** *(rainfall)*, **marine sediments** *(sea surface temperature)*, **ice cores** *(snowfall, isotopes and large-scale circulation)*.
- Multi-decadal variability over the last 1000 years.
- Recent increase of ENSO variance but low confidence to attribute it.

Source: IPCC AR6 WG1 Fig. 2.36

ENSO impacts: teleconnections

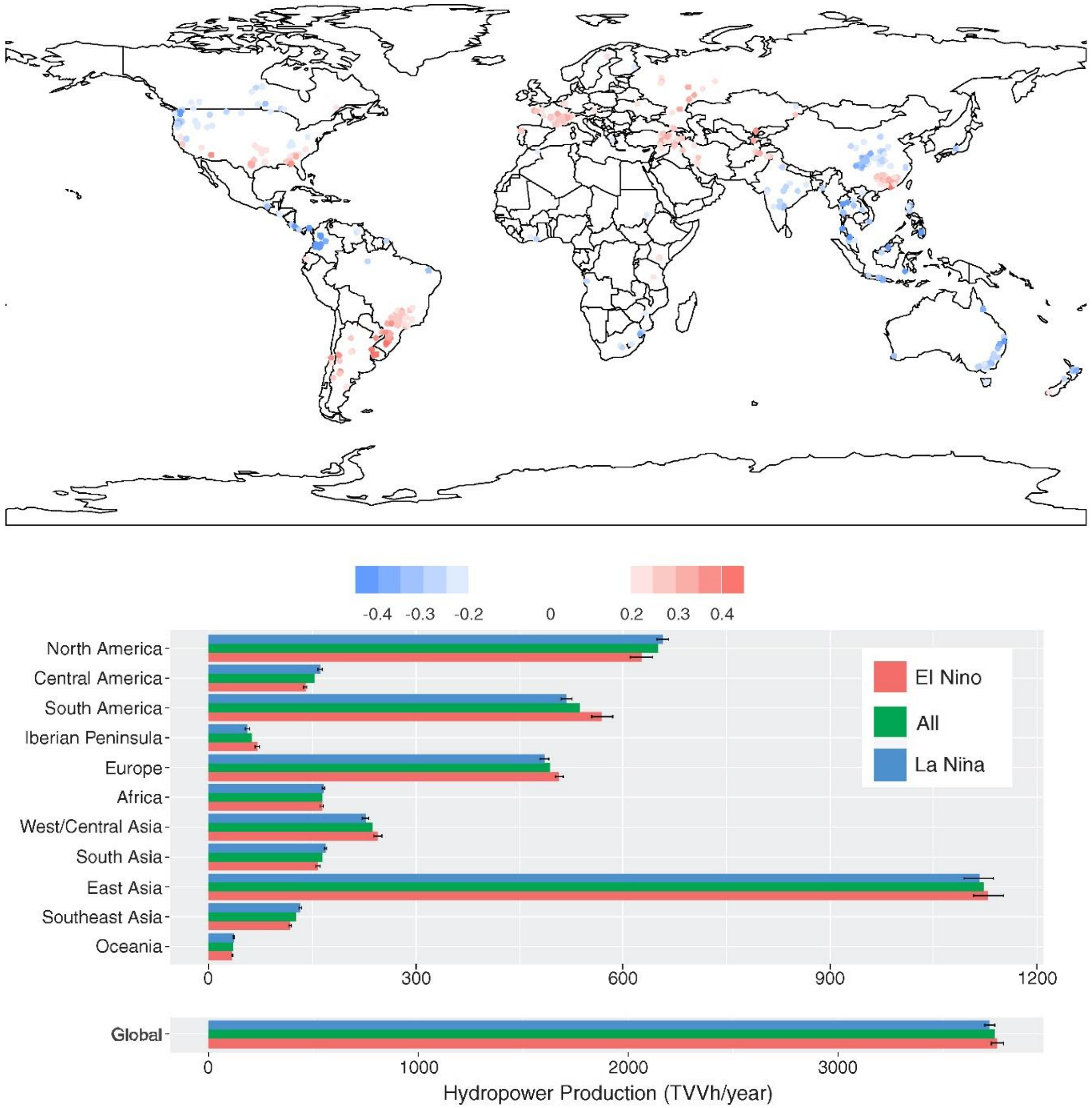




Source: NOAA Climate

ENSO impact on renewable energy

- A positive correlation (red) represents higher production during the El Niño phases
- A negative correlation (blue) represents higher hydropower production during the La Niña phase.



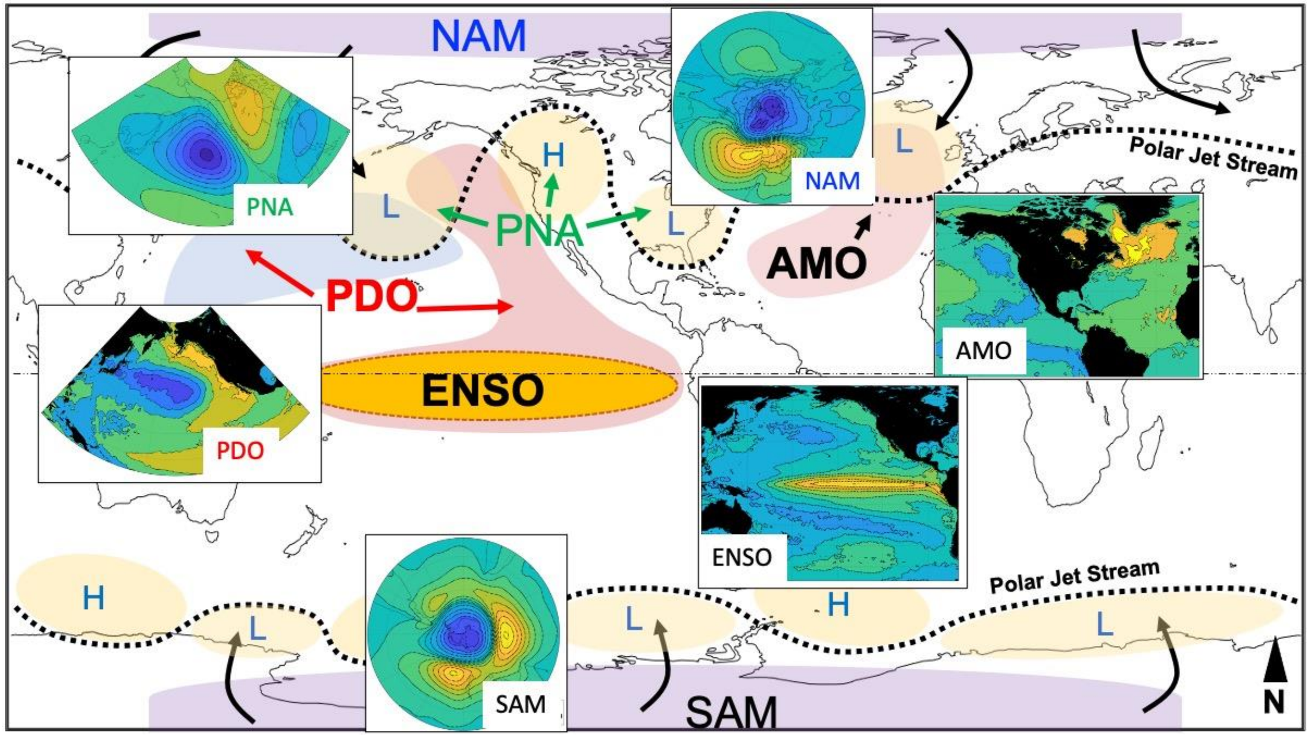
Variations of up to 20% between El Niño and La Niña in south America…

Source: [Ng, Turner and Galelli, Env. Res. Letters 2017]

Further modes of internal climate variability

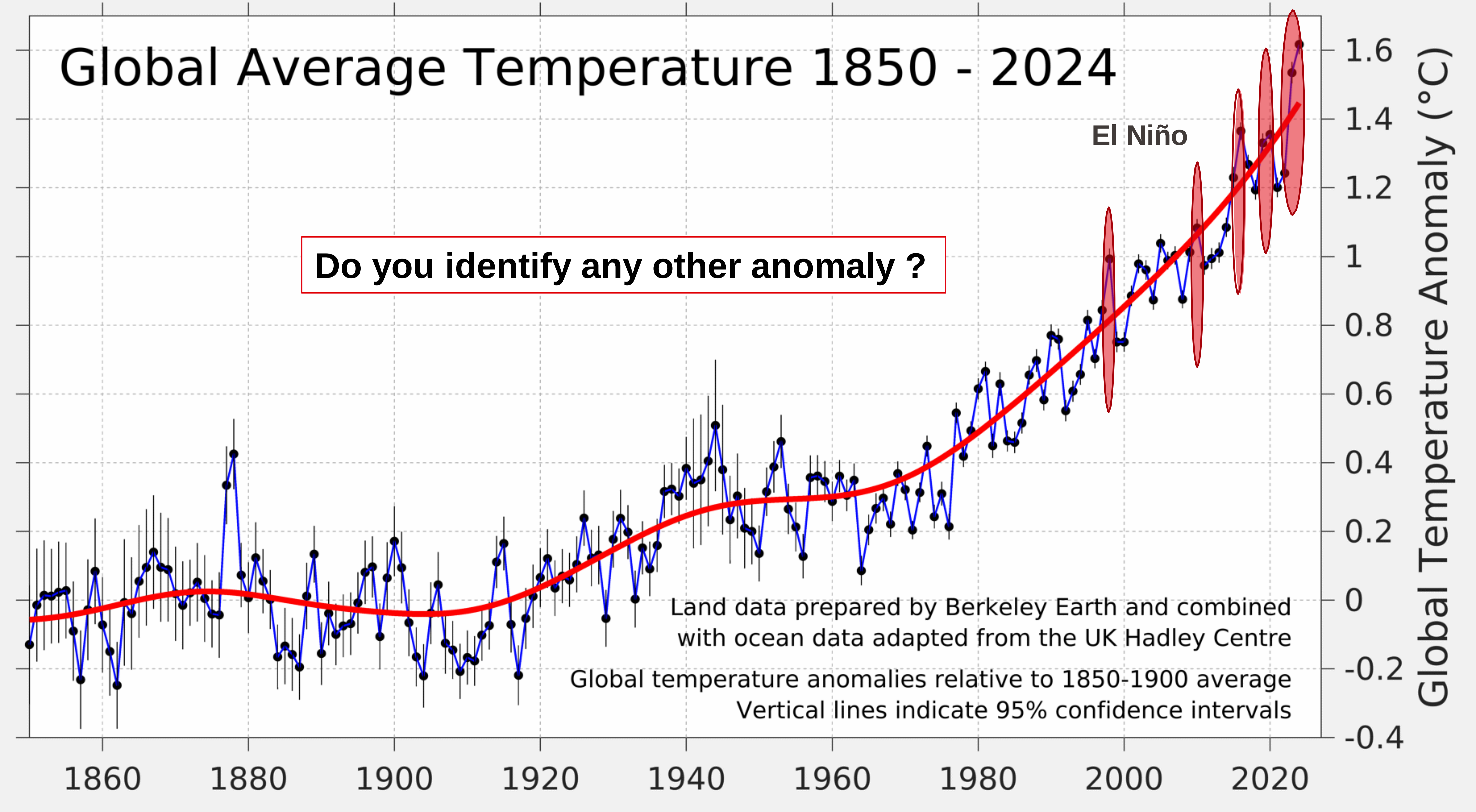
- There are several more modes.

Mode	Name
AMV	Atlantic Multidecadal Variability
AMO	Atlantic Multidecadal Oscillation
DO	Dansgaard Oeschger Event
ENSO	El Niño-Southern Oscillation
HE	Heinrich Event
MJO	Madden Julian Oscillation
NAO	North Atlantic Oscillation
PDO	Pacific Decadal Oscillation
IPO	Interdecadal Pacific Oscillation
QBO	Quasi-biennial Oscillation
SOVC	Southern Ocean Centennial Variability



Source: Earth and Environmental Systems Modeling

For more information: von der Heydt et al., Global and Planetary Change, 2021



Source: [Berkeley annual temperature report for 2024]

Future scenarios

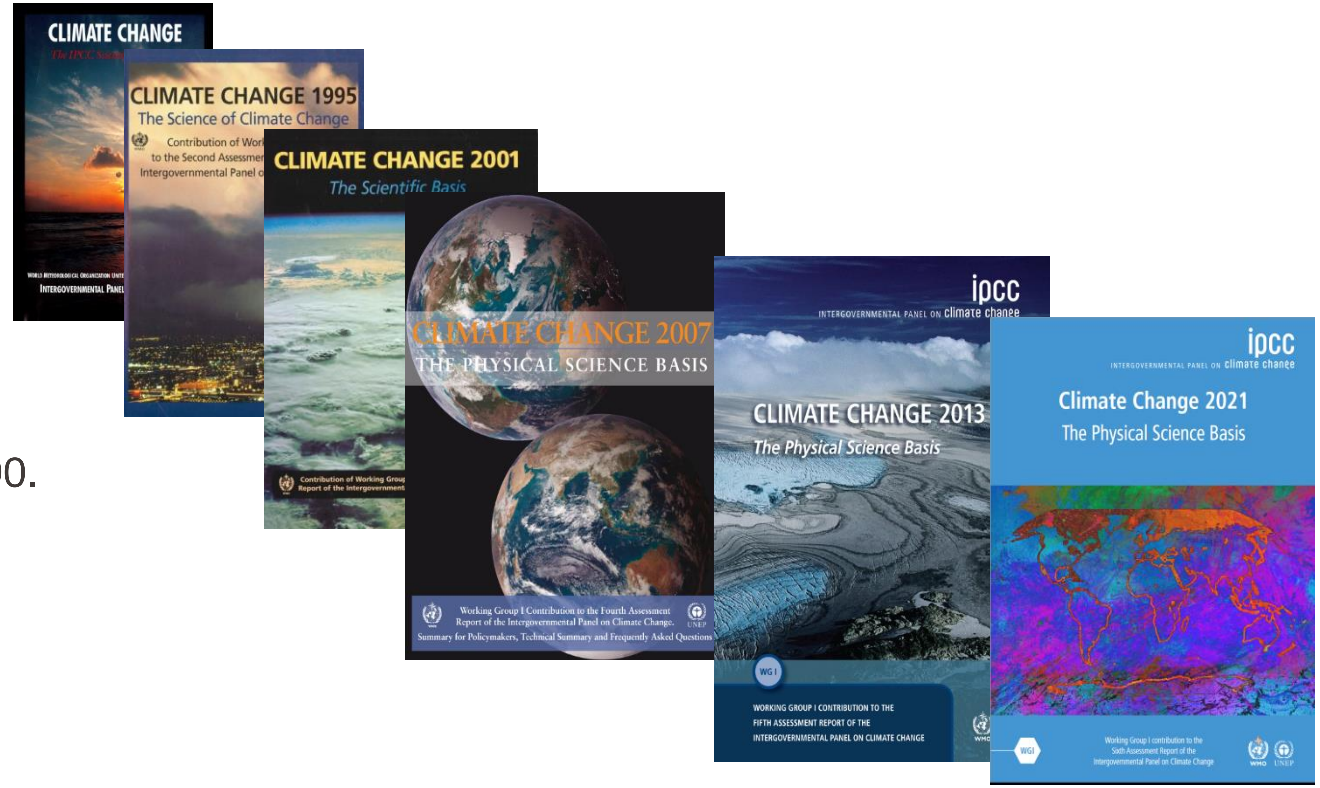
IPCC Intergovernmental Panel on Climate Change

Scientific body establishing assessments

Objectives:

- Determine the current state of climate.
- Estimate the environmental consequences.
- Estimate the socio-economic consequences.

The **Intergovernmental Panel on Climate Change** (**IPCC**) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and later endorsed by the United Nations General Assembly. It is based in Geneva, Switzerland, and is composed of 195 member states.



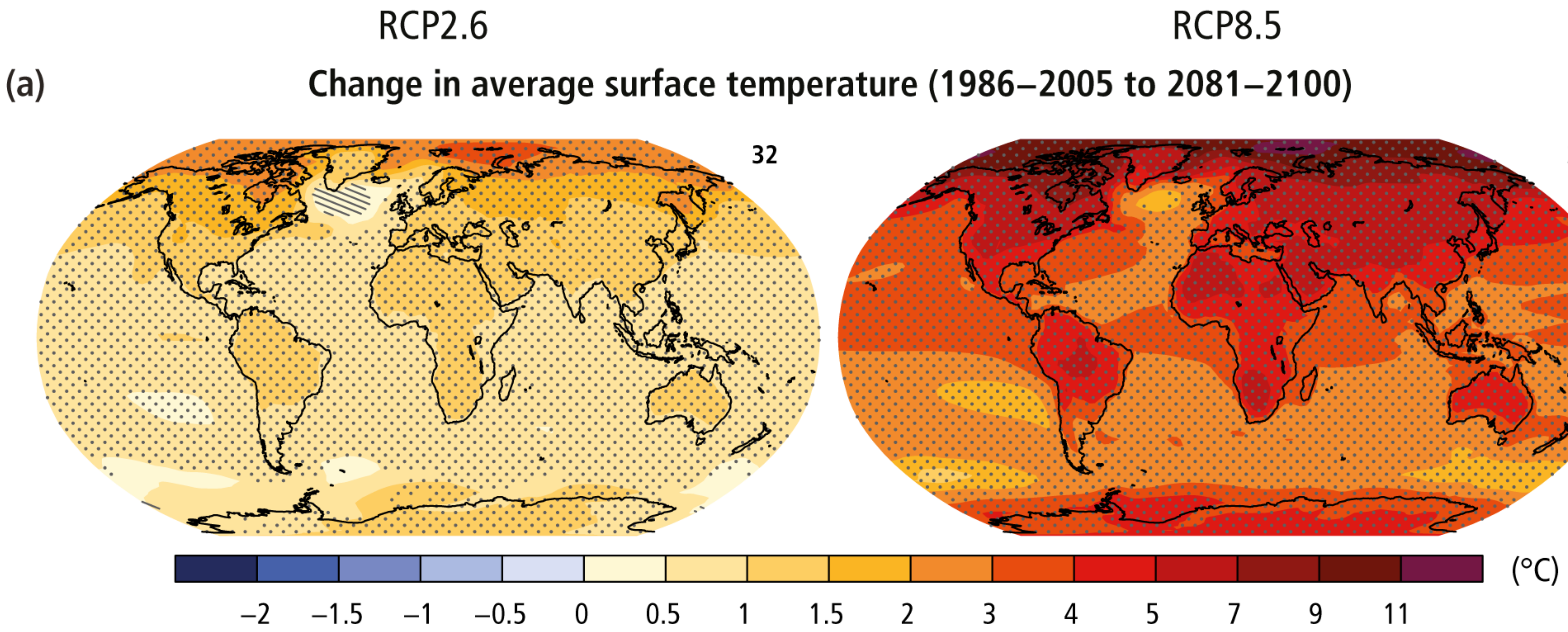
It issues scientific assessments every 5-8 years since 1990.

Three working groups:

- WG1: The physical science basis.
- WG2: Impacts, adaptation and vulnerability.
- WG3: Mitigation of climate change.

Source: IPCC

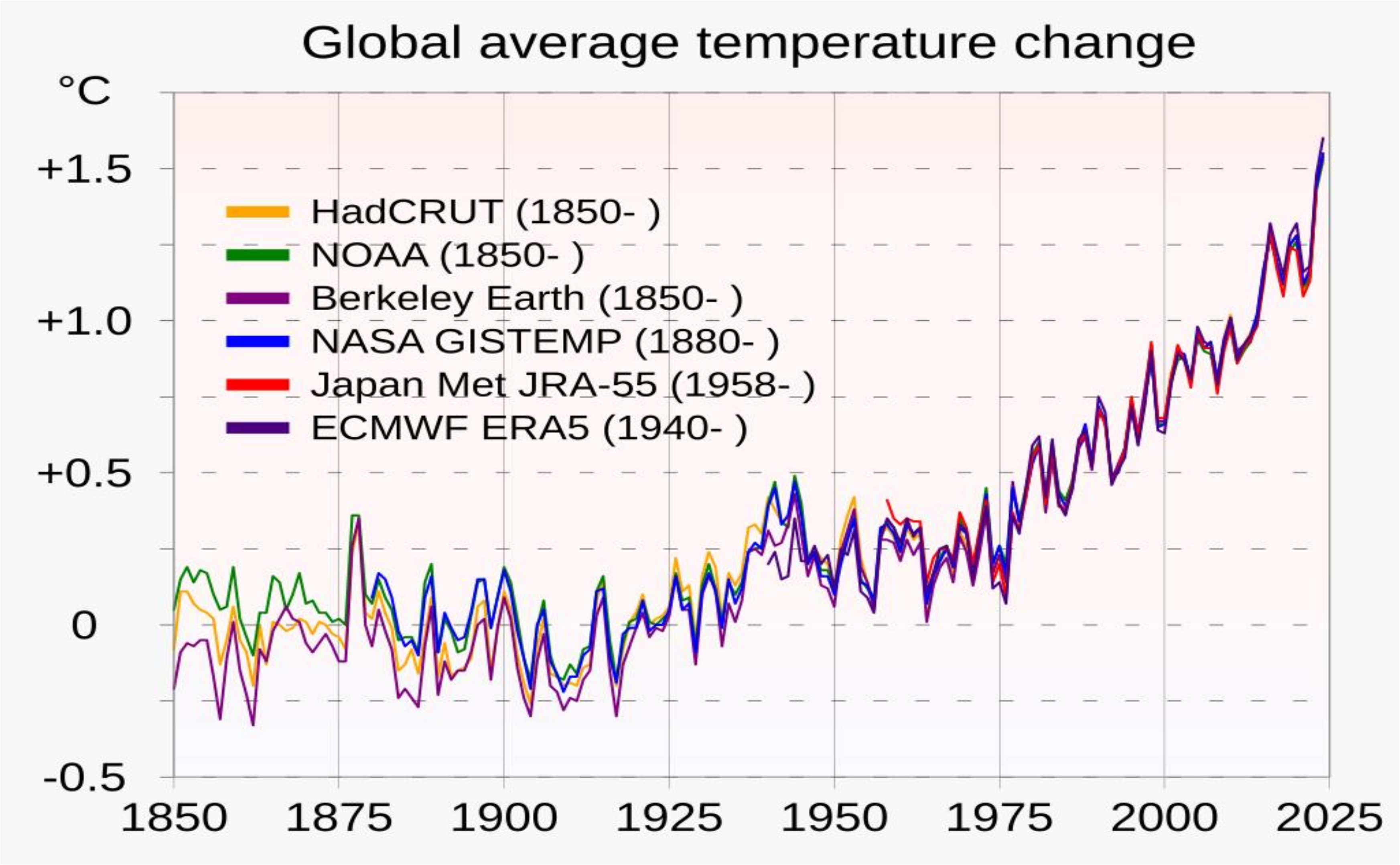
How will Earth look like in 2100 (and beyond) ?



Source: [IPCC AR6 WG1 Fig. SPM.7]

How is it like today compared with preindustrial ?

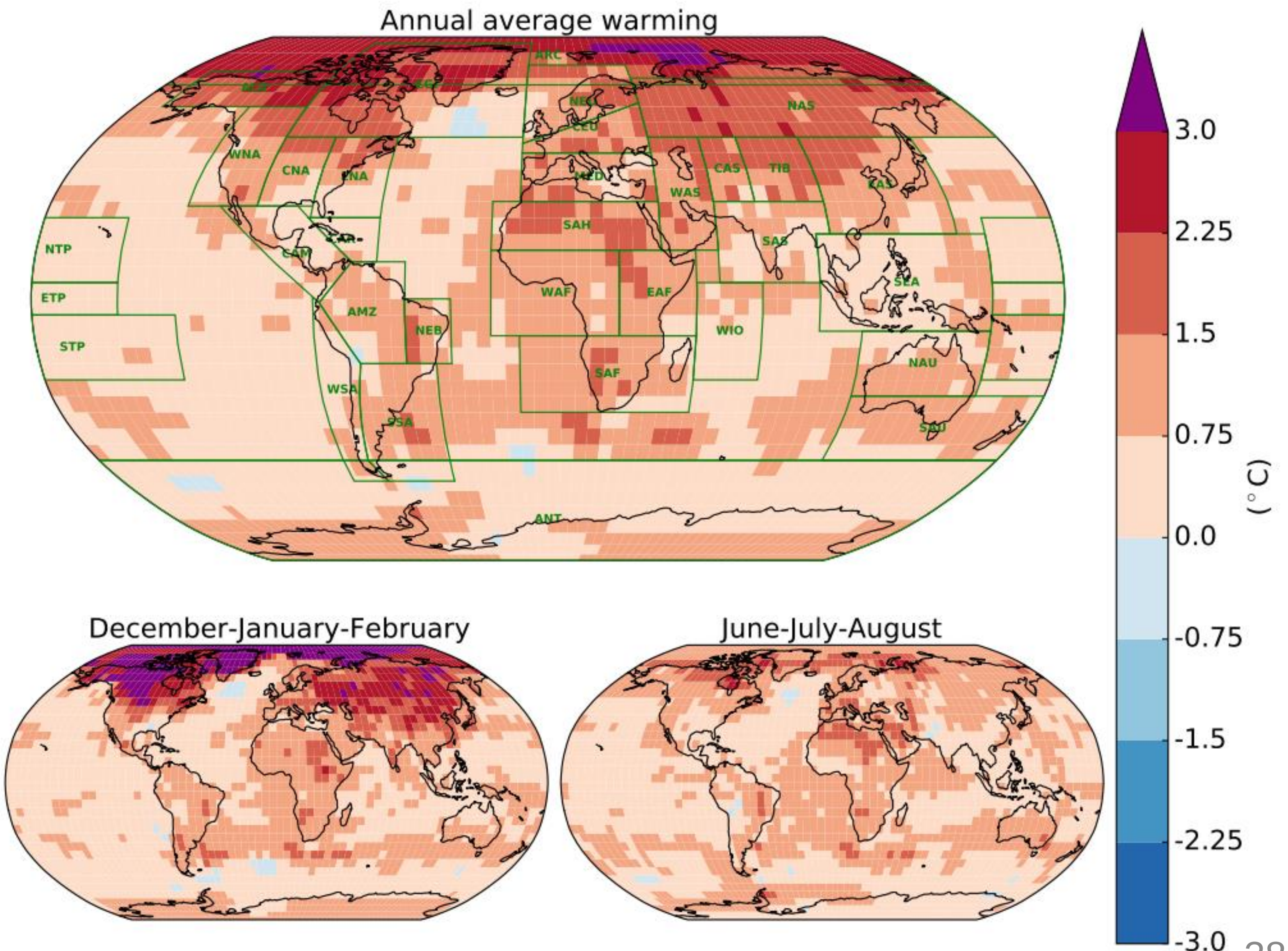
- Six independent evaluations by NOAA, NASA, Japanese Met. Agency, Met Office in UK, European Weather Forecast ECMWF, Berkeley Earth.
- Very similar trends.
- Small differences due to different gridding and weighting methods based on land stations and marine observations.



Source: World Meteorological Organization

How is it like today compared with preindustrial ?

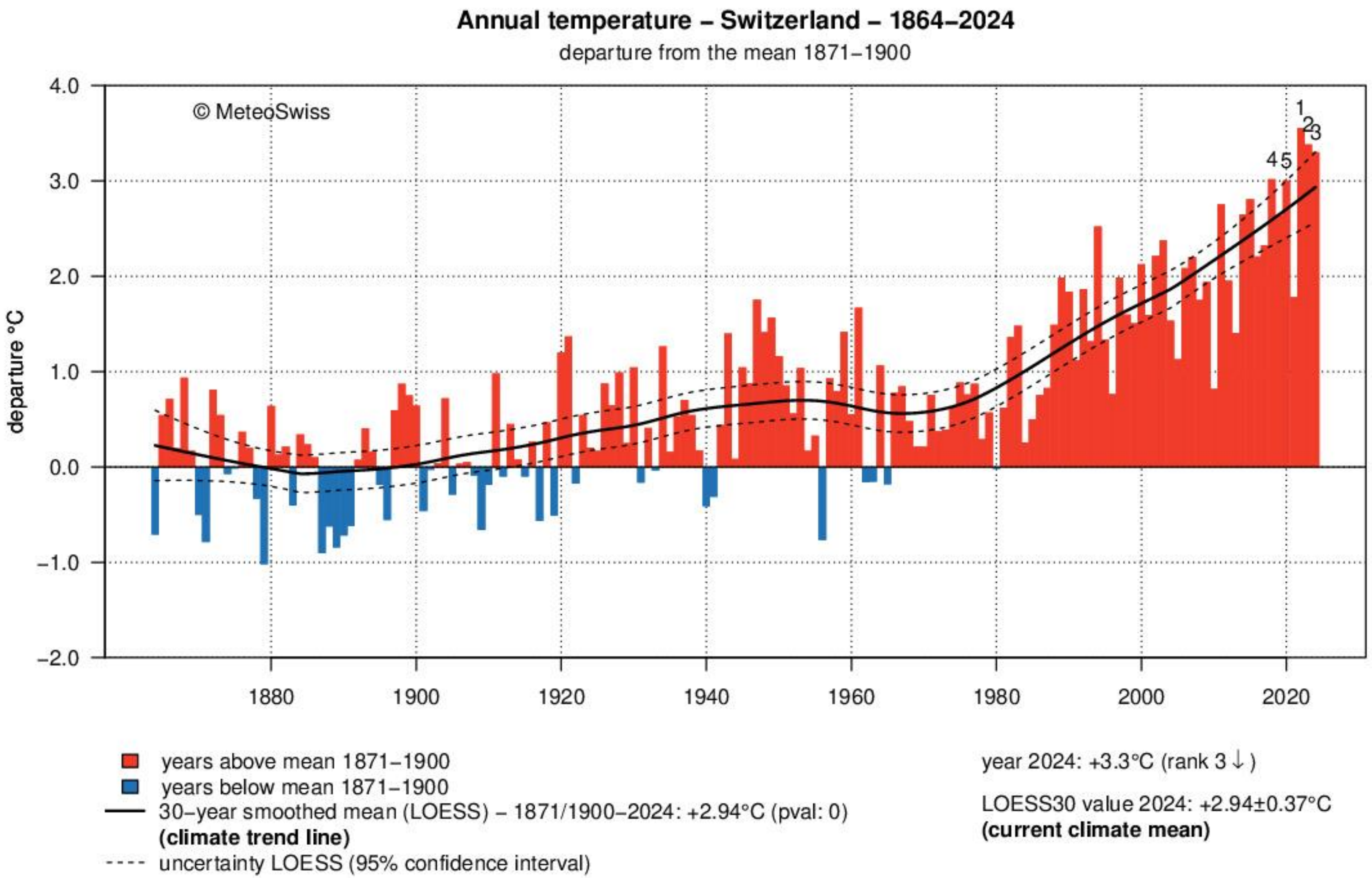
- 2006-2015 versus 1850-1900.
- Large regional and temporal differences:
  - ➢ Amplification in the Arctic.
  - ➢ Amplified warming on land compared with oceans.
- Warming more imprinted in boreal winter.
- **Why such an anomaly in boreal winter ?**
  - Arctic amplification:
  - Less summer sea ice allows more heat release from the ocean in winter.
  - Later refreezing, earlier melting of winter sea ice.
  - Cloud cover.
- *Source: [IPCC SR15 Chapter 1 Fig.1.3]*



How is it like today compared with preindustrial ?

- 2006-2015 versus 1850-1900.
- Large regional and temporal differences:
  - Amplification in the Arctic.
  - Amplified warming on land compared with oceans.
- Warming more imprinted in boreal winter.
- The case of Switzerland: Running mean on 30 years gives **+2.94°C** compared with 1871-1900.
- Warmest 3 years: 2022, 2023, 2024…

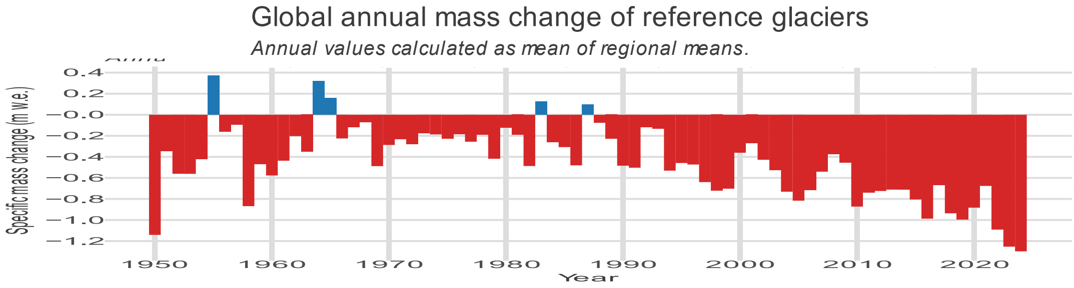
Source: *MétéoSuisse Climat*

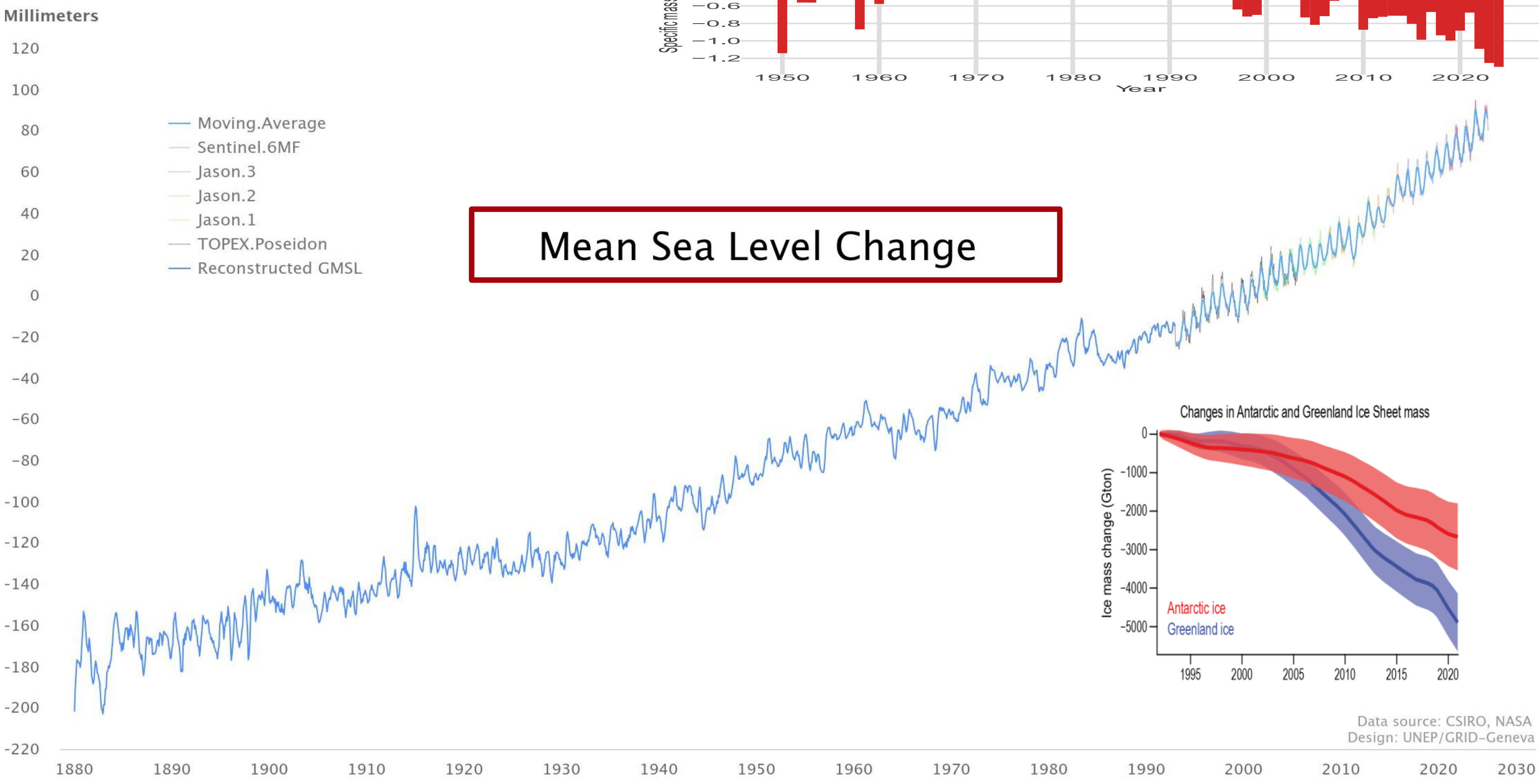


How is it like today compared with preindustrial ?

- Global mean sea level has increased by ~25 cm since the early 20th century.
- The rate of rise has accelerated. Now close to 4 mm per year.
- Between 2006 and 2018:
  - Thermal expansion of oceans: ~37%
  - Mountain glacier loss: ~20%
  - Greenland and Antarctic ice sheet loss: ~33%
  - Groundwater extraction: ~10%

Source: WGMS

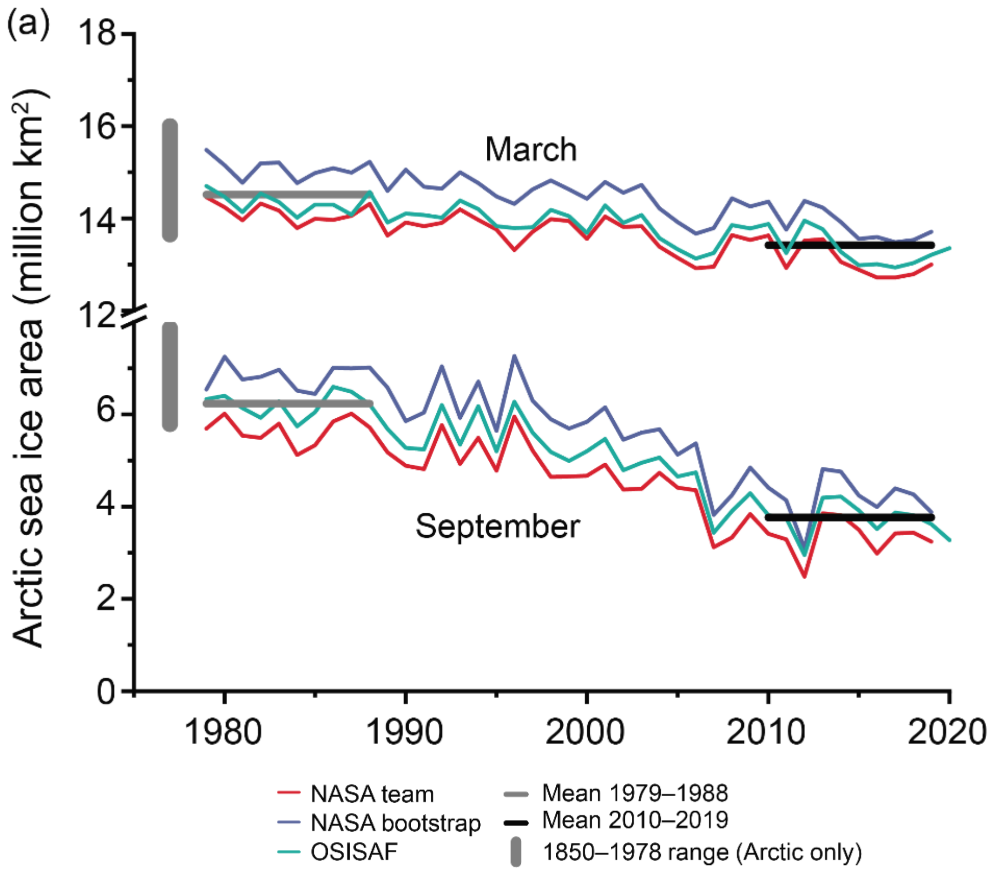


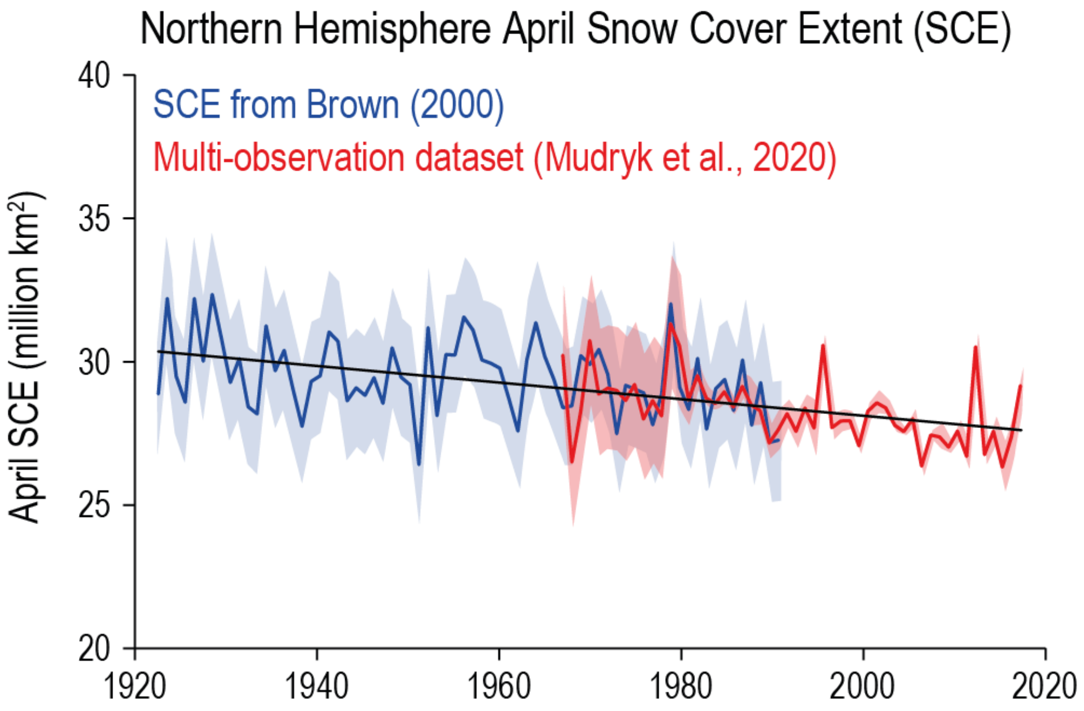


Source: IPCC AR6 WG1 Chapter 2 Fig. 2.24

- Source: UNEP GRID

How is it like today compared with preindustrial ?

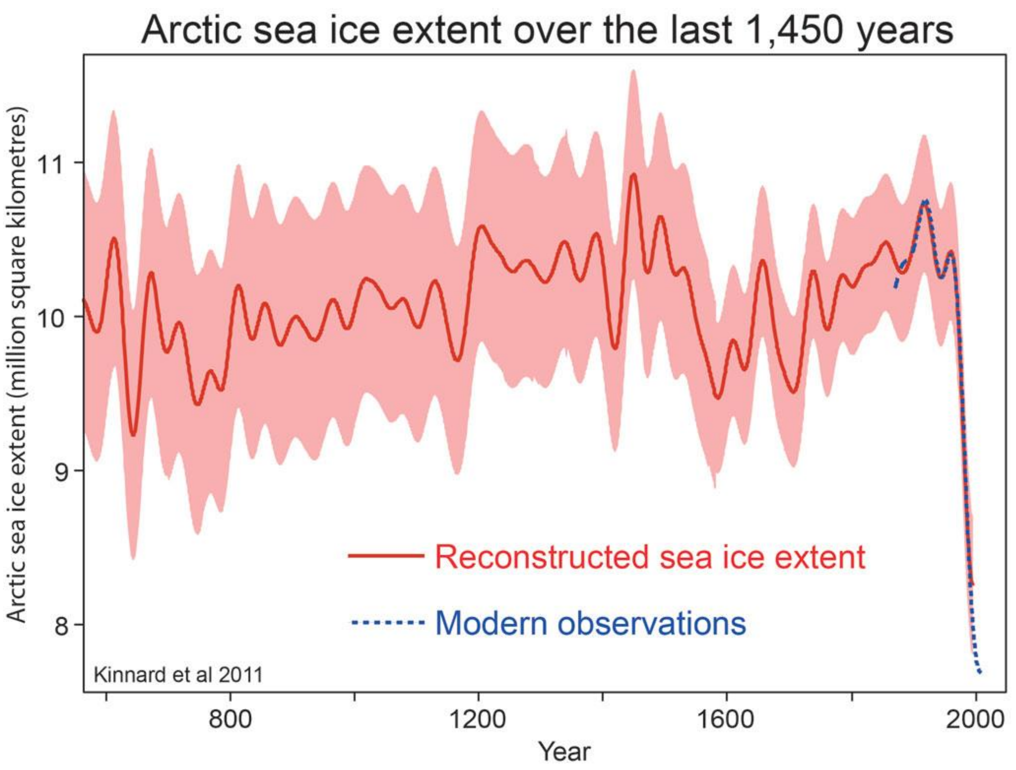




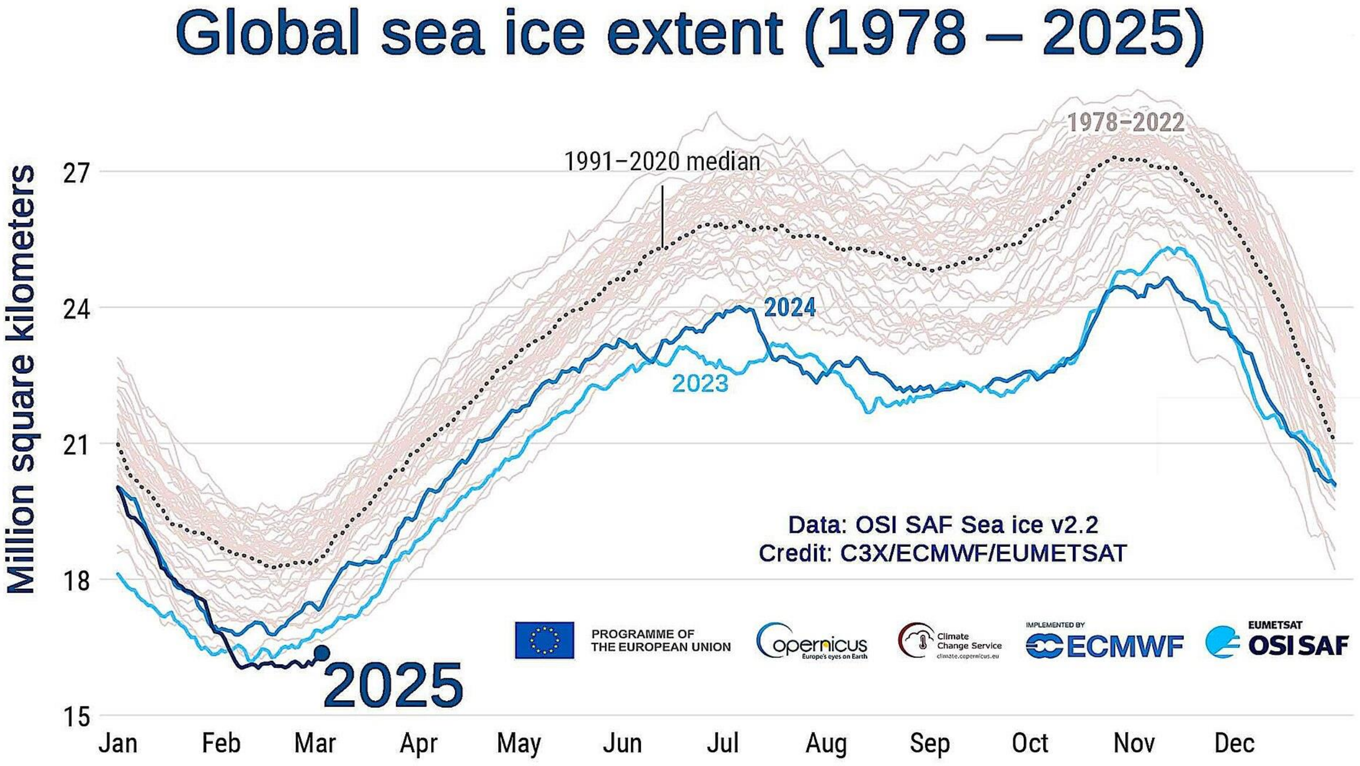
- Other important components of the cryosphere:
- Arctic sea ice and snow cover on the Northern Hemisphere (taken at April time)

Source: [UNEP GRID]

How is it like today compared with preindustrial ?



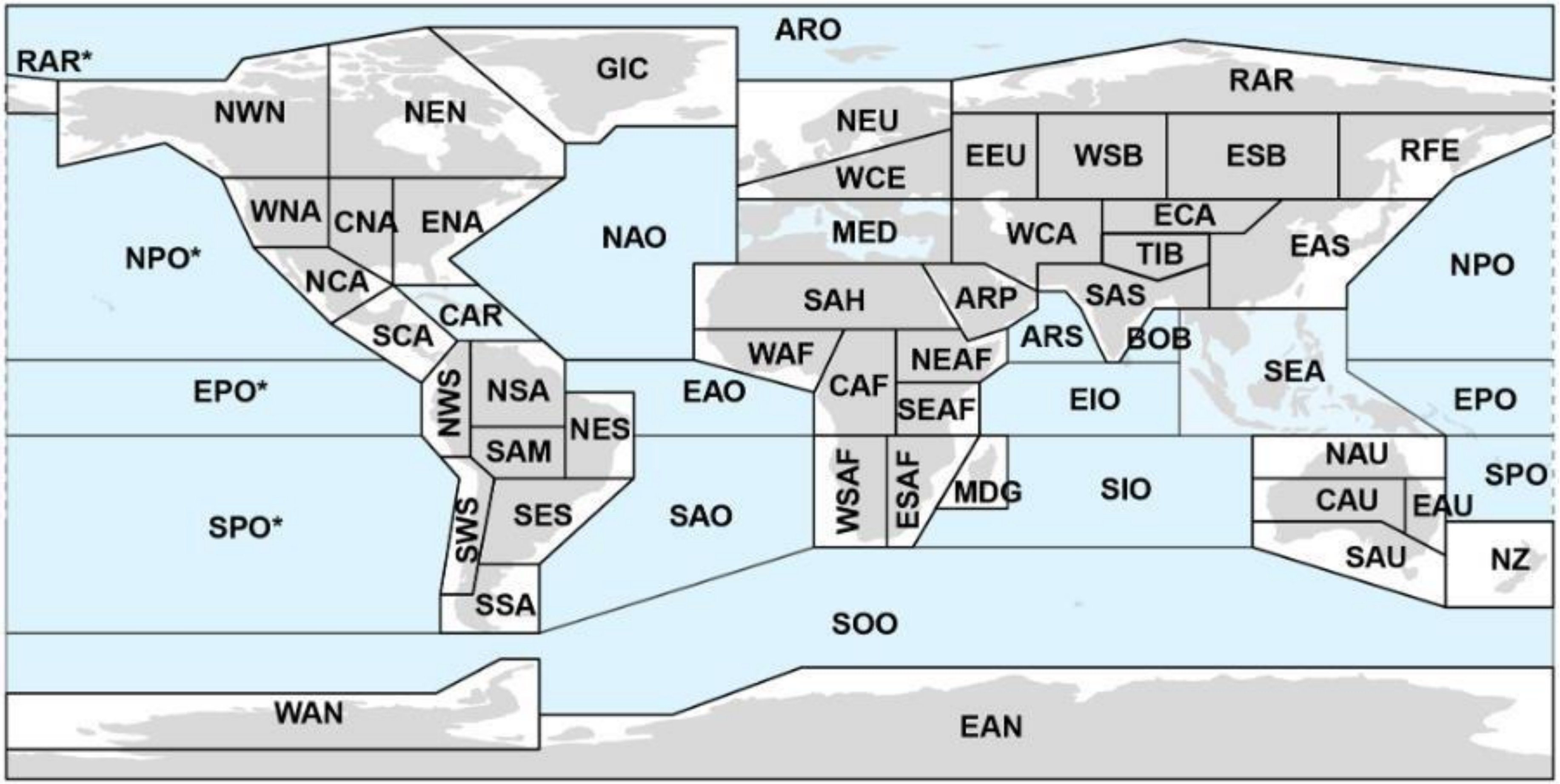
Source: [Kinnard et al., Nature 2011]()



Source: [Copernicus ECMWF]()

- Loss of Arctic sea ice: a 1,450 year perspective based on proxies.
- Recent trend also affects Antarctic sea ice. Today: lowest global sea ice extent ever observed since the start of satellite observations (1978).

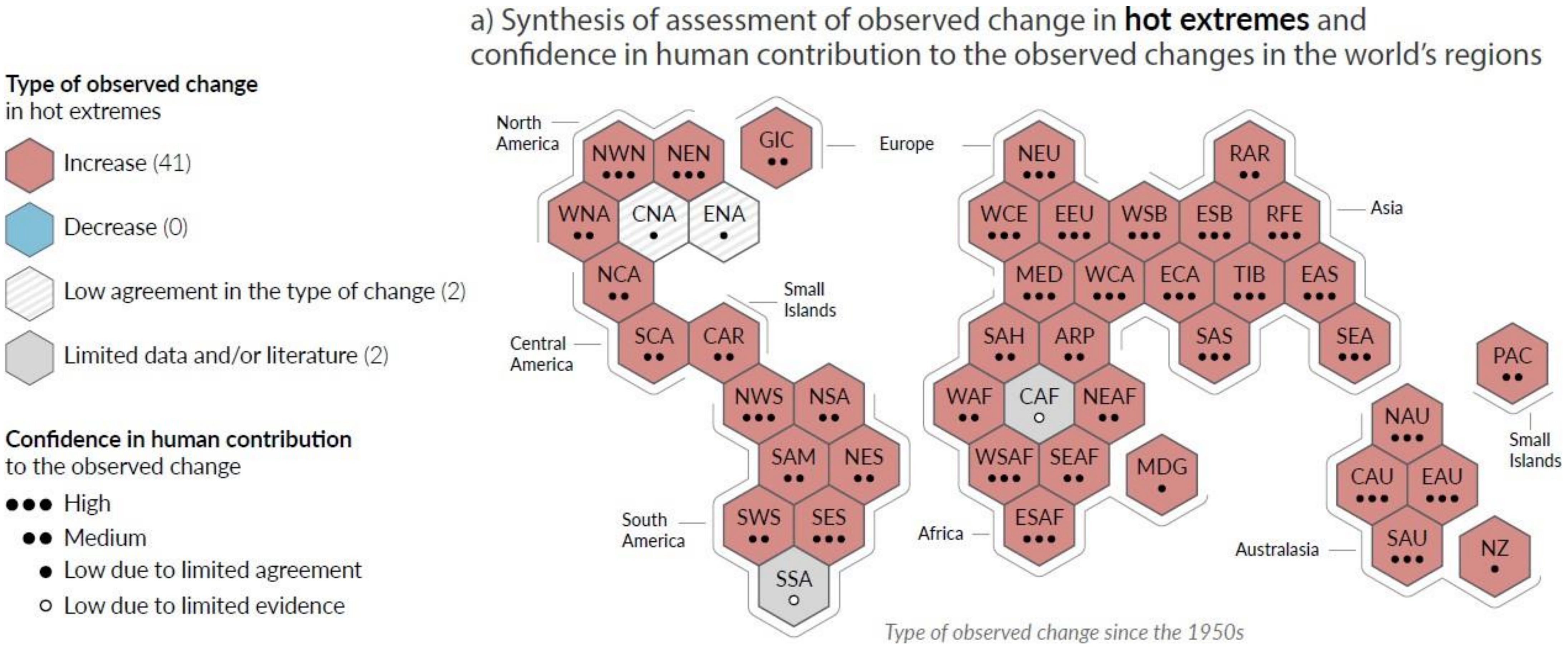
It's not only temperature and not only global



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

Source: Iturbide et al., Earth Syst. Sci. Data 2020

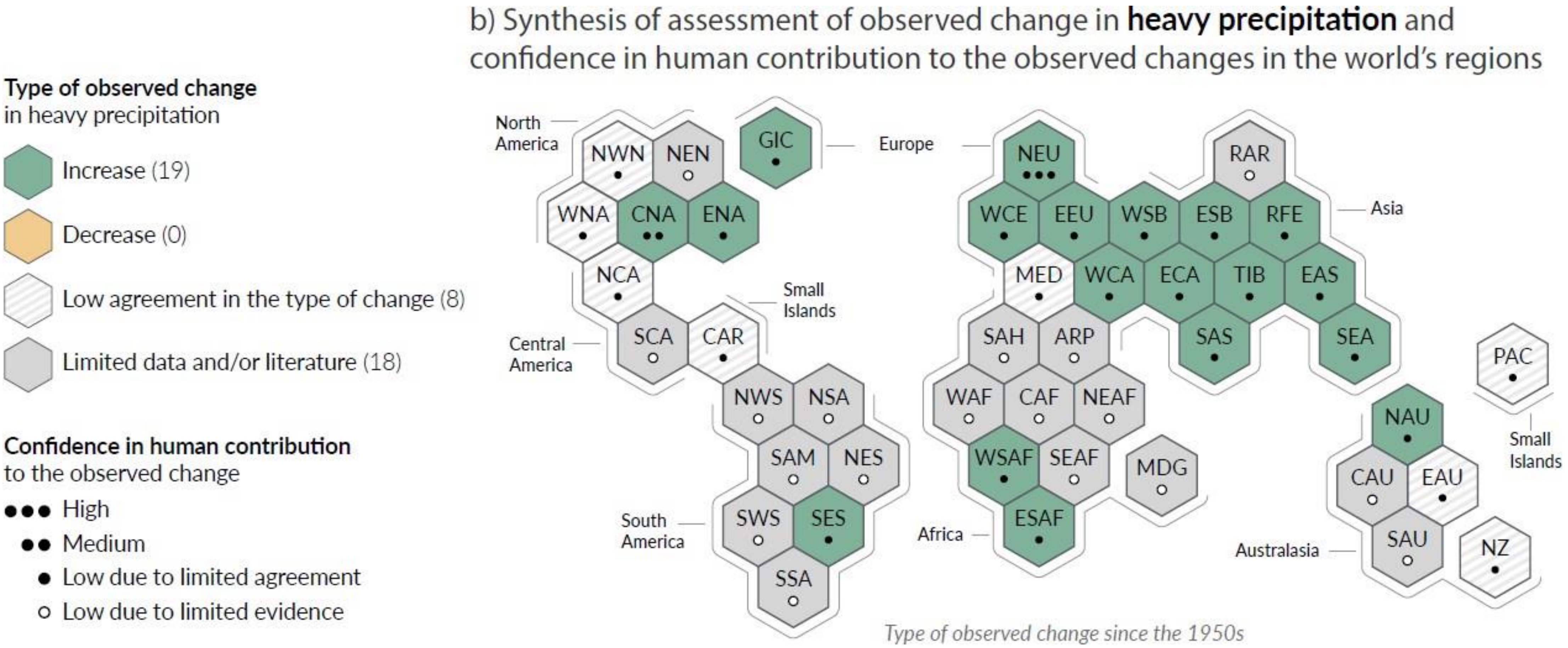
Hot extremes



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

Source: *IPCC AR6 WG1 Fig. SPM3*

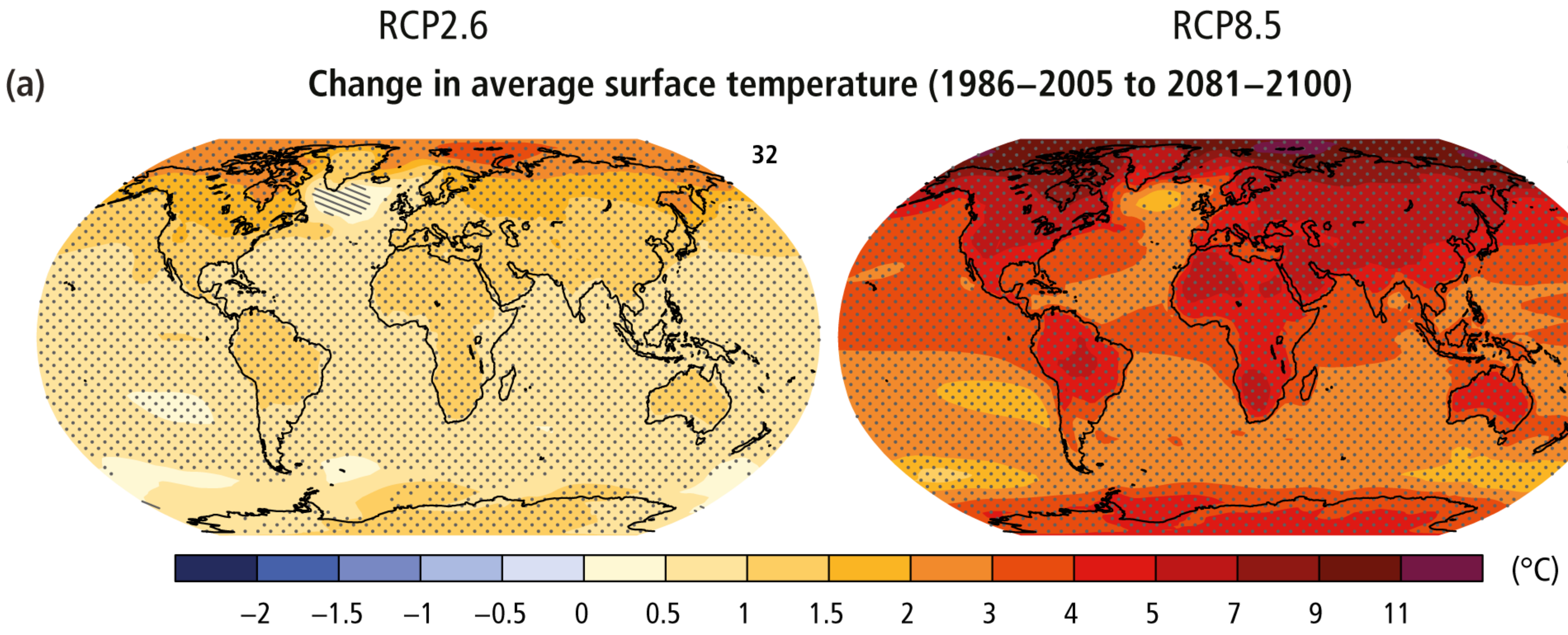
Heavy precipitation



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

Source: IPCC AR6 WG1 Fig. SPM3

How will Earth look like in 2100 (and beyond) ?



Source: [IPCC AR6 WG1 Fig. SPM.7]

How will Earth look like in 2100 ?

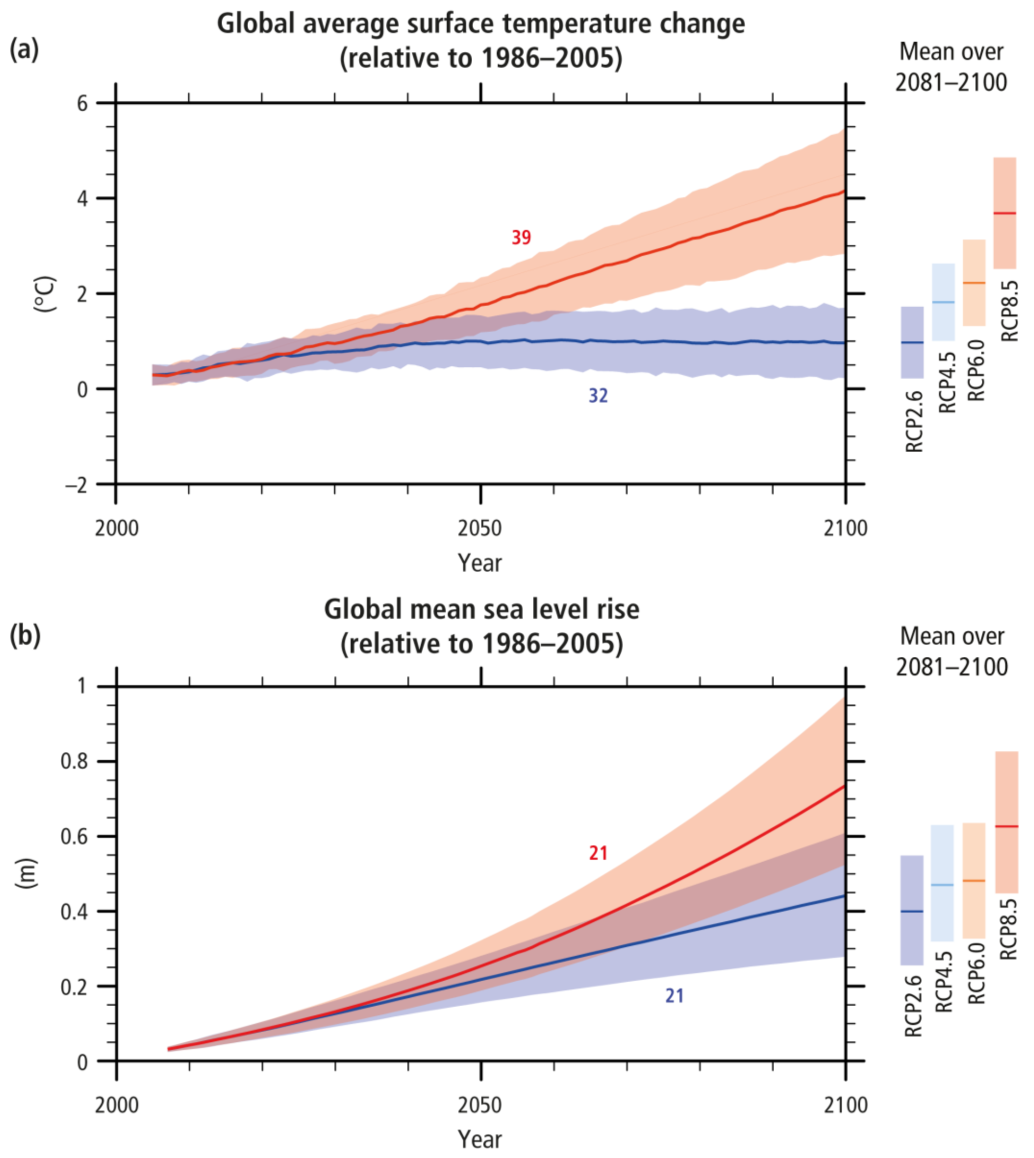
- Scientists use couple climate models and they intercompare their simulations.
  - For IPCC AR5 (2013): 55 models from 20 different institutions.
  - For IPCC AR6 (2021): 120 models from 50 different institutions.

- AR5 focused on scenarios of greenhouse gas and aerosol emissions, taking into accound land-use changes and atmospheric chemistry. Solar and volcanic forcings kept unchanged.

- The scenarios are identified by their **approximate total radiative forcing** in year 2100 relative to 1750, through *«Representative Concentration Pathways» **(RCP)***:

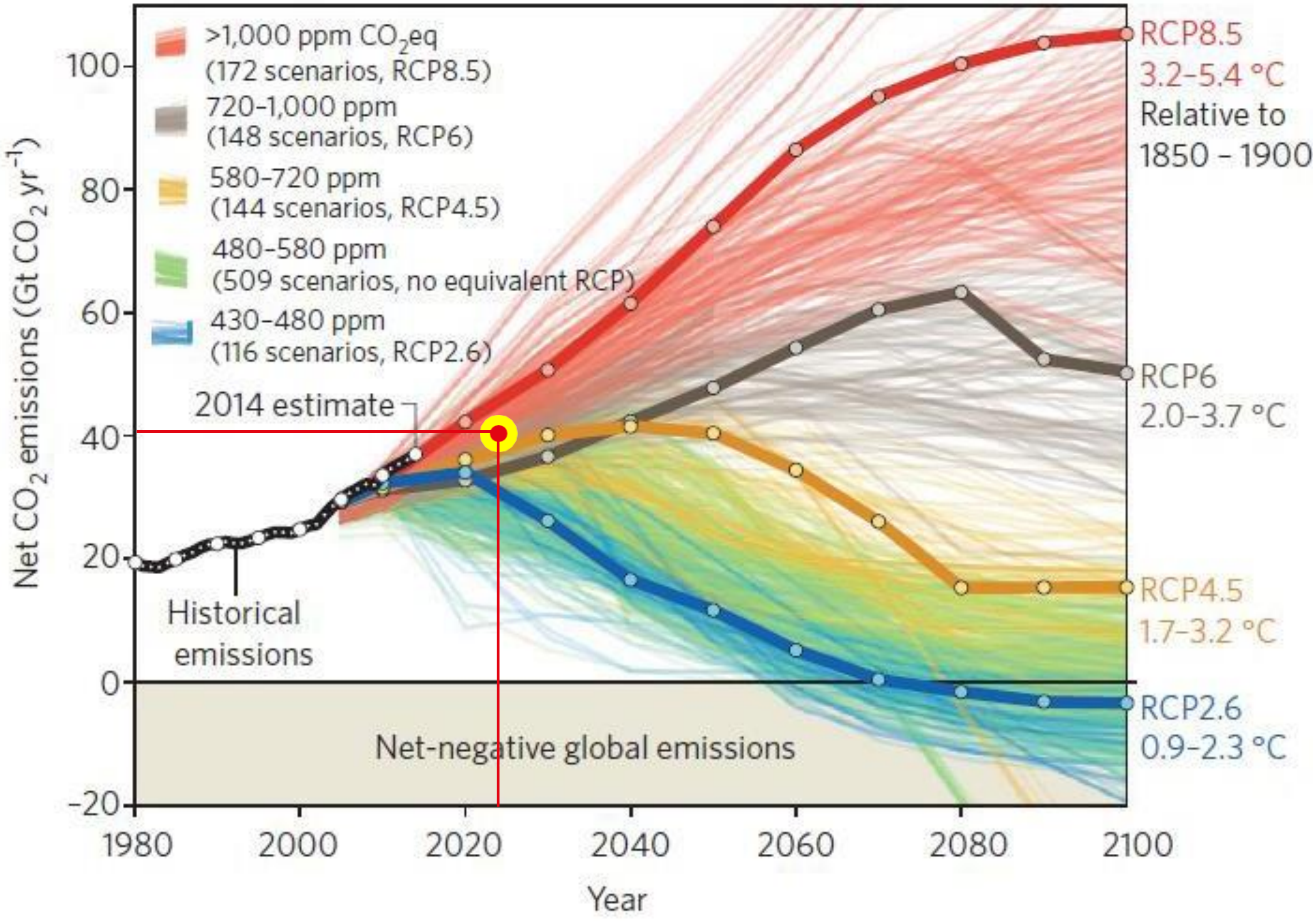
  - 2.6 $W.m^{-2}$ for RCP2.6 – in 2100: 430-480 ppm CO_2 (mitigation)
  - 4.5 $W.m^{-2}$ for RCP4.5 – in 2100: 480 - 720 ppm CO_2 (stabilization)
  - 6.0 $W.m^{-2}$ for RCP6.0 – in 2100: 720 - 1000 ppm CO_2 (stabilization)
  - 8.5 $W.m^{-2}$ for RCP8.5 – in 2100: > 1000 ppm CO_2 (uncontrolled)

- It translates into ,e.g., a global average surface temperature change



Source: IPCC AR5 WG1 Figure SPM6

What CO_2 emissions associated with RCPs ?



- 2023 and 2024: **41.6 Gt** (including fossil fuel and land-use)
- Highest ever recorded since pre-industrial times…

Source: Global Carbon Project

- Reminder: anthropogenic radiative forcing since 1750 = +2.2 W.m^{-2} (RCP2.6 is only +0.4 W.m^{-2} above)

Any comment about the right part of the graph ?

Negative emissions needed to stay < 2 °C.

- *Source: Fuss et al., Nature Climate Change 2014*

EPFL

How will Earth look like in 2100 ?

- Since IPCC AR6 (2021), use of «Shared Socioeconomic Pathways» **(SSP)** in addition to RCP.
- SSPs are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios based on different climate policies.
- **More relevant for climate policy analysis**.
- **SSPs** are:
    - Narratives describing alternative socio- economic developments.
    - Qualitative description relating elements of the narratives to each other.
    - Quantitative elements. SSPs provide data with the scenarios, e.g., on national population, urbanization and GDP (per capita).

SSP5: Competitive markets, innovation, rapid technological progress toward sustainable development.

SSP3: Nationalism, priority on security, regional conflicts.

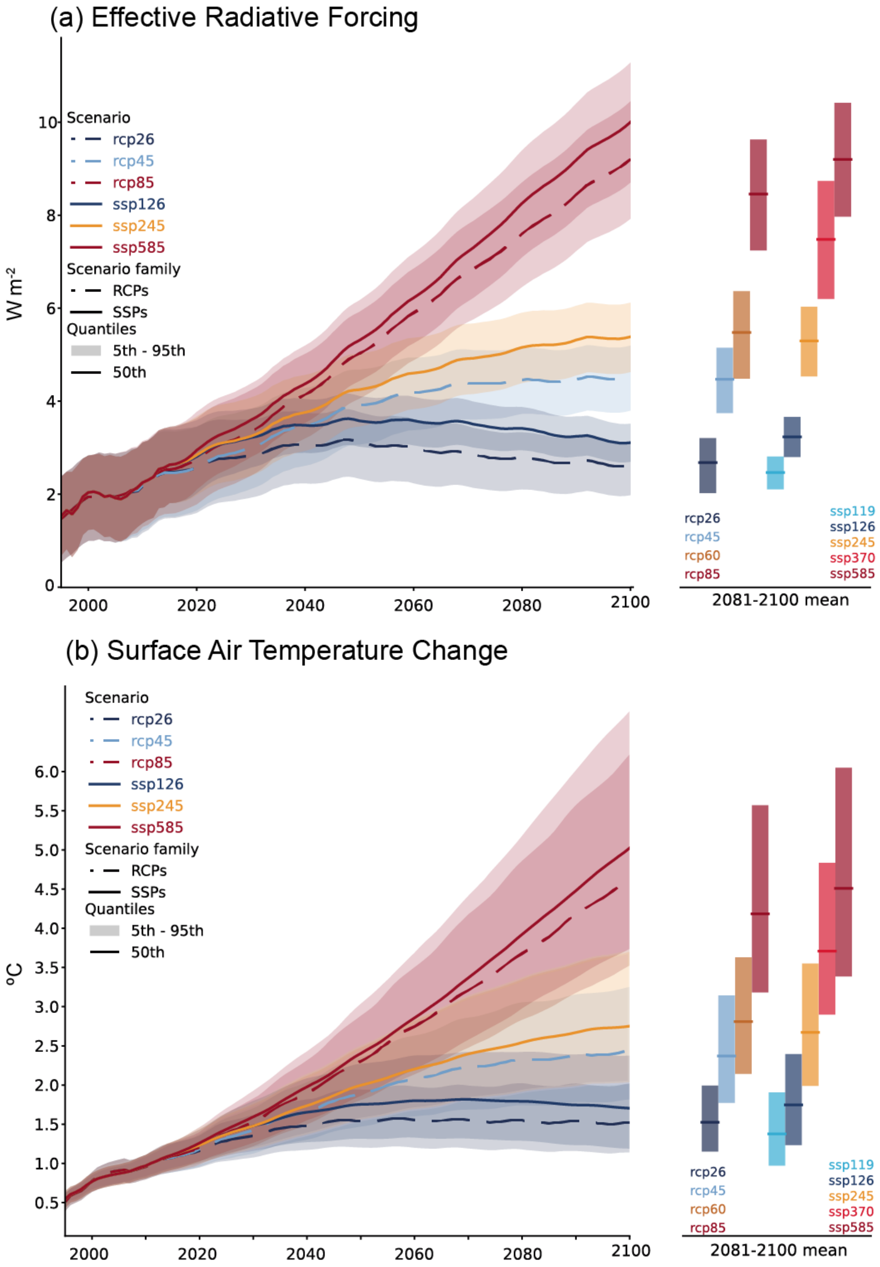
SSP1: More sustainable path, with inclusive development.

SSP2: Social, economic, and technological trends similar to today.

SSP4: Unequal investments. Increasing disparities across and within countries.

Source: Wikipedia

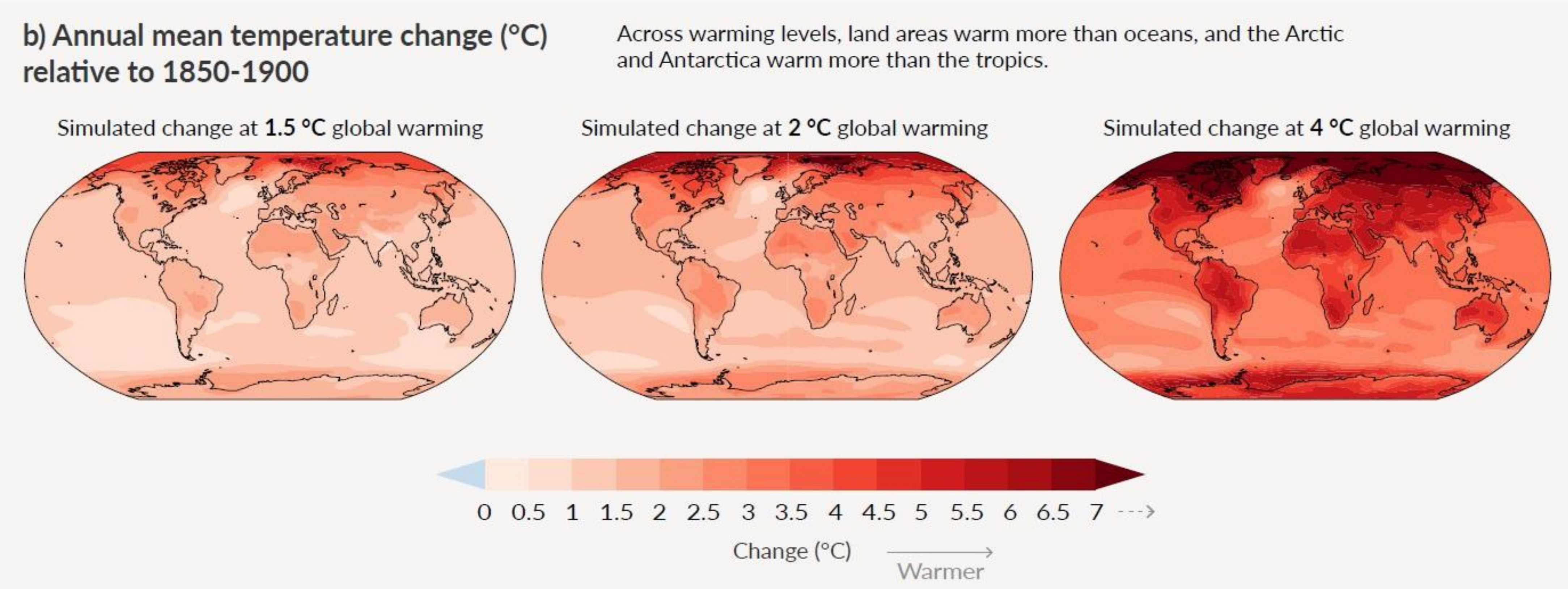
How will Earth look like in 2100 ?



Source: [IPCC AR6 WG1 Fig. 4.35, 2021]

Source: [Wikipedia]

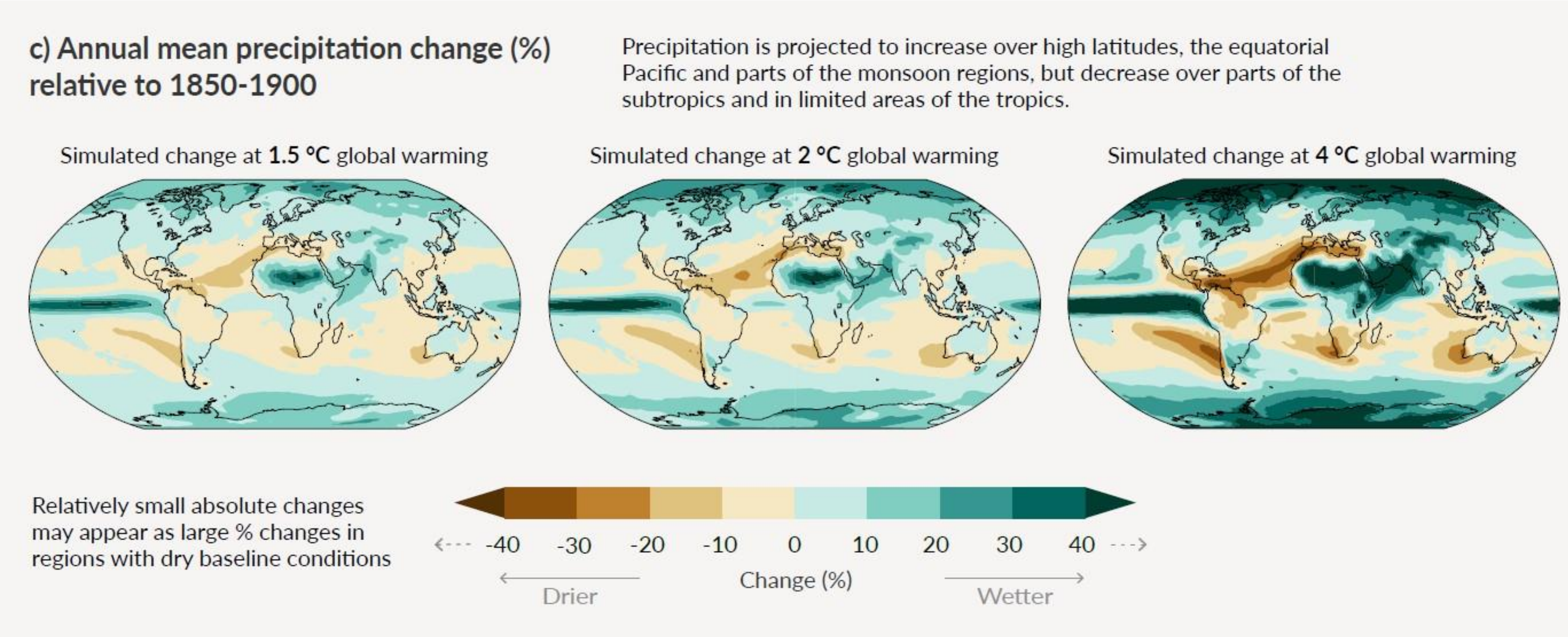
How will Earth look like in 2100 ? Temperature



See lecture on Tipping Points: why we don't really want to go for a +4°C scenario…

- IPCC AR6, Figure SPM.5

How will Earth look like in 2100 ? Precipitation

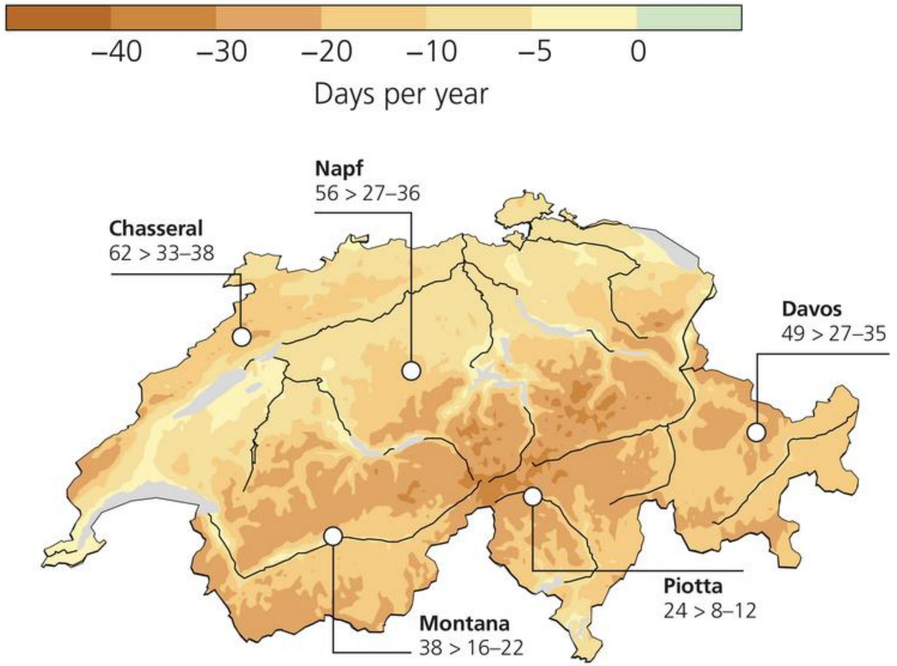


- IPCC AR6, Figure SPM.5

How will Switzerland look like in 2100 ? Snow

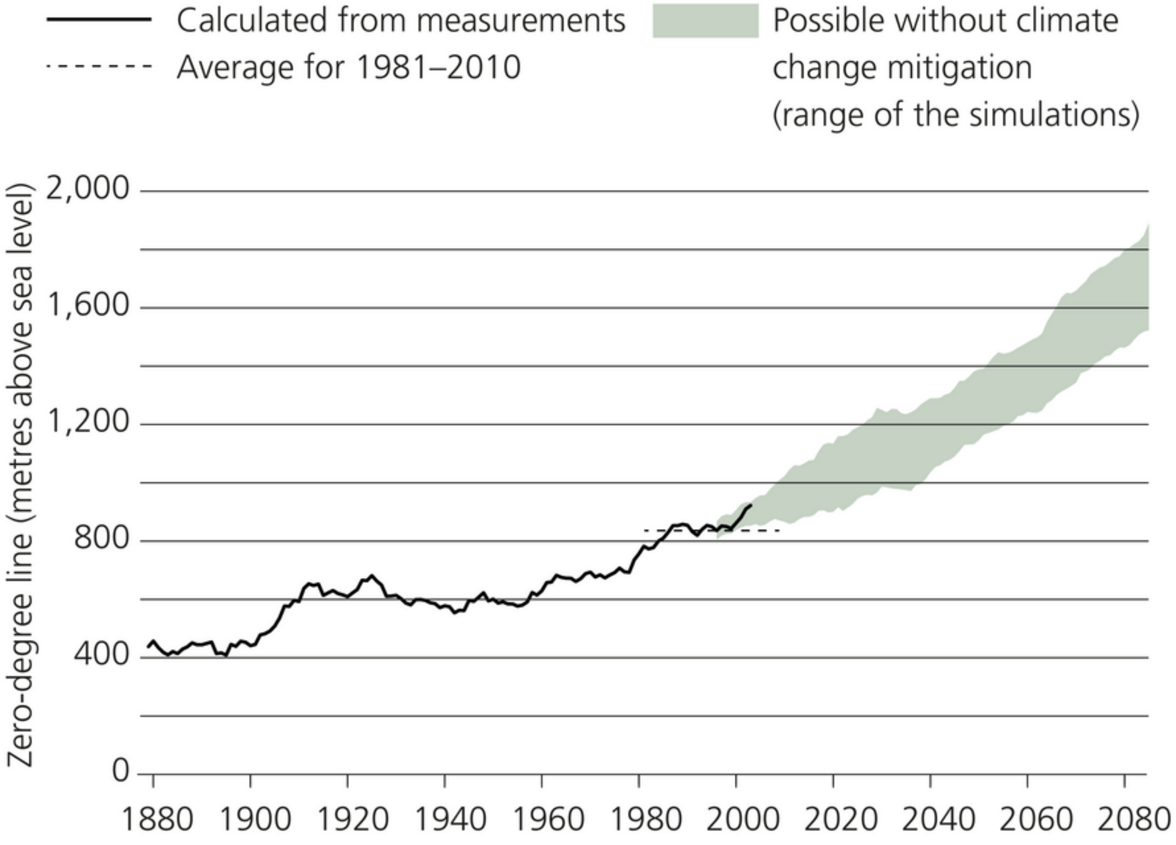
Change in number of days with snowfall

Expected changes around 2060 without climate change mitigation, in comparison to 1981–2010 (30-year averages). The values show the norms for the period of 1981–2010 and the possible range around 2060.



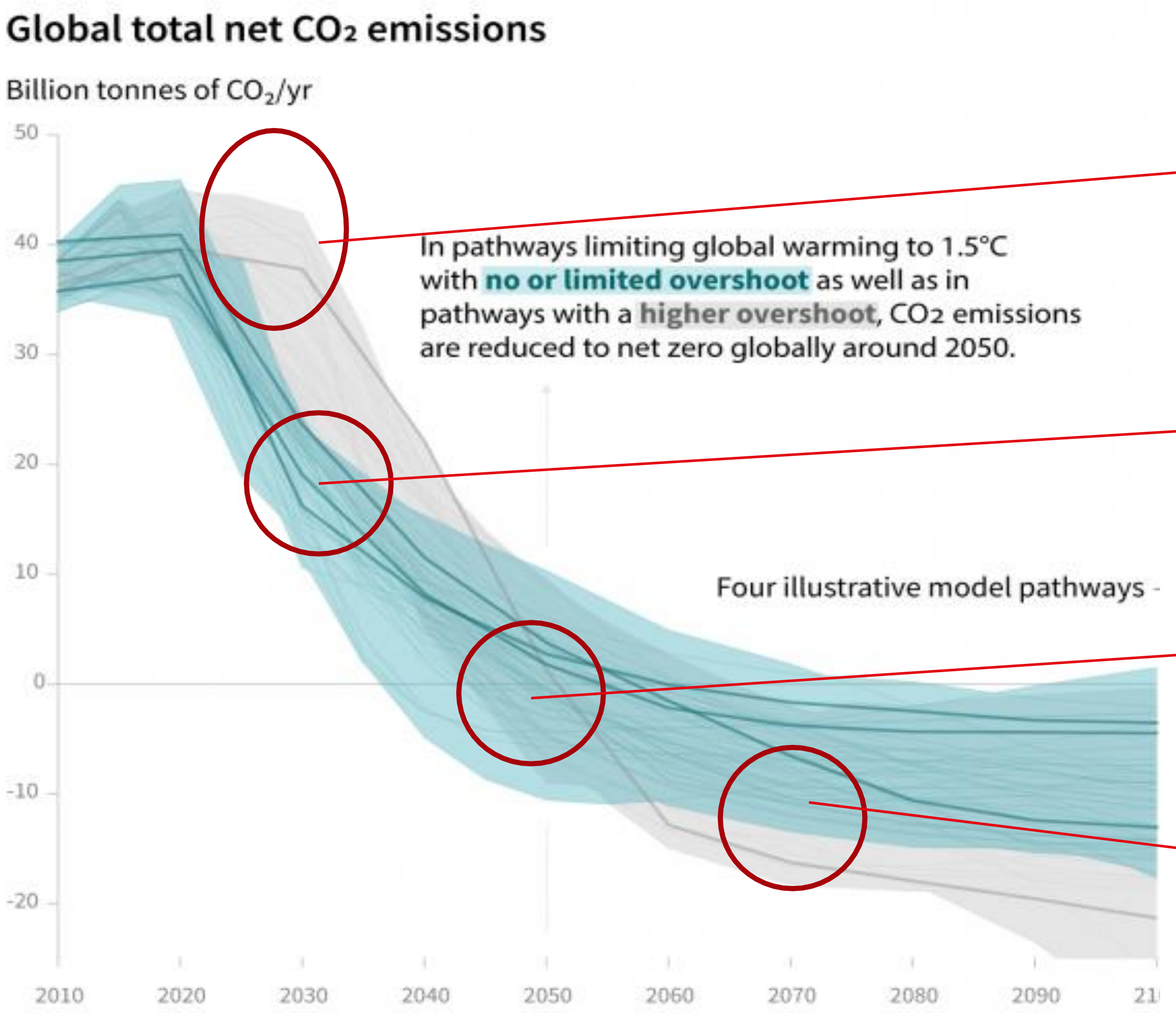
Zero-degree line

Zero-degree line in winter (Swiss average and 30-year running average).



Source: MétéoSuisse CH2018

Pathways to +2.0 or +1.5°C: Reducing emissions



«Overshoot» allowed, followed by steeper reduction

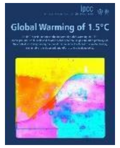
In 2030: only 50 % of emissions compared to 2010

Decisive Decade

Net-zero at the latest in 2040-2050

«Negative emissions»: ~25 % of present- day emissions!

IPCC, SP1.5



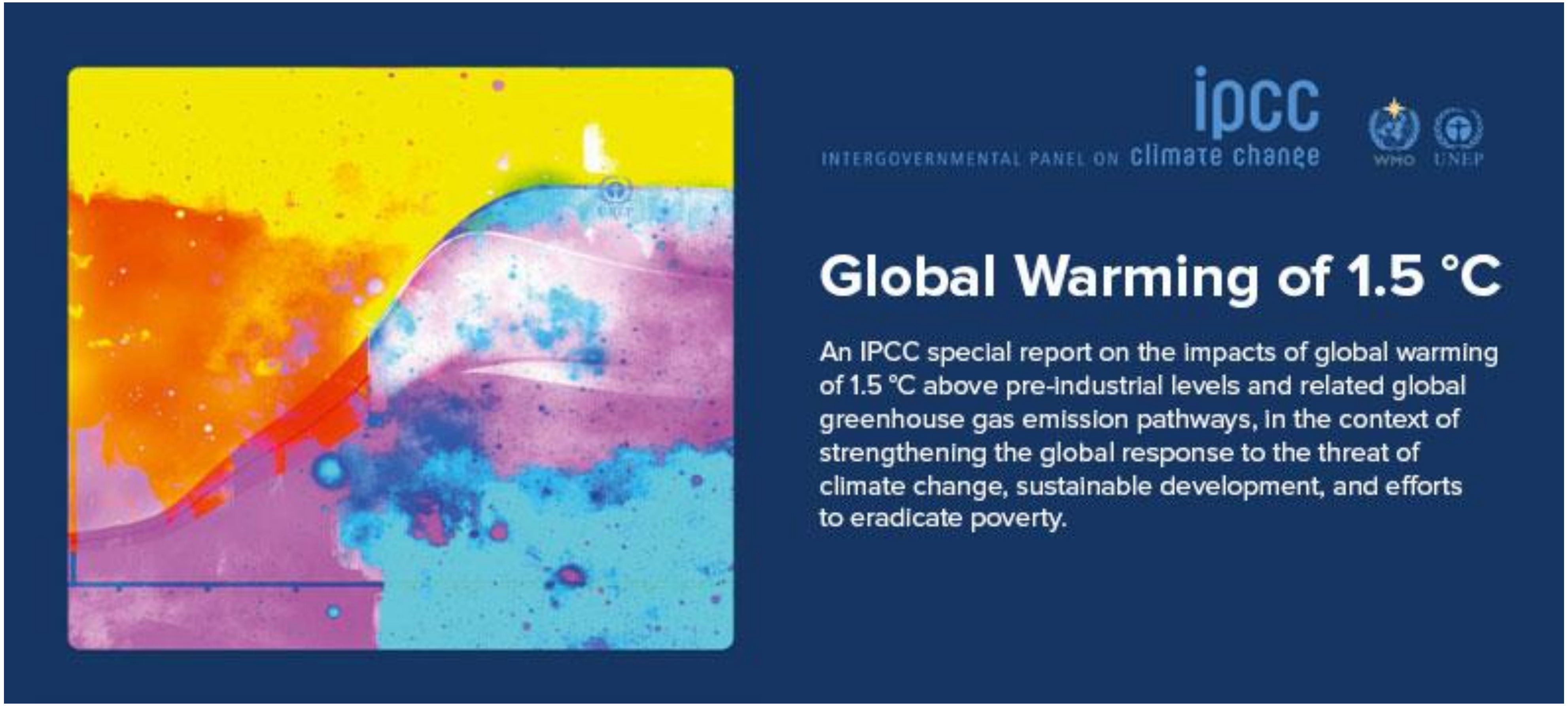
Timing of net zero CO2
Line widths depict the 5-95th percentile and the 25-75th percentile of scenarios

Pathways limiting global warming to 1.5°C with **no or limited** overshoot

Pathways with **higher overshoot**

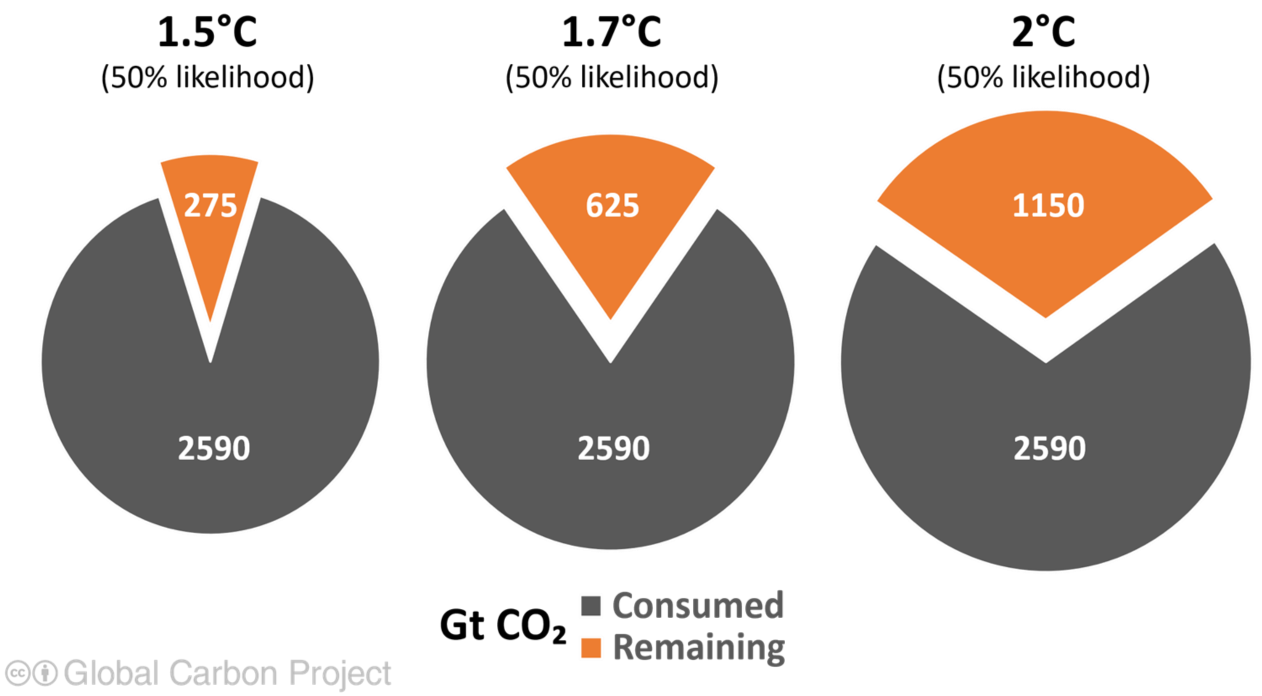
Pathways limiting global warming below 2°C
(Not shown above)

Pathways to +2.0 or +1.5°C: Reducing emissions

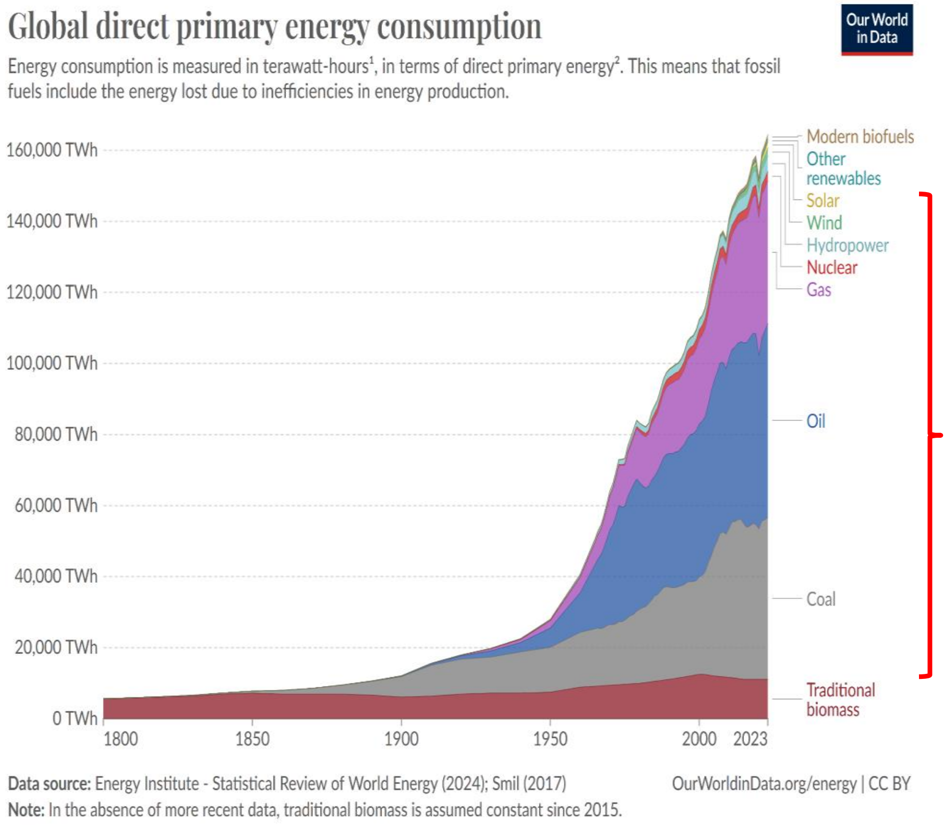


If you want to know more about possible pathways, please read the IPCC Special Report «Global Warming of 1.5°C», published on October 2018. It is a follow-up of the Paris agreement of 2015 (COP 21).

Remaining carbon budget

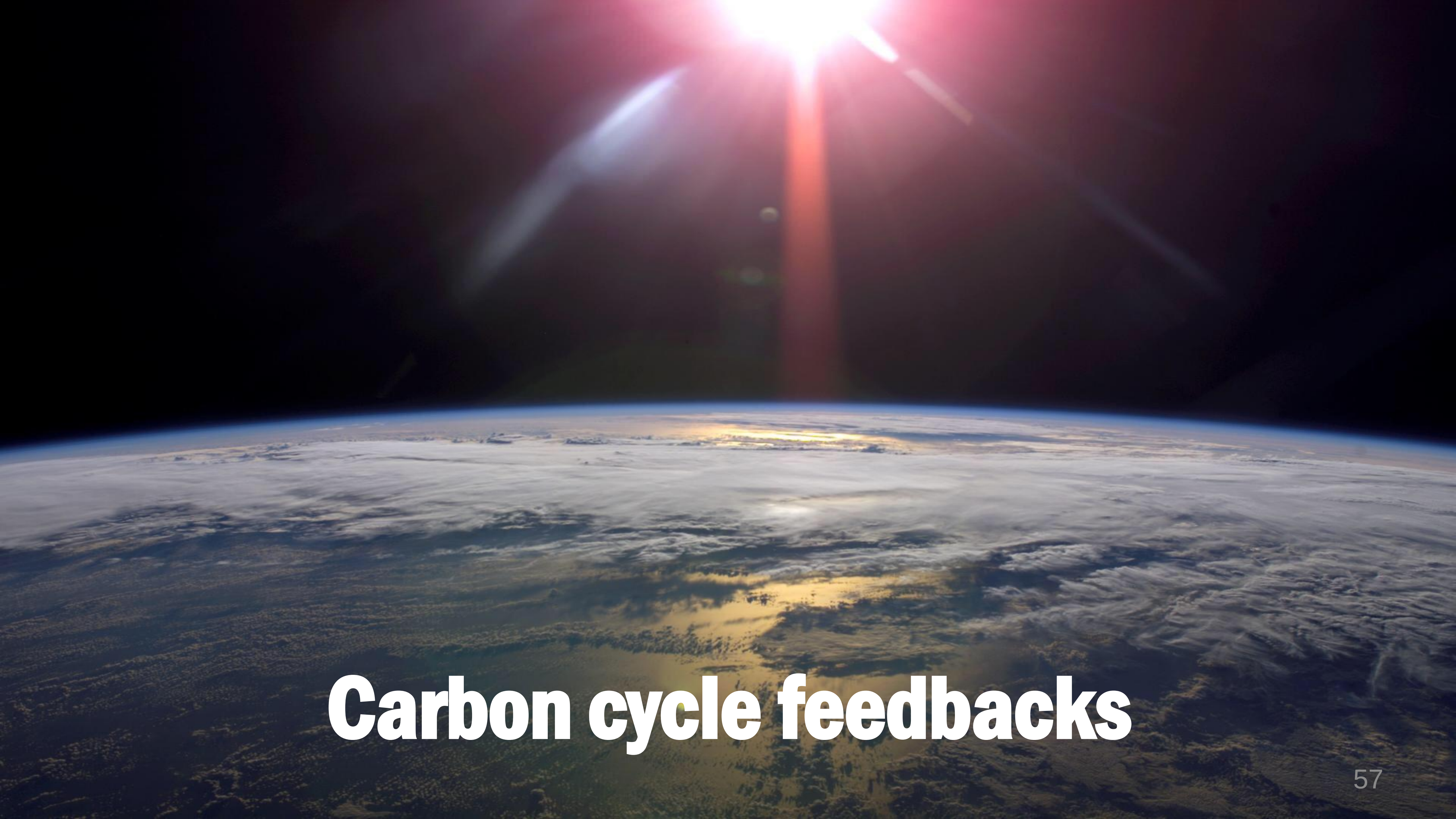


~7 years left | **~ 15 years left** | **~ 28 years left**



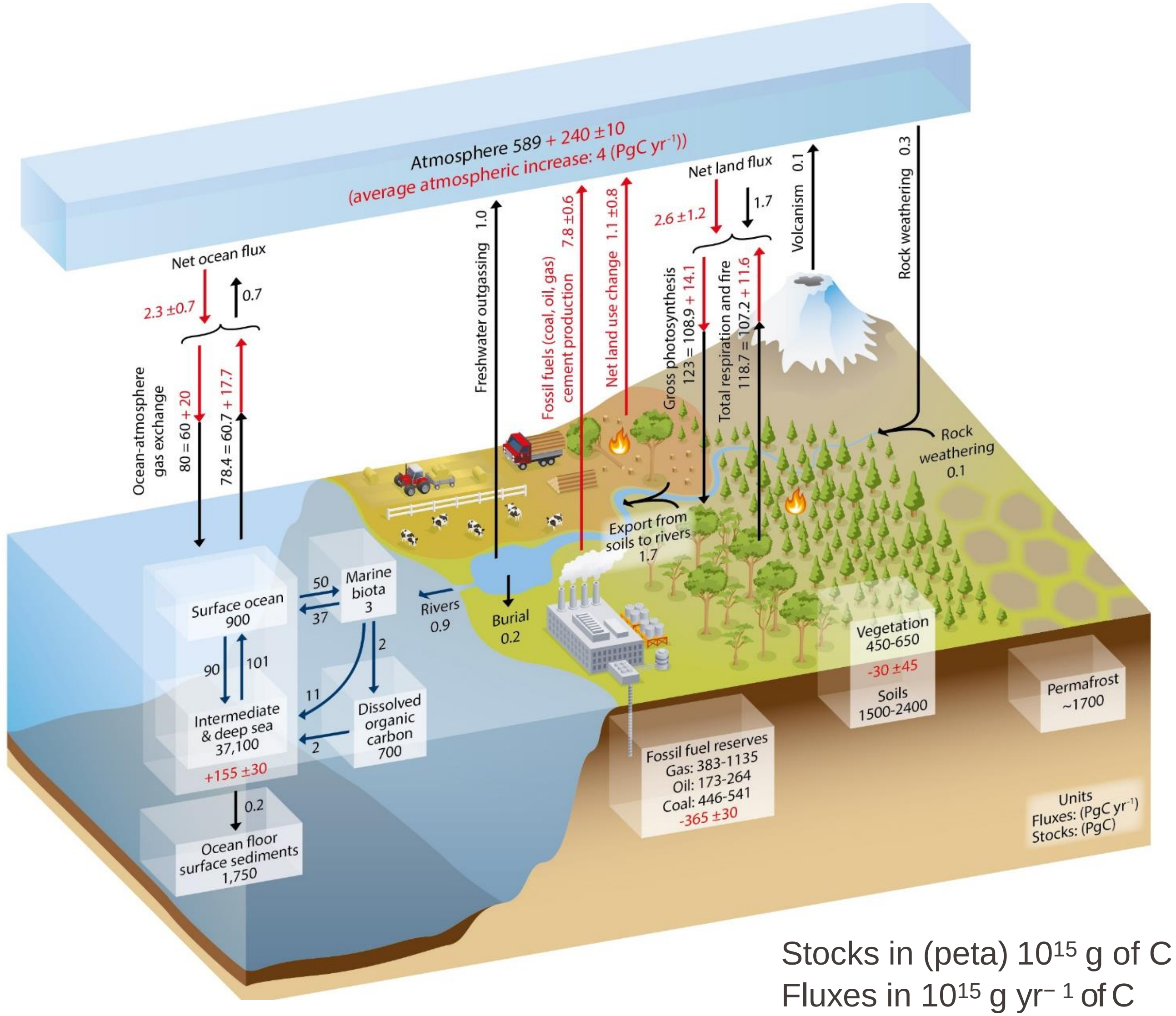
82%

Importance to get a sense of energy systems and potentialities, through Jonas' lectures !



Carbon cycle feedbacks

Carbon cycle : connecting climate system components



Stocks in (peta) 10^{15} g of C
Fluxes in 10^{15} g yr^{-1} of C

<u>Reservoirs</u>:

- Continental biosphere.
- Oceans.
- Cryosphere (permafrost).
- Atmosphere.
- Lithosphere (tectonics, volcanism).
- Anthroposphere (fossil fuel, land use).

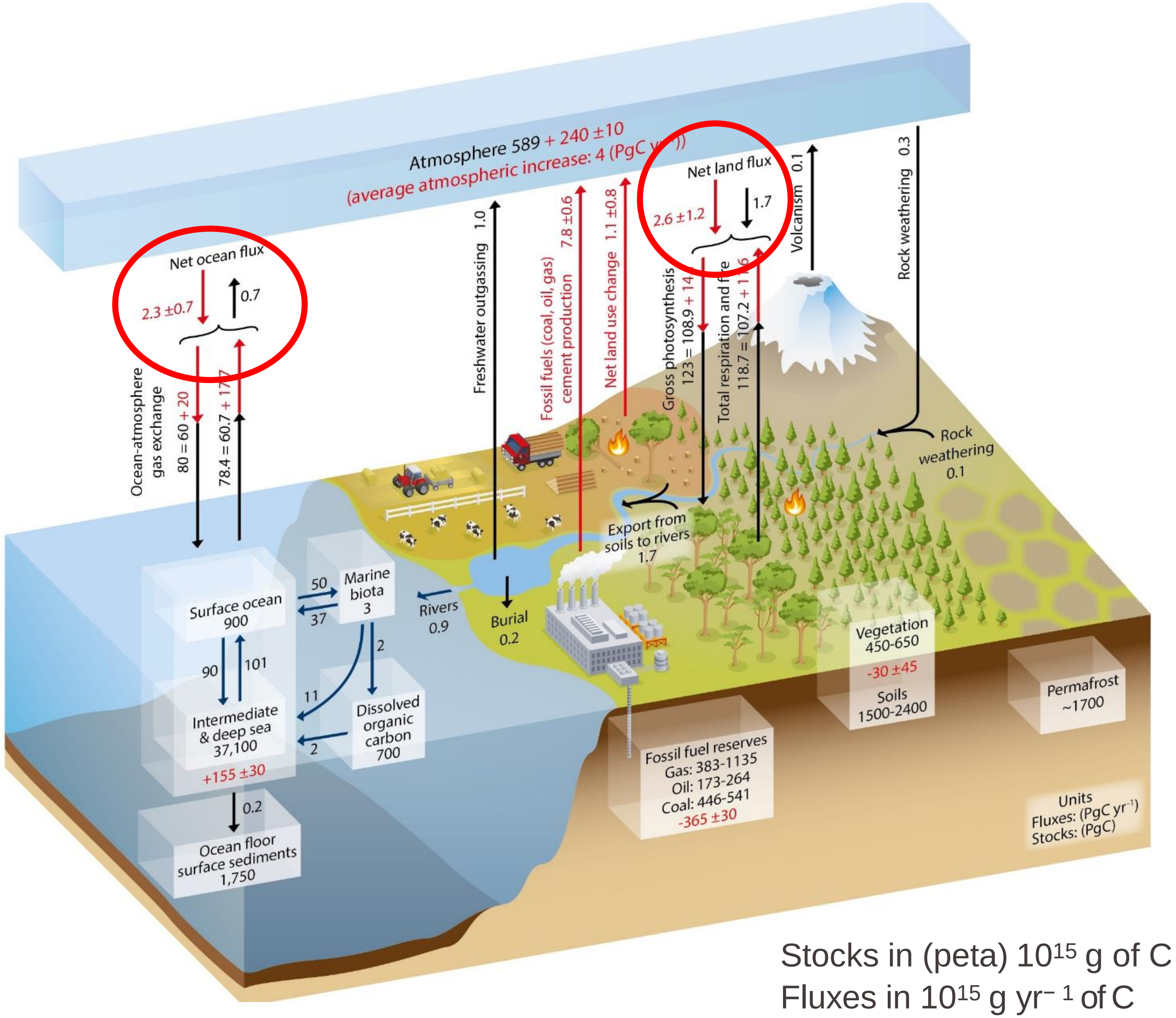
<u>Fluxes and time scales</u>:

- Yearly driven by photosynthesis and respiration.
- Decadal-centennial time scales by anthropogenic impact and climate variability.
- Millenial to millionary time scales by orbital forcing.
- Multi-millionary time scales by tectonics and volcanism.

Black: natural stocks and annual fluxes.
Red: annual anthropogenic fluxes (2000-2009).

- Source: *NOAA PMEL Carbon Program*

CO_2 cycle: Sources and sinks



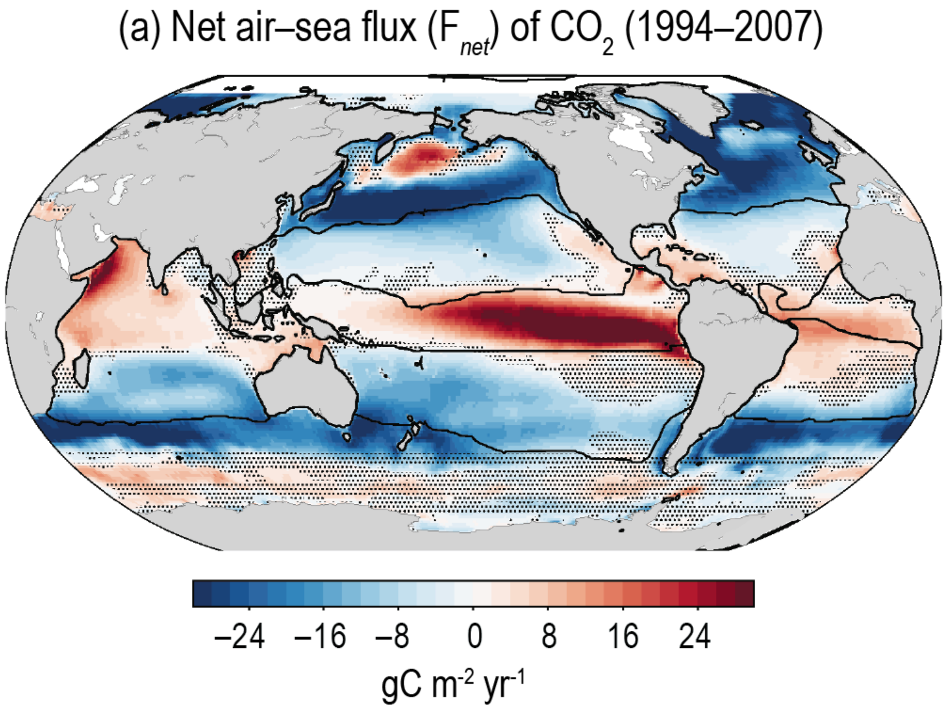
Stocks in (peta) 10^{15} g of C
Fluxes in 10^{15} g yr^{-1} of C

- **In 2024**, total anthropogenic CO_2 emissions were **~41.6 Gt**.
- Through photosynthesis and regrowth of vegetation, the terrestrial biosphere has absorbed 11.5 Gt CO_2.
- By diffusion of CO_2 into surface waters and mixing toward the deep ocean, the oceans have absorbed 10.5 Gt CO_2.
- **~53% of anthropogenic CO_2 is absorbed by natural sinks (land and oceans).**

Black: natural stocks and annual fluxes.
Red: annual anthropogenic fluxes (2000-2009).

- Source: *NOAA PMEL Carbon Program*

The ocean CO_2 sink



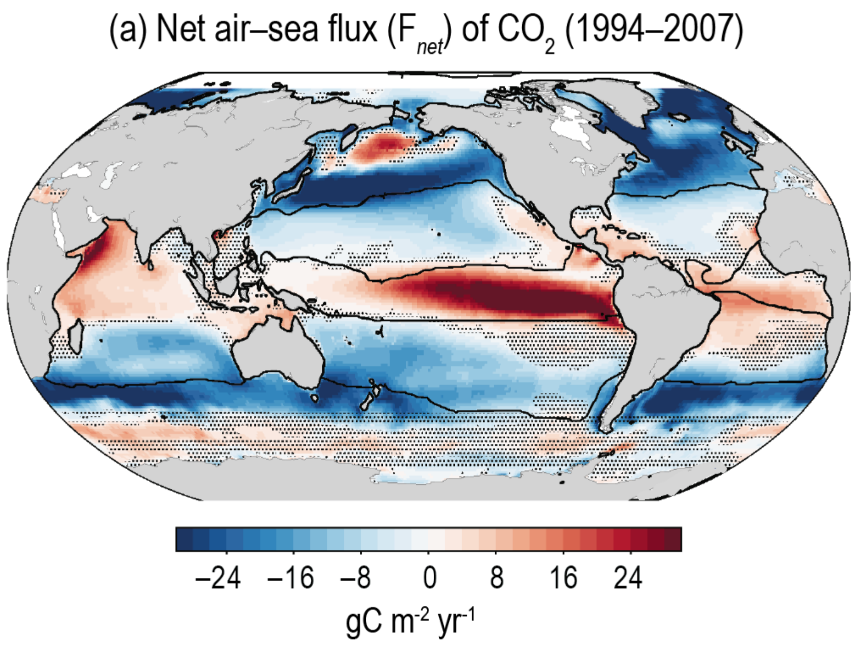
Source: [IPCC AR6 WG1 Chapter 5 Fig. 5.9]

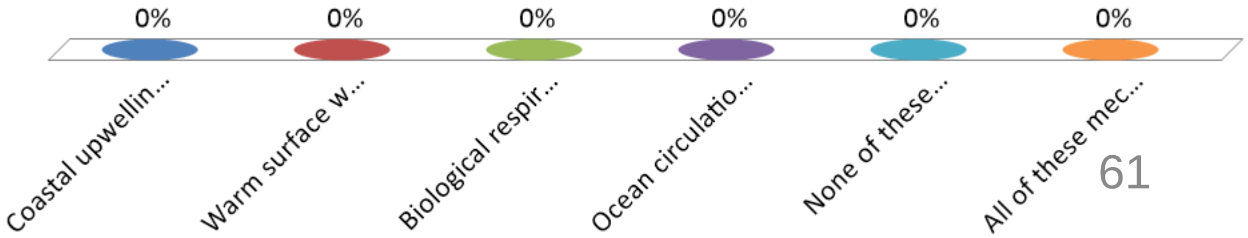
Blue: CO_2 uptake. Red: CO_2 release.

- The Southern Ocean and the North Atlantic are major CO_2 sinks (low surface temperature and ocean circulation effects).
- The equatorial Pacific and northwest Indian oceans are strong CO_2 outgassing areas.

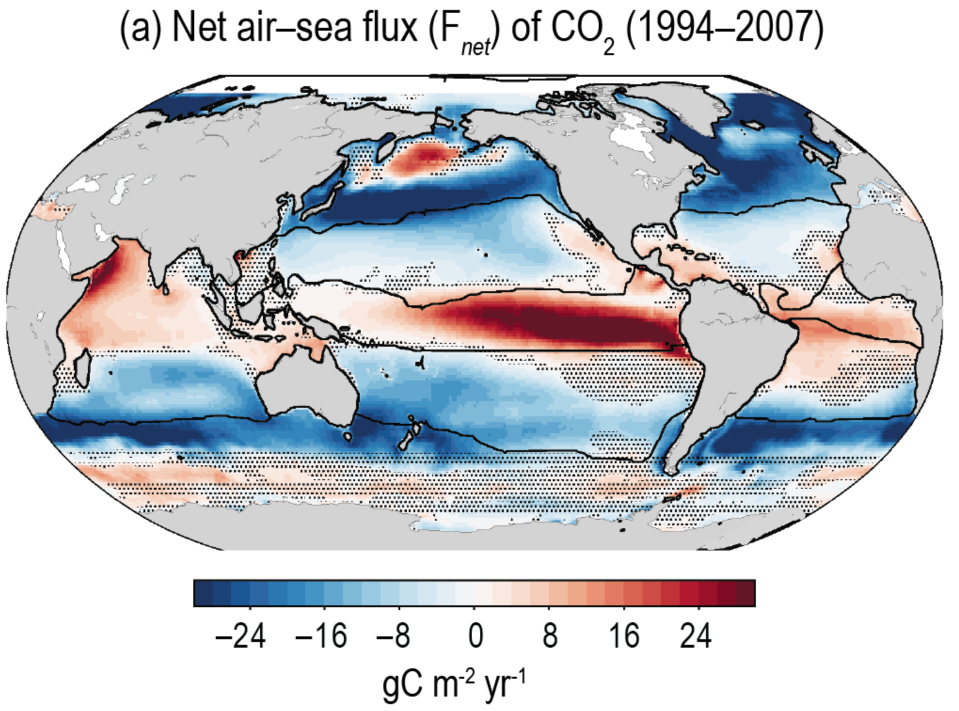
What explains the red patches on the map ?

A. Coastal upwelling brings carbon-rich water to the surface, which releases CO_2.
B. Warm surface waters near the equator hold more CO_2, increasing outgassing.
C. Biological respiration at the surface contributes to CO_2 loss.
D. Ocean circulation in the equatorial Pacific leads to persistent outgassing.
E. None of these mechanisms.
F. All of these mechanisms.

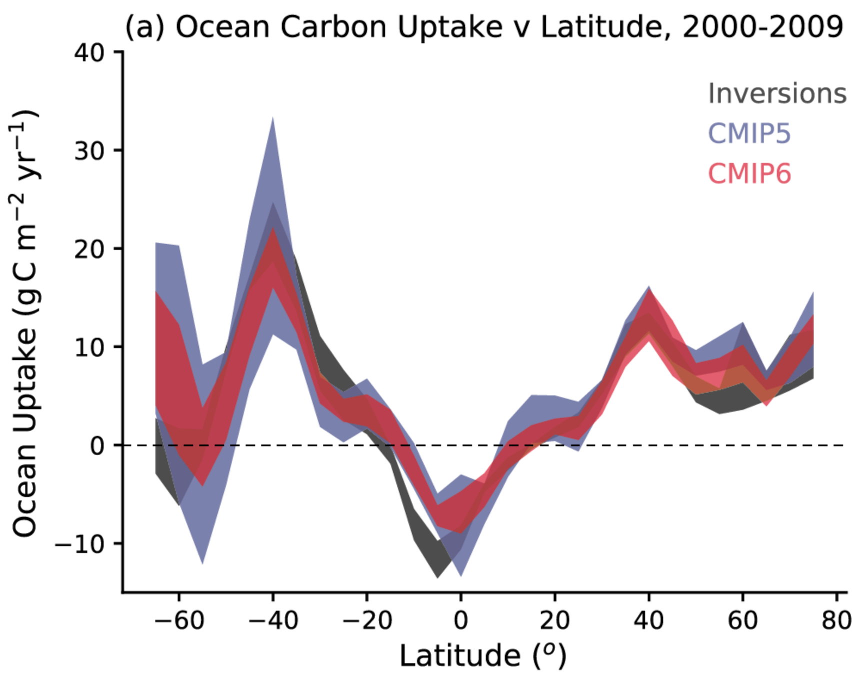




The ocean CO_2 sink



Source: *[IPCC AR6 WG1 Chapter 5 Fig. 5.9]*



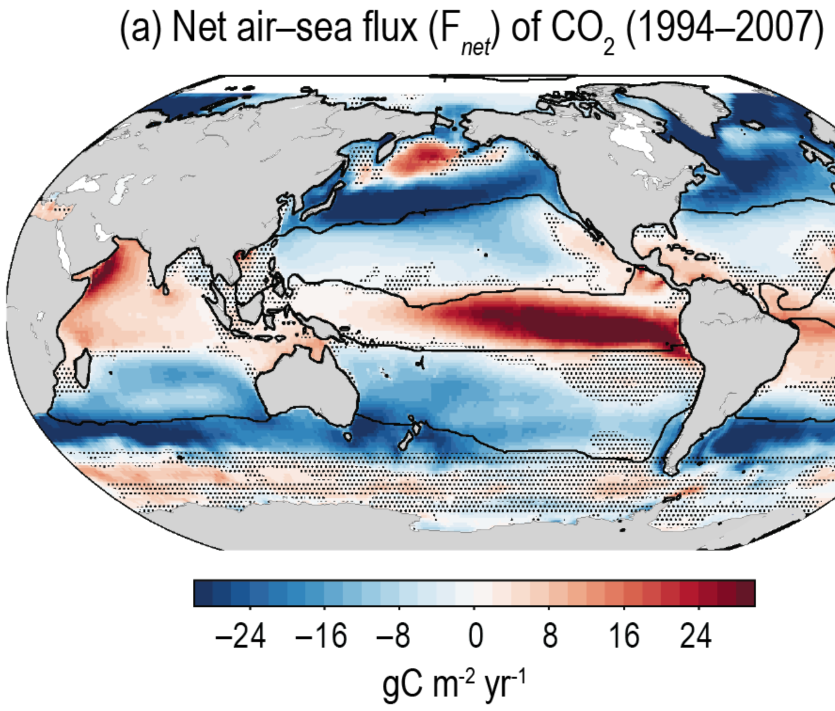
Source: *[IPCC AR6 WG1 Chapter 5 Fig. 5.24]*

Blue: CO_2 uptake. Red: CO_2 release.

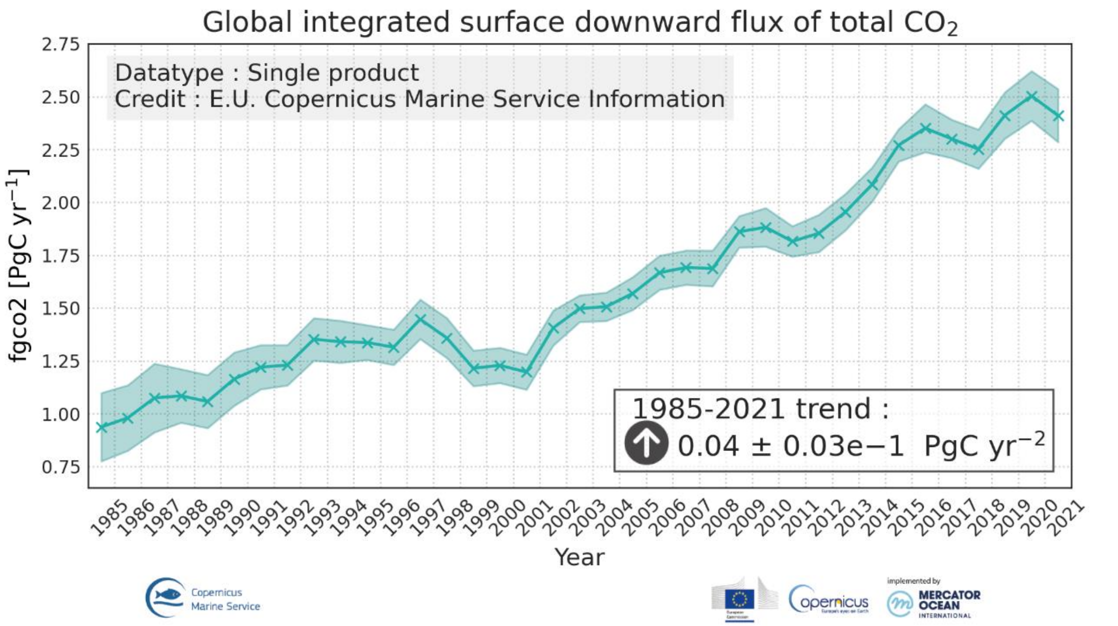
- The Southern Ocean and the North Atlantic are major CO_2 sinks (low surface temperature and ocean circulation effects).
- The equatorial Pacific and northwest Indian oceans are strong CO_2 outgassing areas

- Good fit between simulations and inversions of observations.
- The latitudinal distribution of the ocean carbon uptake shows the importance of the Southern and North Atlantic oceans.
- Deep around 55°S reflects upwelling areas of deep, carbon-rich waters and areas of low biological productivity (iron limitation).

The ocean CO_2 sink



Source: [IPCC AR6 WG1 Chapter 5 Fig. 5.9]



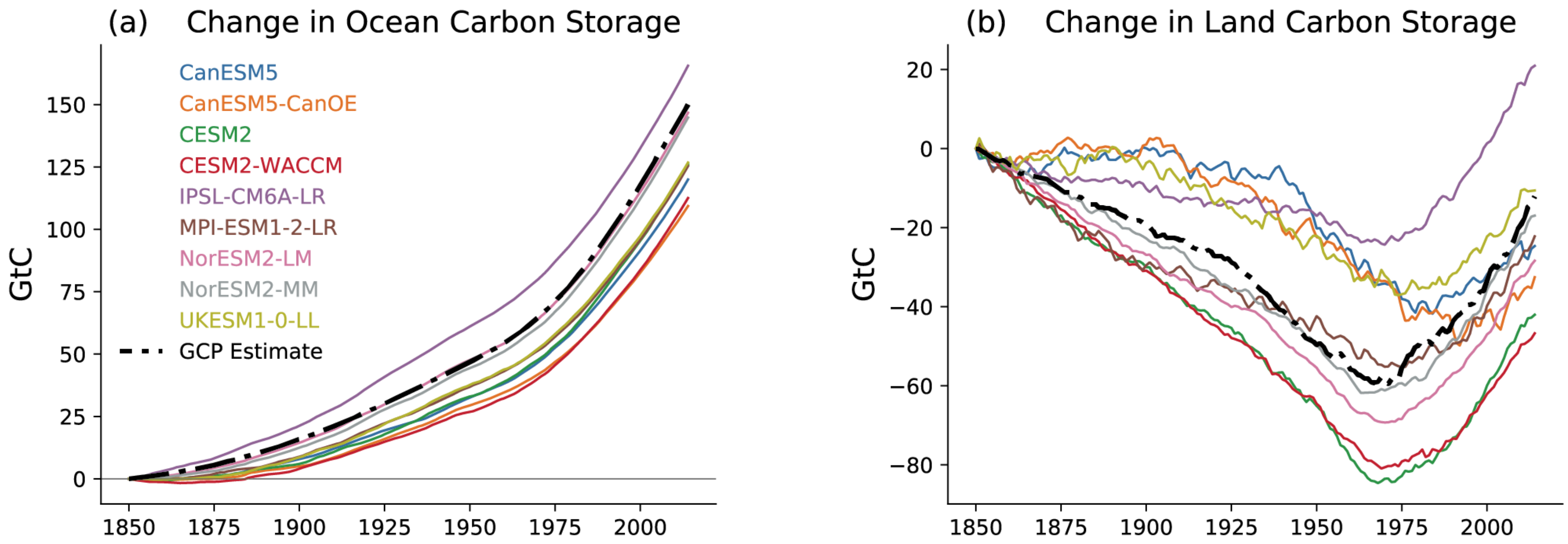
Source: [Copernicus Marine Service]

Blue: CO_2 uptake. Red: CO_2 release.

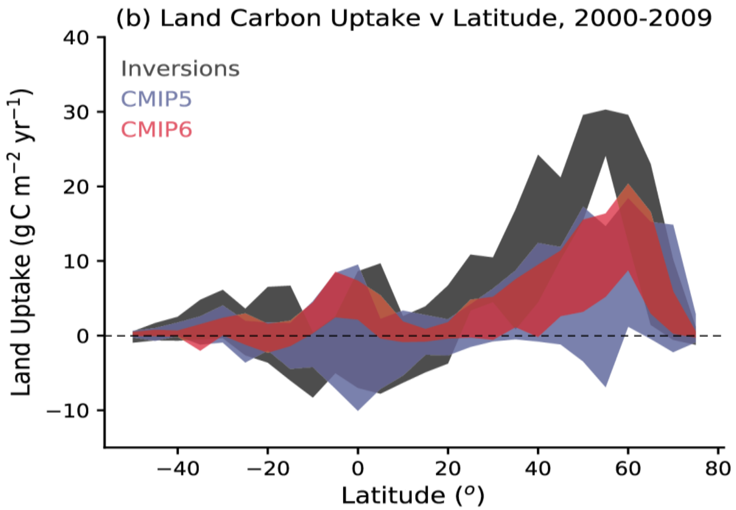
- The Southern Ocean and the North Atlantic are major CO_2 sinks (low surface temperature and ocean circulation effects).
- The equatorial Pacific and northwest Indian oceans are strong CO_2 outgassing areas (high surface temperature and upwelling).
- The global oceans absorb increasing amounts of CO_2 with time, due to the dissolution effect.
- Interannual variability, in particular due to ENSO.

Evolution of ocean and land carbon storage since 1850

Source: IPCC AR6 WG1 Chapter 5 Fig. 5.23

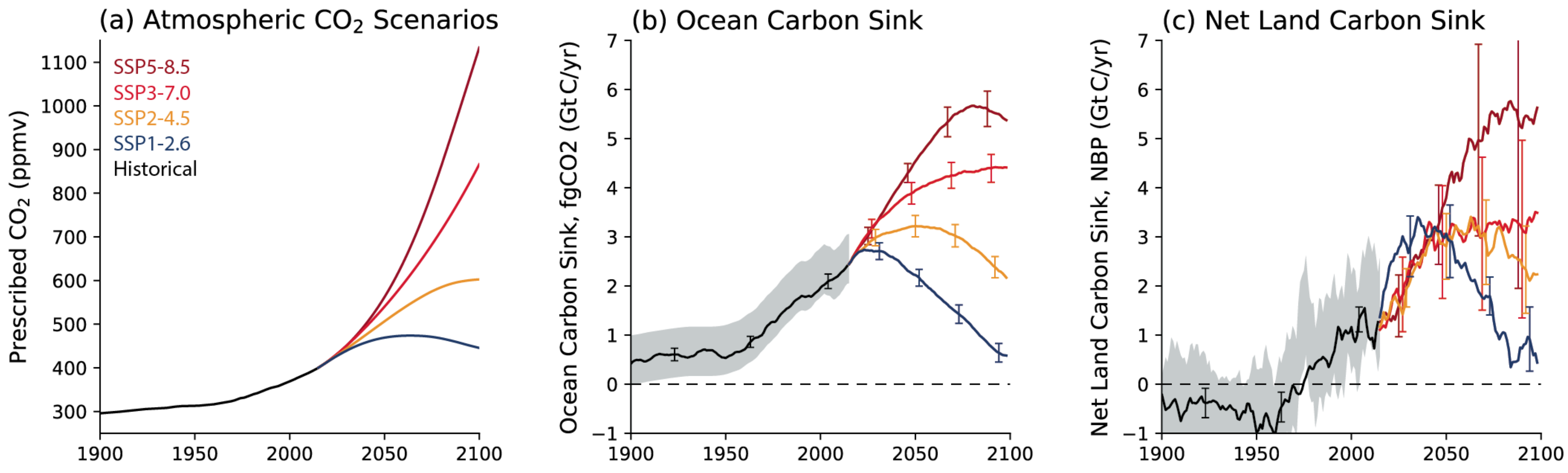


- The global oceans absorb increasing amounts of CO_2 with time, due to the dissolution effect. Follows the atmospheric CO_2 curve.
- On land: deforestation and land-use have dominated land carbon storage changes since 1850 (negative). Since ~1975, CO_2 fertilization starts to imprint the trend + reforestation / afforestation policies.
- Temperate and boreal forests are currently major carbon sinks. But climate models have still a large spread and they underestimate.

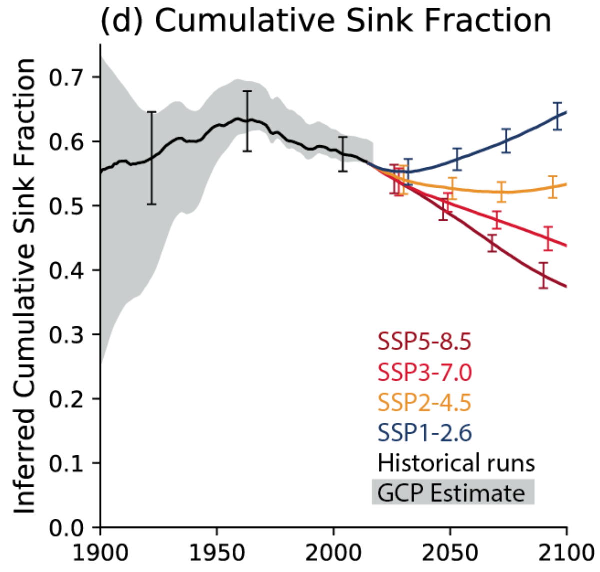


Source: IPCC AR6 WG1 Chapter 5 Fig. 5.24

Future evolution of ocean and land carbon storage



- Global ocean carbon sink levels off and declines in low CO_2 emission scenarios (atmospheric stabilization). Idem fo high-emission scenarios by end of century due to surface water saturation, lower solubilization and stratification.
- On land: decline of the carbon sink (low emissions) or leveling off (high emissions). CO_2 fertilization effect. But highly uncertain (droughts, fires, soil respiration,…).
- The cumulative sink fraction (53% today) would remain stable or even increase with low emission scenarios. It declines with high emission ones.

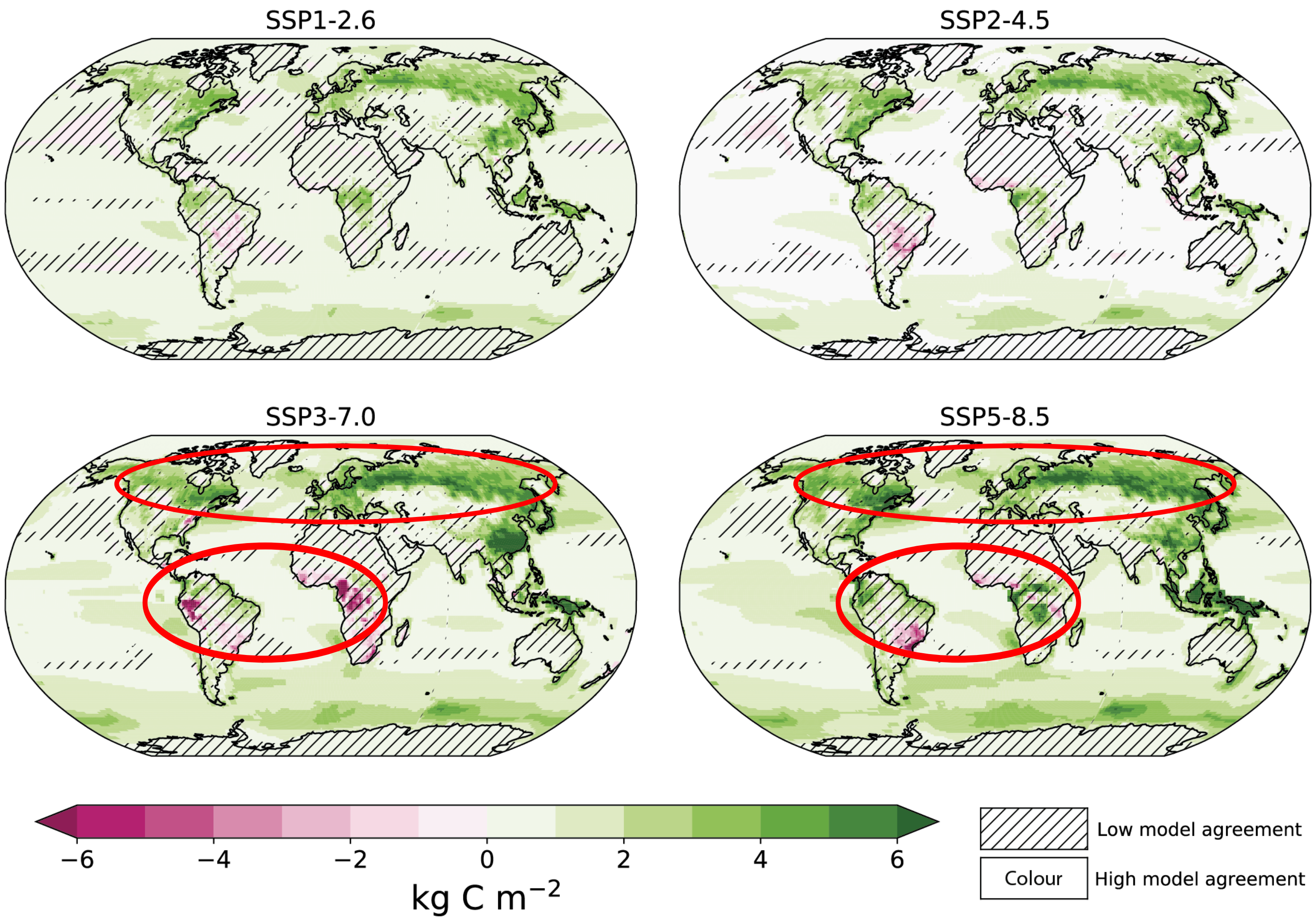


Source: *IPCC AR6 WG1 Chapter 5 Fig. 5.25*

Future evolution of land carbon storage

- Large uncertainties between models (hatched areas).
- High SSPs: heat stress, droughts, fires in tropical forests.
- CO_2 fertilization strongest in the Arctic. But could be limited by nutrient availability, heat and moisture stress.
- Land use pressure considered more important in the Tropics with SSP3.7 *(«regional rivalry»)*.
- Note the contrast between SSP3.7 and SSP8.5 in South America: it reflects different socio-economical assumptions: SSP3.7 = more deforestation. SSP8.5 = more urbanization / industrialization and thus less farming.

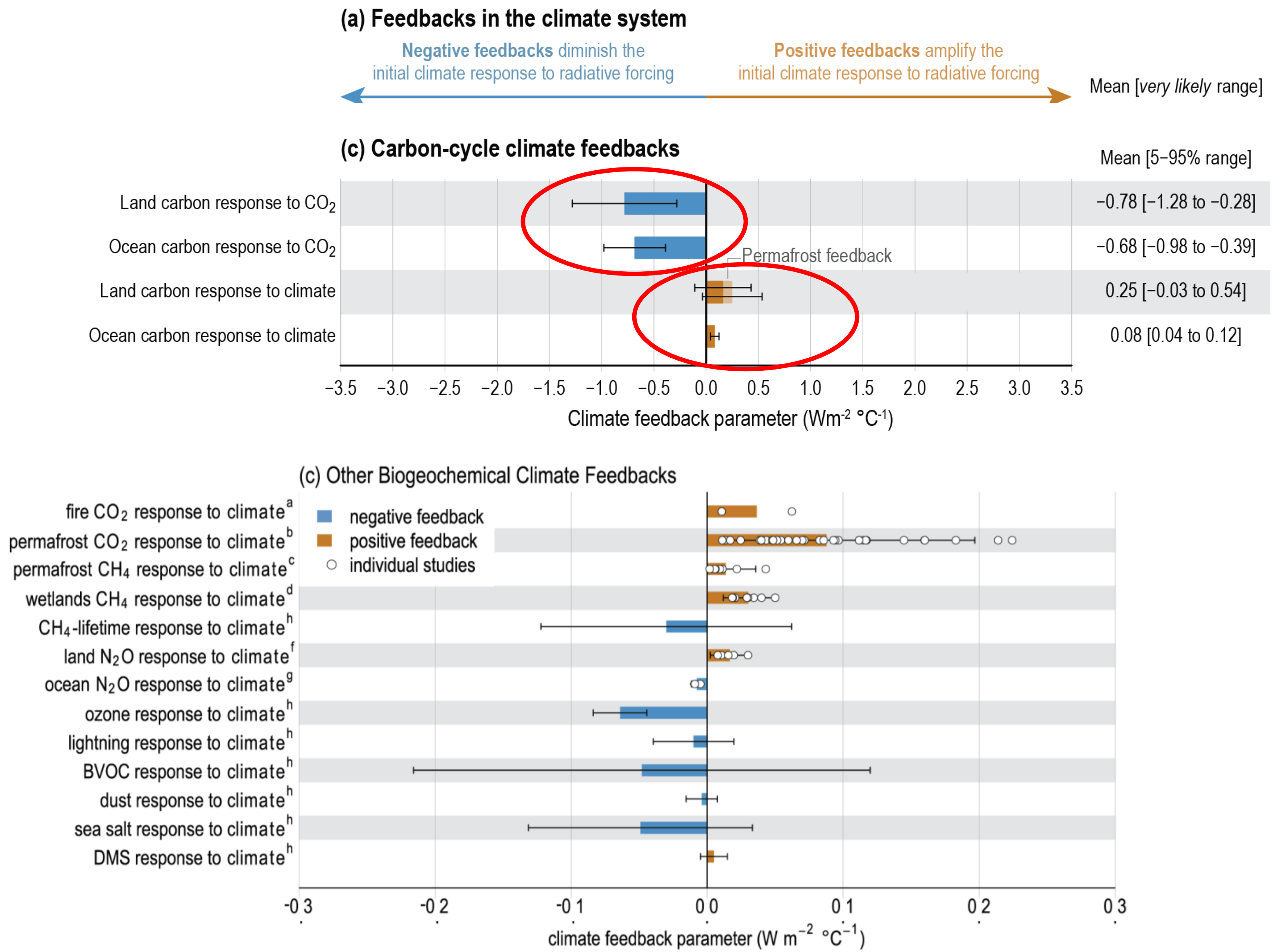
Change in carbon from 2015 to 2100 under SSP scenarios



Source: IPCC AR6 WG1 Chapter 5 Fig. 5.26

Future evolution of ocean and land carbon feedbacks

- Overall, oceans and land would still provide a negative feedback on CO_2 (dampening).
- However, oceans and land response to climate could lead to positive feedbacks (amplifying).
- Many other biogeochemical climate feedbacks to consider in the system (CH_4, N_2O, O_3, dust, sea salt,…).
- Want to learn more: please read [Chapter 5 of the IPCC AR5 report *«Global carbon and other biogeochemical cycles and feedbacks»*.]()



Source: *[IPCC AR6 WG1 Technical Summary Fig. 17]()*

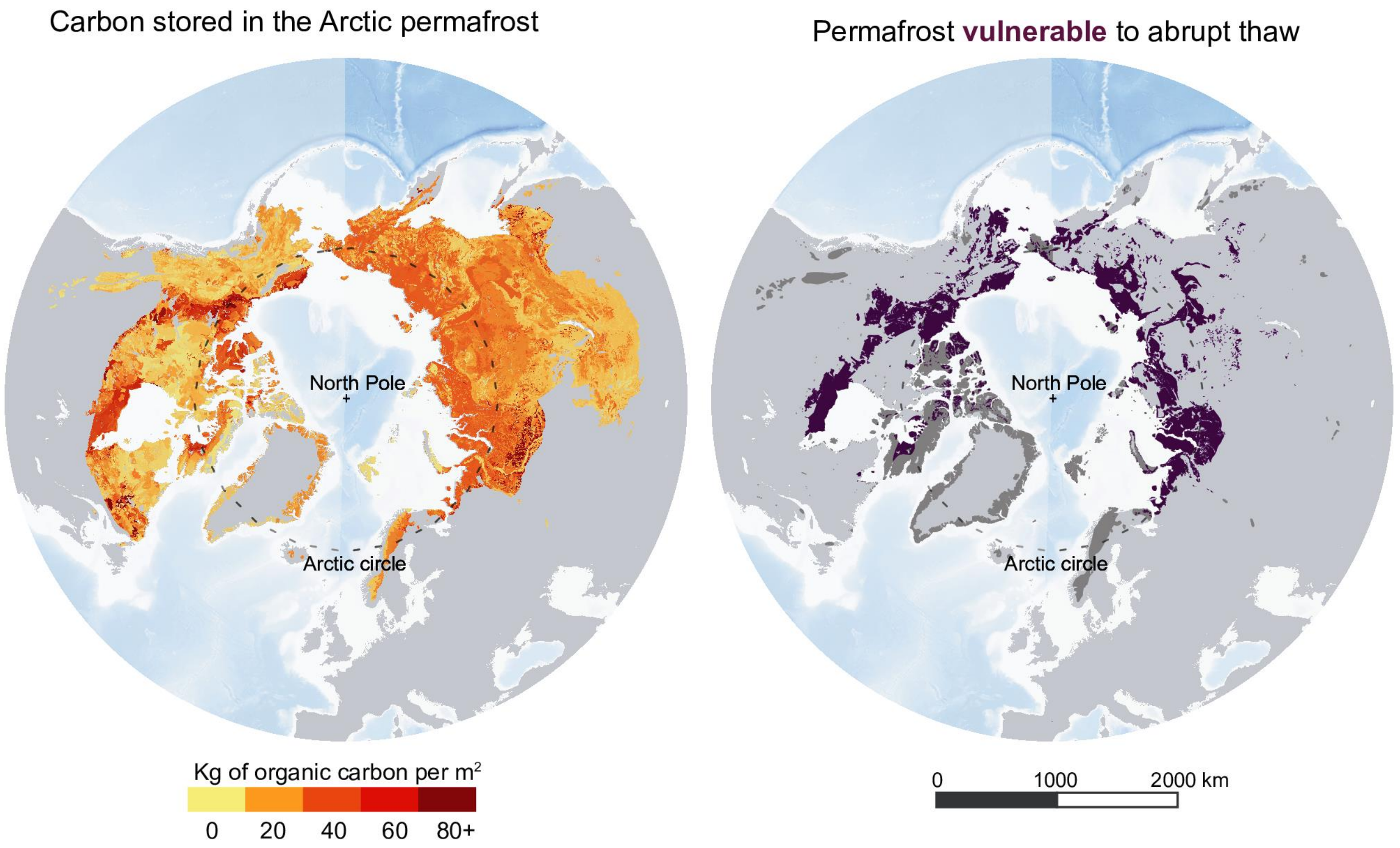
One of the «wild cards»: boreal permafrost

- Boreal permafrost contains twice as much carbon than the atmosphere (in the form of CO_2): ~1500 Gt of carbon.
- Its degradation is already observed today, amplified by boreal forest fires.
- Big uncertainties on the partitioning between CO_2 or CH_4 emissions from carbon degradation (depends on water saturation of soils).
- Even with SSP1-1.5, possibility that it brings ~100 GtC of extra carbon in the atmosphere, although slowly.

Source: Wikipedia

FAQ5.2: **Can thawing permafrost substantially increase global temperatures?**

The thawing of frozen ground in the Arcrtic will release carbon that will amplify global warming but this will not lead to runaway warming.



Carbon stored down to 3 m of depth

Source: IPCC AR6 WG1 Chapter 5 FAQ5.2.1

Summary: Climate variability, climate change scenarios, carbon cycle feedbacks

- **Modes of climate variability** are important to document and understand as they impact our societies and could evolve in a warmer future.
- **NAO and ENSO** are two important examples of atmospheric and atmosphere/ocean variability, with consequences at continental scales.
- The current warming leaves important imprint in the **cryosphere** (phase change…), but also on **extreme events**.
- **RCP and SSP scenarios** provide possible roadmaps for policymakers and societies. If we want to keep global warming under +1.5°C or event +2.0°C, the decarbonation trajectories require huge ambition… And **negative emissions !**
- Land and oceans help us limit the impact by sequestering carbon. But this may partly vanish under different warming scenarios.
- Large **uncertainties about carbon cycle feedbacks** through land and marine processes. A major topic of research today!