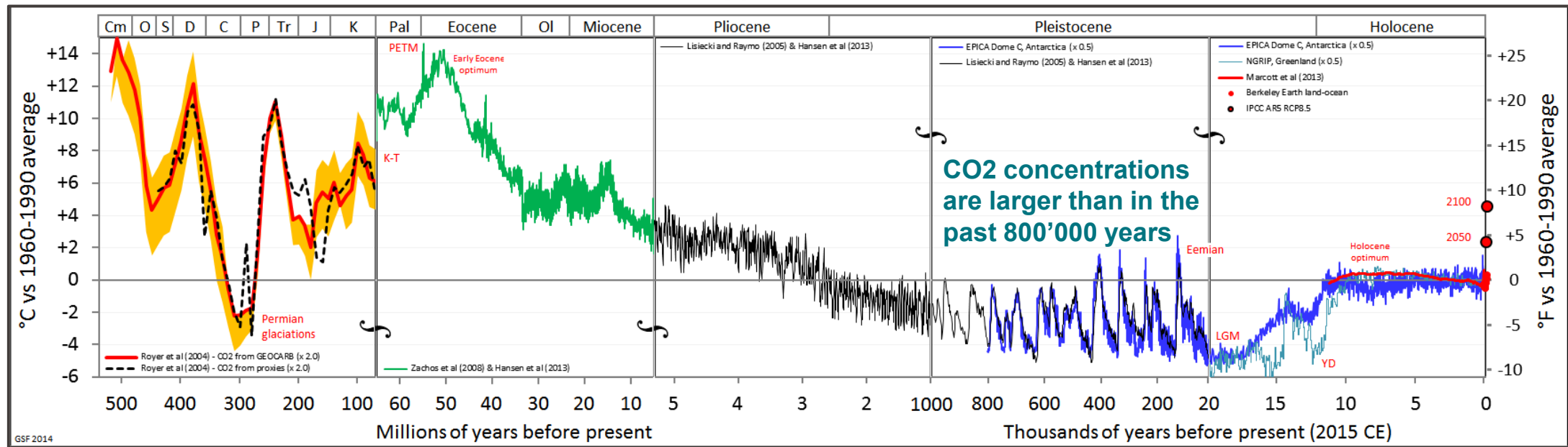
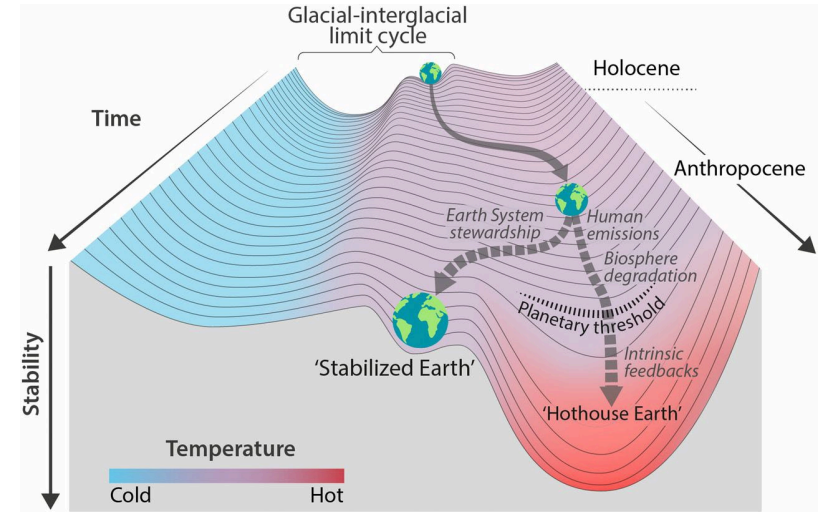
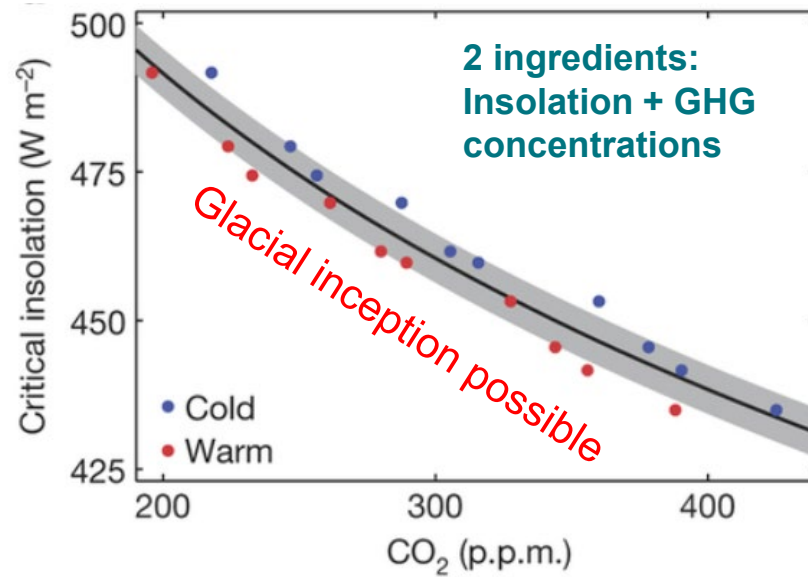
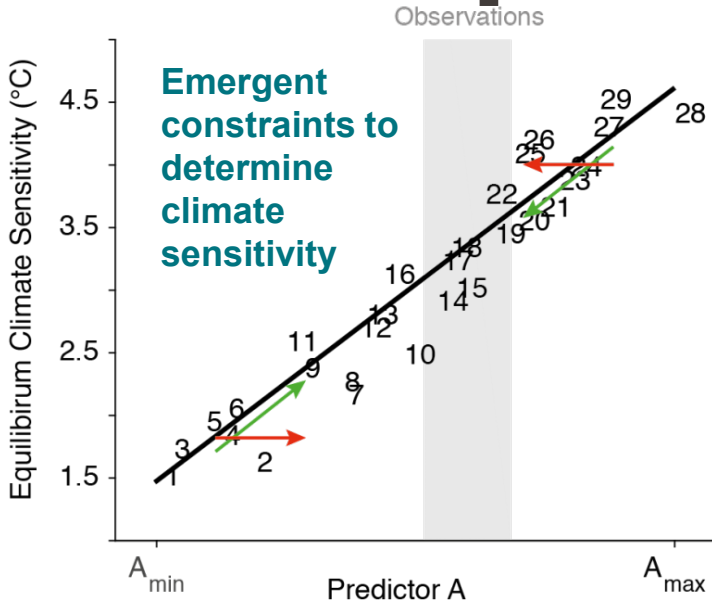


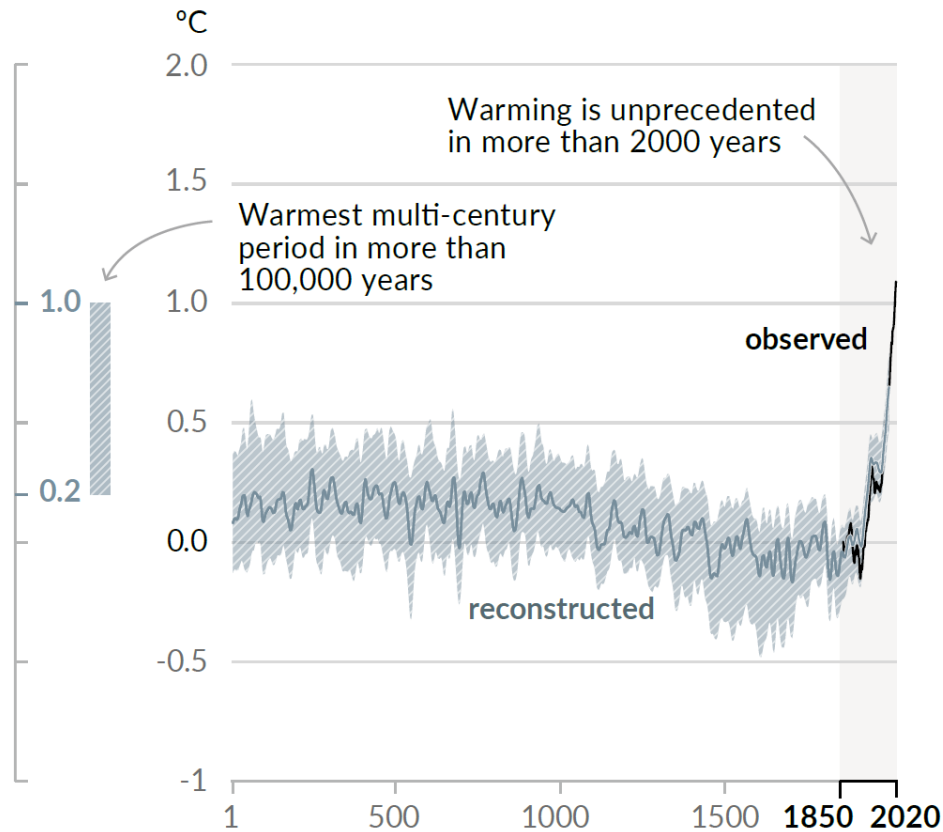
# Recap from last lecture



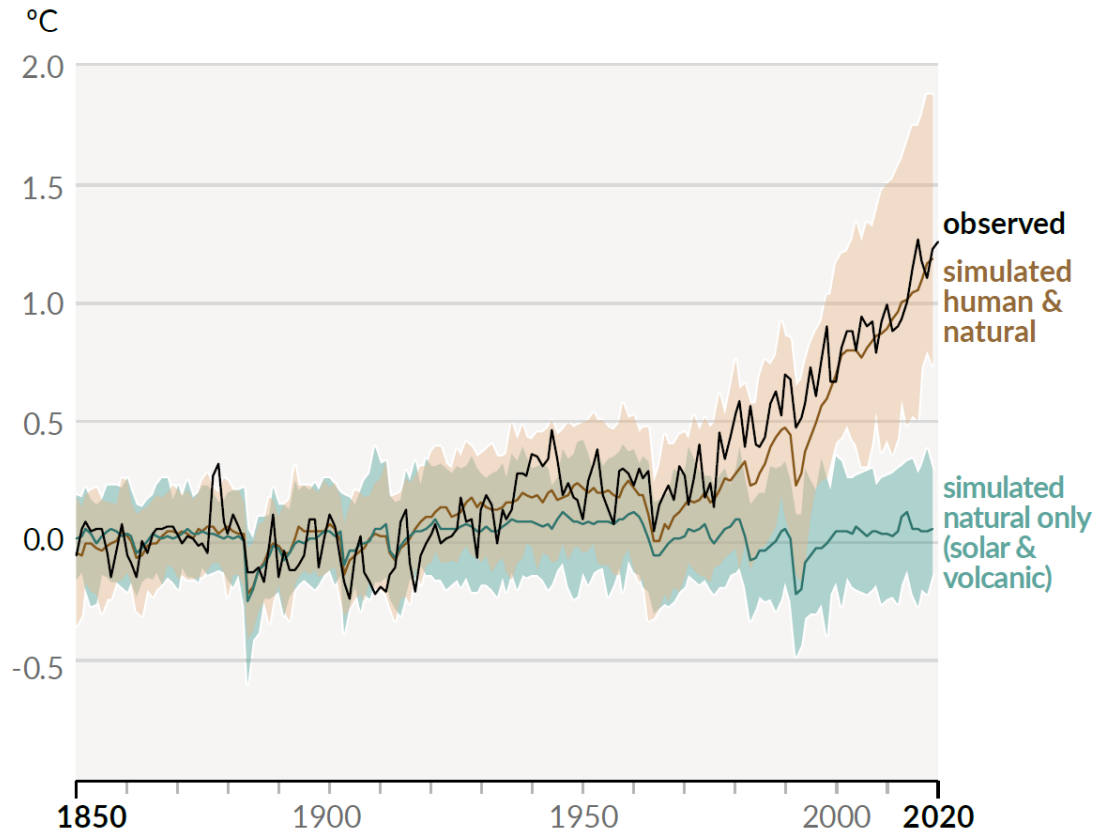
	No.	Date	Topics	Deadlines / tentative
Basics	1.	11.09.2025	Introduction to the climate system	Questionnaire (not graded)
	2.	18.09.2025	Climate System, Radiation	
	3.	25.09.2025	Radiation, Earth's Energy balance, Greenhouse effect	launch of first assignment
	4.	02.10.2025	Aerosols & clouds, Radiative Forcing	Launch of poster project
	5.	09.10.2025	Feedback mechanisms, Climate Sensitivity	
	6.	16.10.2025	Paleoclimate	submission of Poster proposal (graded)
Present and future Climate change	7.	30.10.2025	Climate variability, Introduction to IPCC	
	8.	06.11.2025	Paris Agreement, IPCC – report, Climate scenarios (RCPs, SSPs),	
	9.	13.11.2025	Tipping elements, 1.5 vs 2.0°C vs warmer, Emissions, Carbon budget, Emissions Gap	submission of Poster draft (graded)
	10.	20.11.2025	Carbon budget, Emissions Gap, Metrics	
	11.	27.11.2025	Metrics, Extreme Events	submission of assignment (graded)
Actions	12.	04.12.2025	Polar climate change	
	13.	11.12.2025	Mitigation measures	Poster Conference (graded)
	14.	18.12.2025	Climate engineering, questions and answers session	fill in Questionnaire in exercises (not graded)

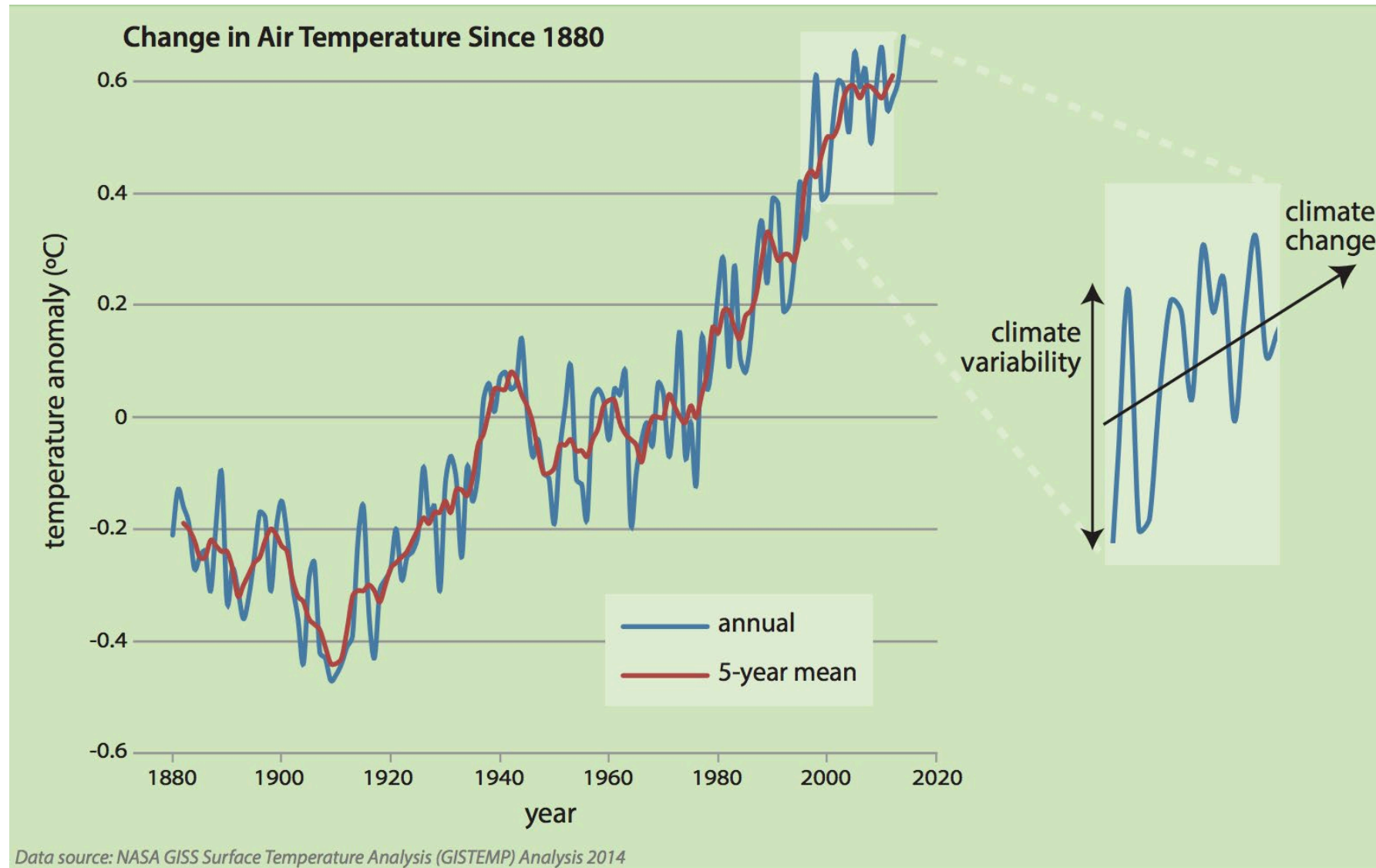
# Today's temperature change

a) Change in global surface temperature (decadal average) as **reconstructed** (1-2000) and **observed** (1850-2020)



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





- <https://scied.ucar.edu/learning-zone/how-climate-works/climate-variability>

# Natural Climate Variability – Why do we care?

- Climate change since the preindustrial time is a combination of long-term anthropogenic change and natural variations.
- The relative importance (anthropogenic vs natural) depends on the climate variable (e.g., temperature, precipitation) and location (e.g., Arctic, Europe). Natural variations tend to have stronger impact on more local or regional and short-term changes.
- Climate models need to be able to represent natural climate variability in order to distinguish the anthropogenic signal.

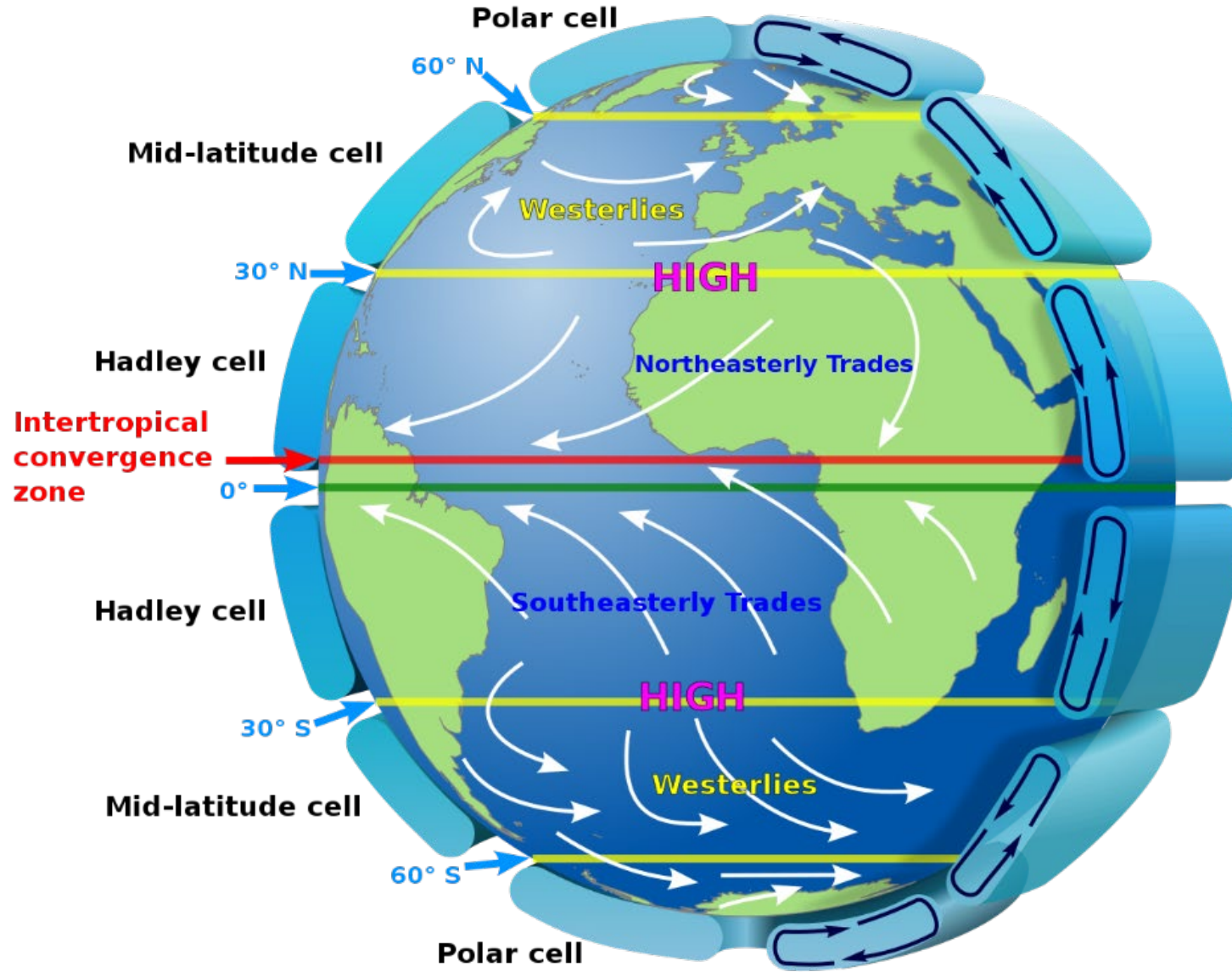
# Natural Climate Variability

- External forcing
  - Solar forcing: day / night, seasons → periodic
  - Astronomical forcing: position of Earth relative to the sun → periodic
  - Volcanic eruptions → aperiodic/random
  
- Internal (intrinsic) variability
  - Recurring modes (this lecture)

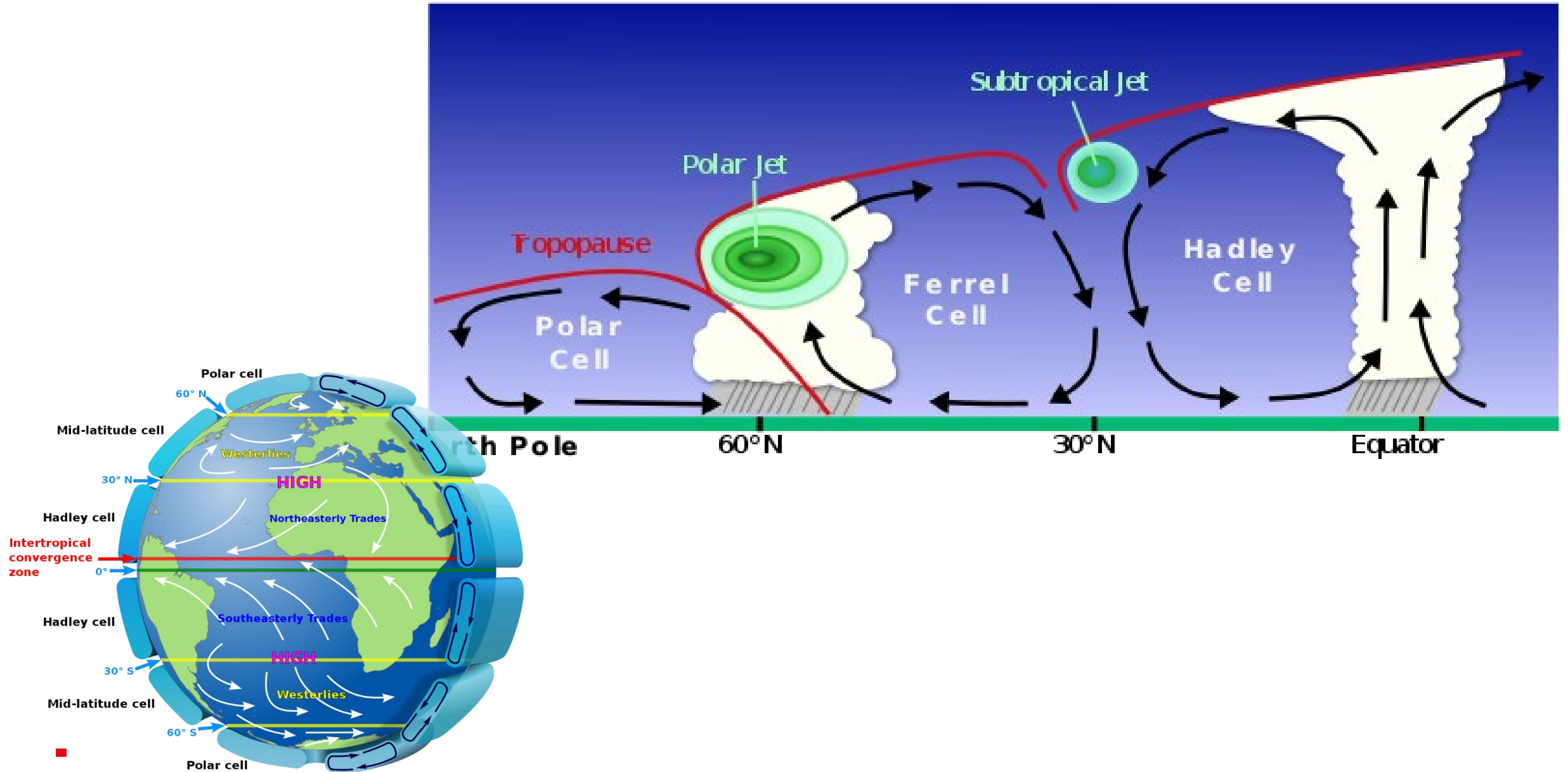
# Natural Climate Variability

- Modes of **climate variability** are defined as **recurrent space-time structures** of variability of the climate system with intrinsic **spatial patterns, seasonality** and **timescales**.
- They can arise through the dynamical characteristics of the **atmospheric circulation** but also through **coupling between the ocean and the atmosphere**.
- The variability of the climate system at ocean- or continental-basin scales, and in particular on **seasonal-to-multidecadal timescales**, can be described to a large extent by the **occurrence and often combination of several modes of climate variability** which lead to local impacts and remote responses through teleconnection processes on top of externally forced trends.
- The concept of “**teleconnection**” refers to the ability of modes of variability to relate climate in **remote regions** through **associated atmospheric or oceanic pathways**.

# Global circulation patterns

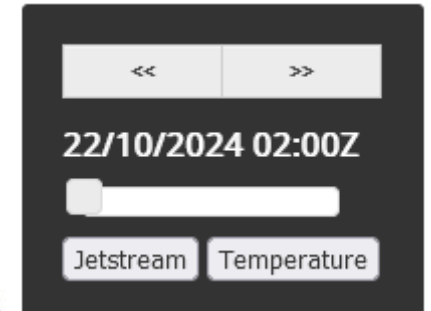
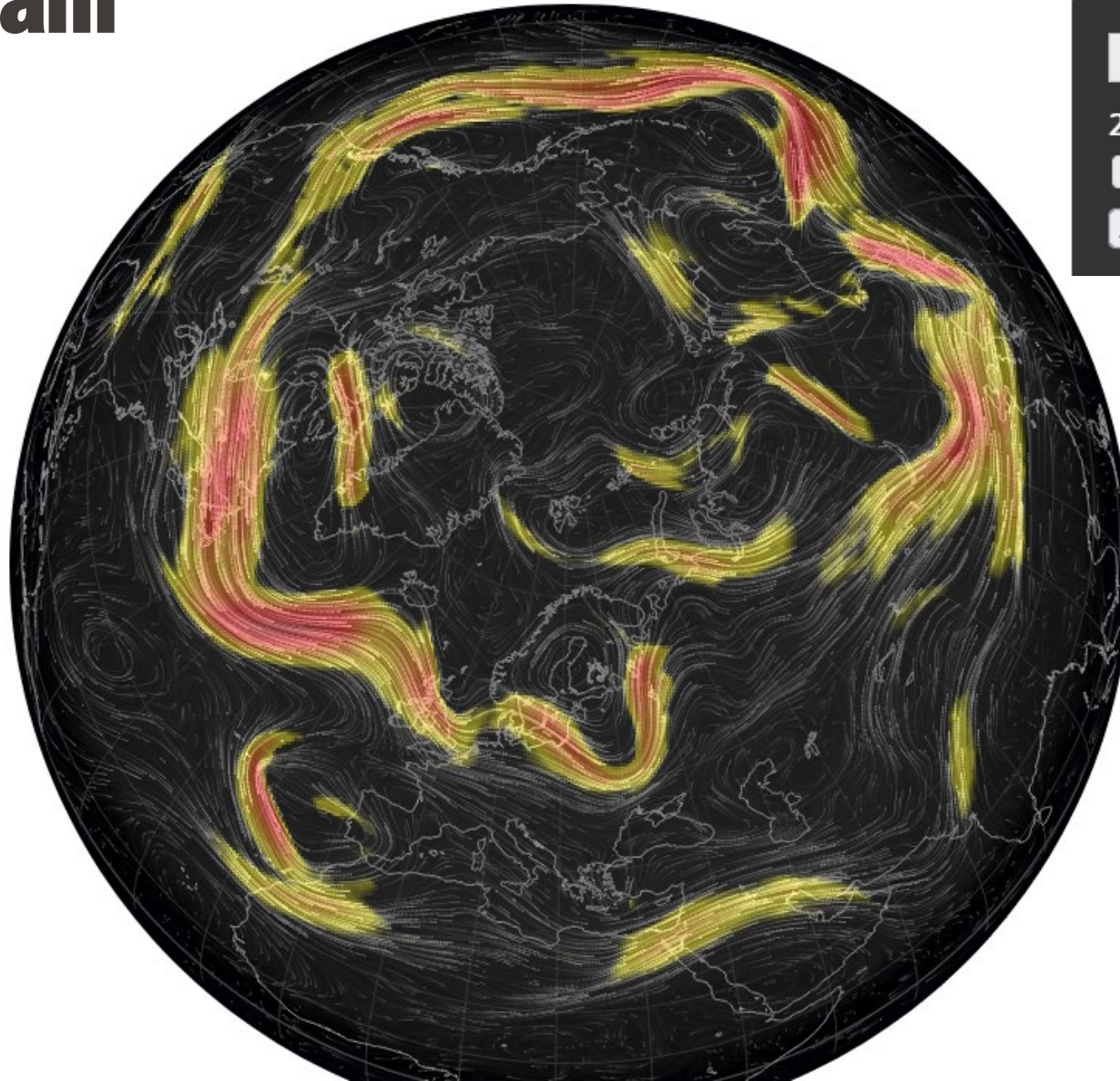


# Global circulation patterns



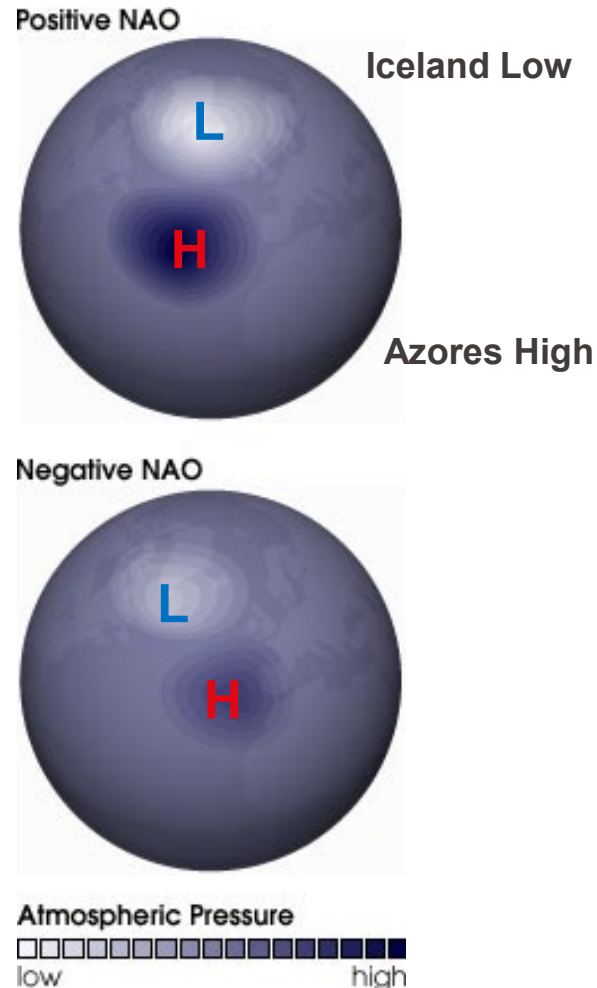
# Polar jetstream

- Cold air to the north, warm air to the south
- Low pressure systems to the north, high pressure systems to the south
- Winds up to several hundred km/h
- Important for weather in the northern hemisphere



■ <https://www.netweather.tv/charts-and-data/global-jetstream#current/wind/surface/level/orthographic=-338.50,73.33,234>

# North Atlantic Oscillation (NAO)

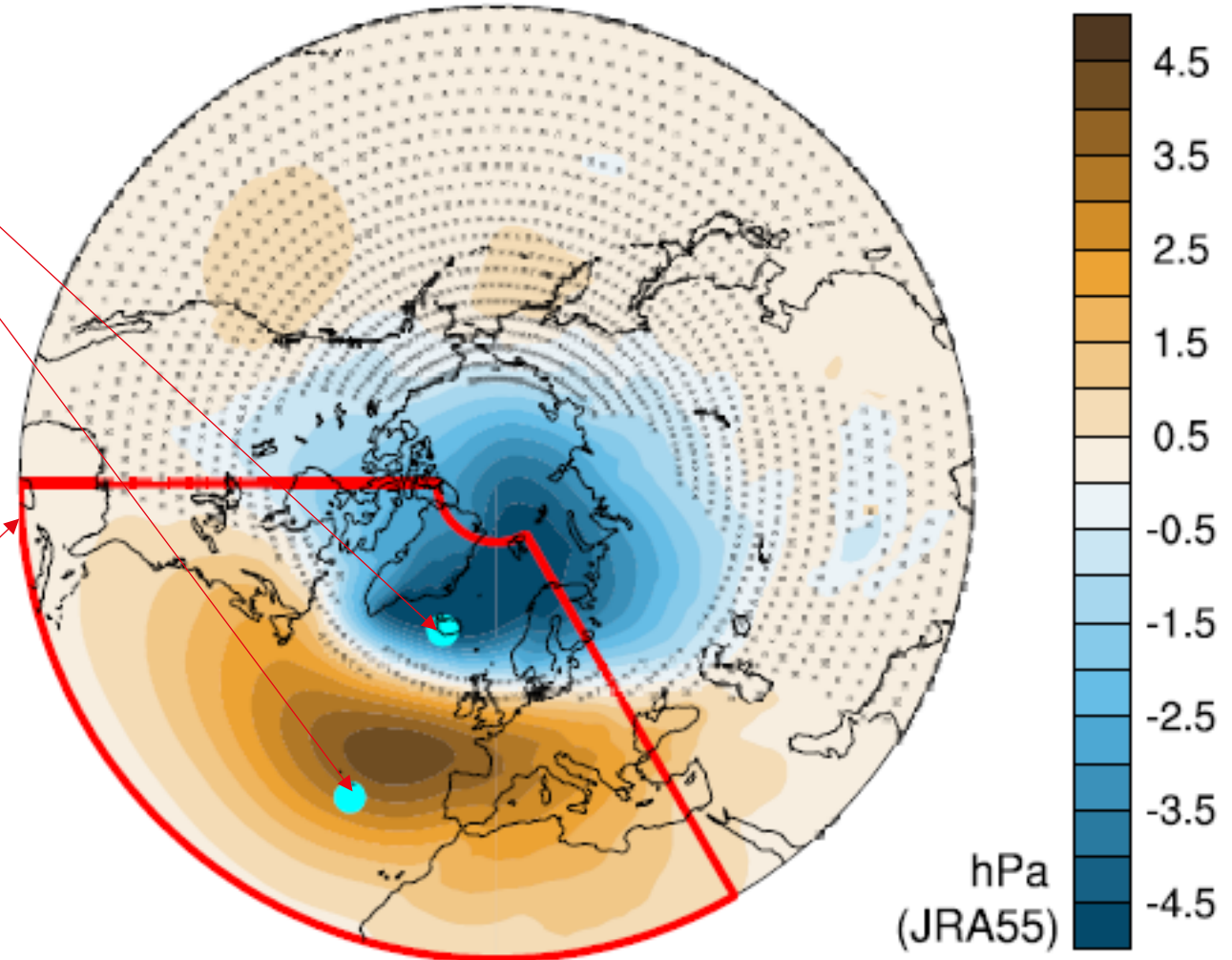


- Oscillation between pressure states of the Icelandic Low and Azores High. **Atmospheric variability.**
- **Positive** mode: **strong** high and **strong** low
- **Negative** mode: **slackened** high and **slackened** low
- The NAO is the main mode of climate variability over a broad North Atlantic-Europe region in all seasons for **intra-seasonal to multidecadal timescales**
- Influences the **weather** over Europe and North America: temperature, precipitation, wind
- Controls **extremes** over Europe and Eastern North America: cold waves, very strong wind episodes related to explosive storminess, heavy precipitation events...

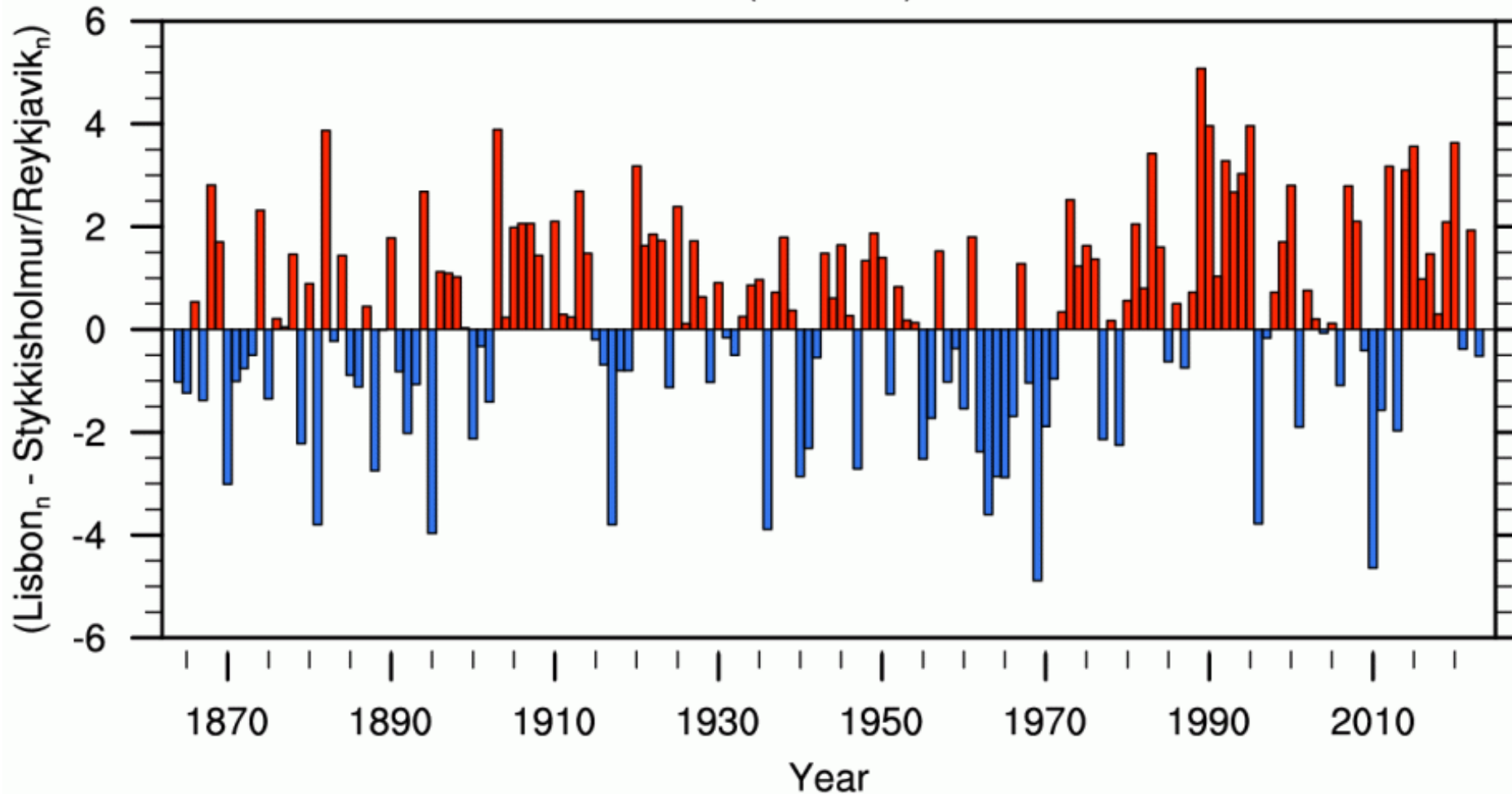
These two observatories on Iceland and the Azores are often used to calculate the **weather station-based NAO index**: i.e. the difference of the normalized sea level pressures (SLP) anomalies at the Azores minus those on Iceland

Caveat: does not capture the latitudinal spread.  
 → Calculate the index from the normalized average across longitudes at 35 °N and 65°N (zonal average).

a. MSLP spatial pattern for NAO in Dec-Feb (DJF)



### NAO Index (Dec-Mar) 1864-2023



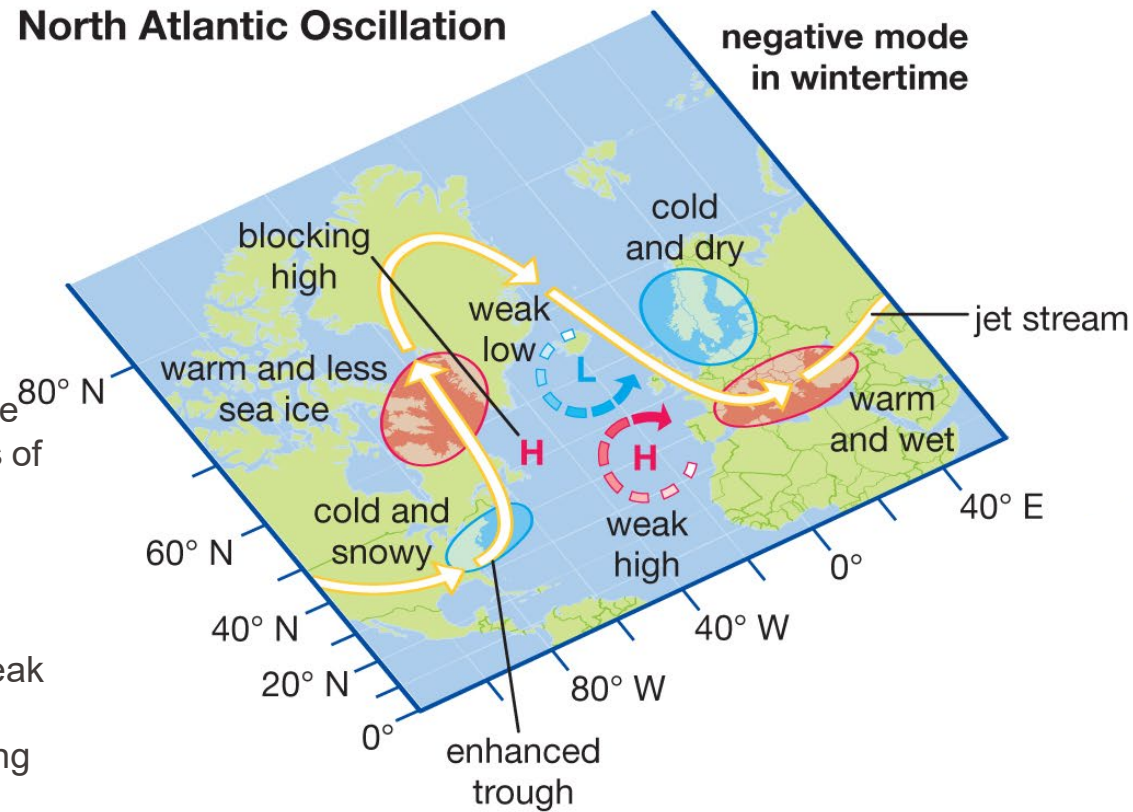
Winter (December through March) index of the NAO based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland since 1864.

The SLP values at each station were normalized by removing the long-term mean and by dividing by the long-term standard deviation. Both the long-term means and standard deviations are based on the period 1864-1983.

Normalization is used to avoid the series being dominated by the greater variability of the northern station.

## Negative mode:

During winters governed by the negative mode of the NAO, colder conditions are brought to eastern North America and northern Europe mainly by more-frequent intrusions of Arctic air. North America receives additional snow, while Europe receives less precipitation than normal. The drier conditions over northern Europe result from the weak state of the pressure cells over Iceland and the North Atlantic during the NAO's negative mode; the reduced pressure gradient over the region slows the pace of westerly winds, which allows cold, dry air to be drawn into northern Europe from northern Russia and the Arctic.



## Positive mode:

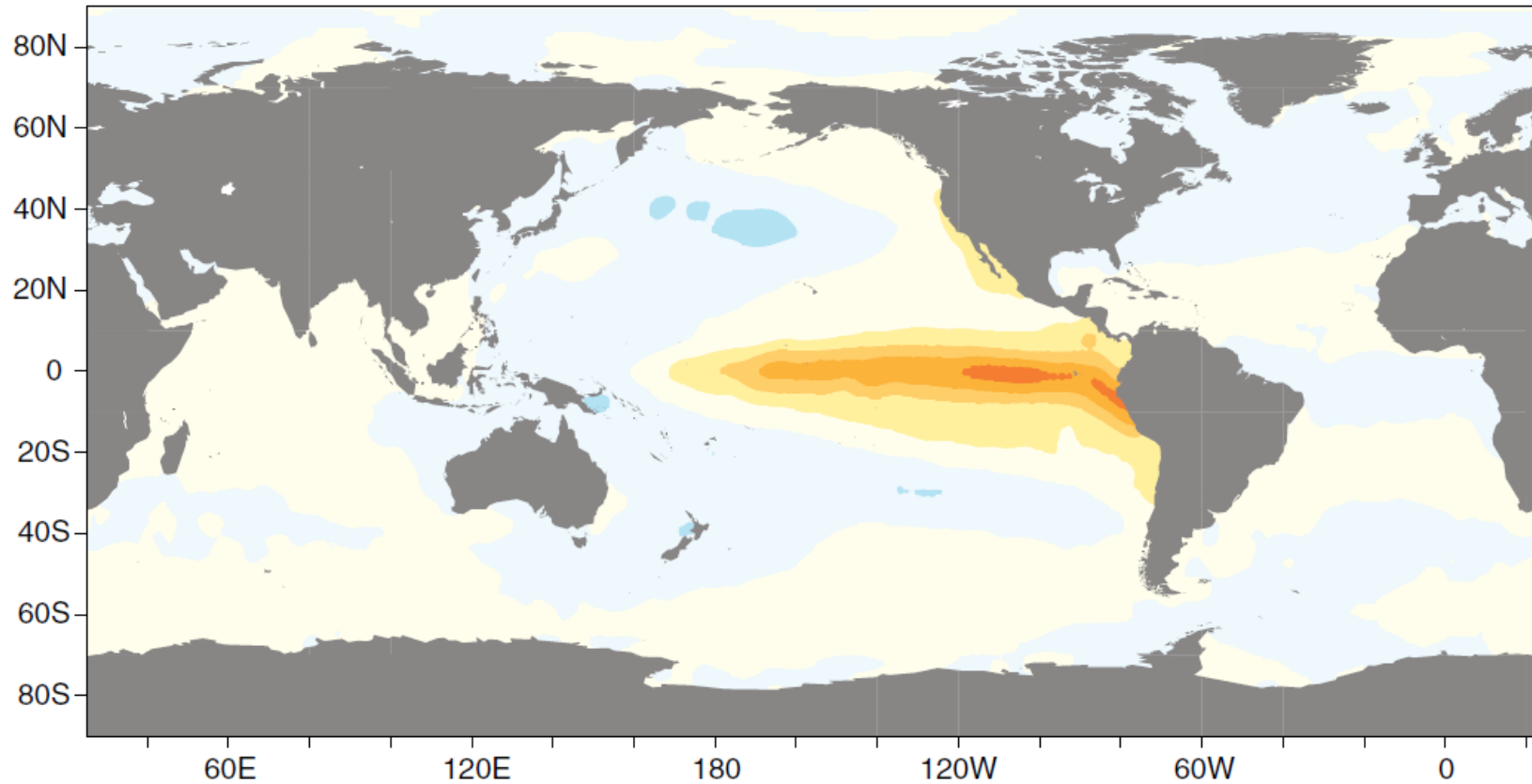
The polar-front jet stream tends to be free of large undulations and the jet stream's westerly winds funnel storms over the Mid-Atlantic states, between the strong North Atlantic pressure cells, and over northern Europe.

Northern Europe: warm, wet, stormy

# El Niño Southern Oscillation (ENSO)

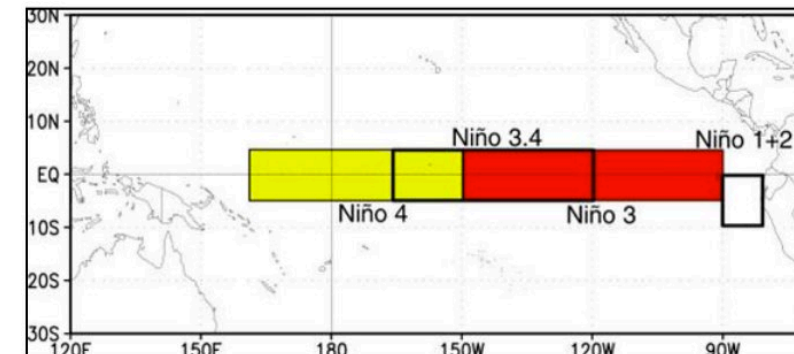
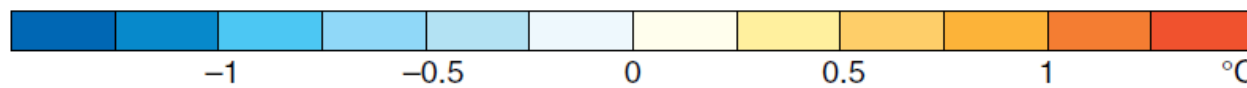
- **Coupled ocean-atmosphere** climate variability mode.
- The El Niño Southern Oscillation (ENSO) refers to the **large-scale** alternation between anomalous warming (El Niño) and cooling (La Niña) of central/eastern equatorial Pacific sea surface temperature (SST) that coincide with changes in winds and precipitation.
- ENSO is the **primary mode of tropical variability on interannual timescales**. It also triggers climate teleconnections in many other parts of the world.
- **ENSO is consistently the main modulator of the global surface temperature at interannual timescales. It is the main predictor of climate on seasonal to interannual timescales.**

# El Niño sea surface temperature anomaly (El Niño)



Unusually warm water off the western coast of South America. Normally there is the northward flowing and cold Humboldt current.

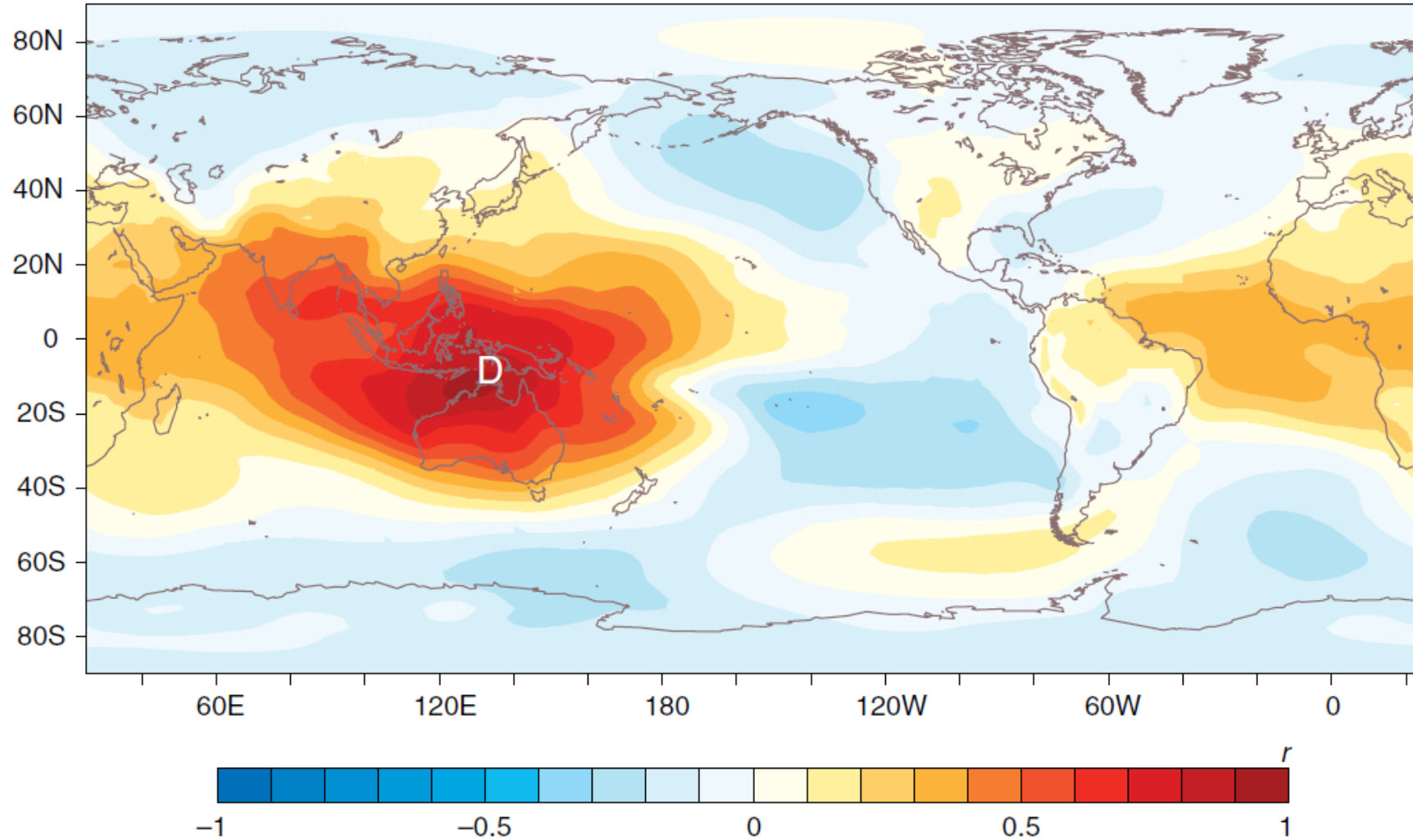
Regions where sea surface temperatures are monitored.



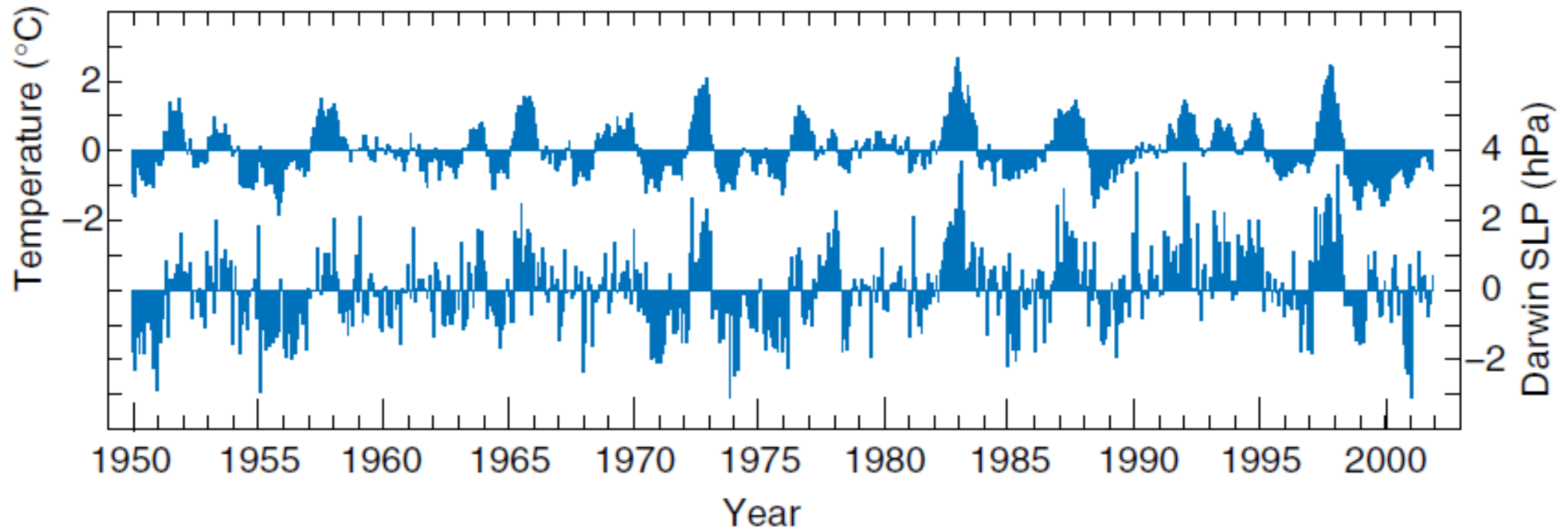
■ Wallace and Hobbs, 2006, Fig. 10.18

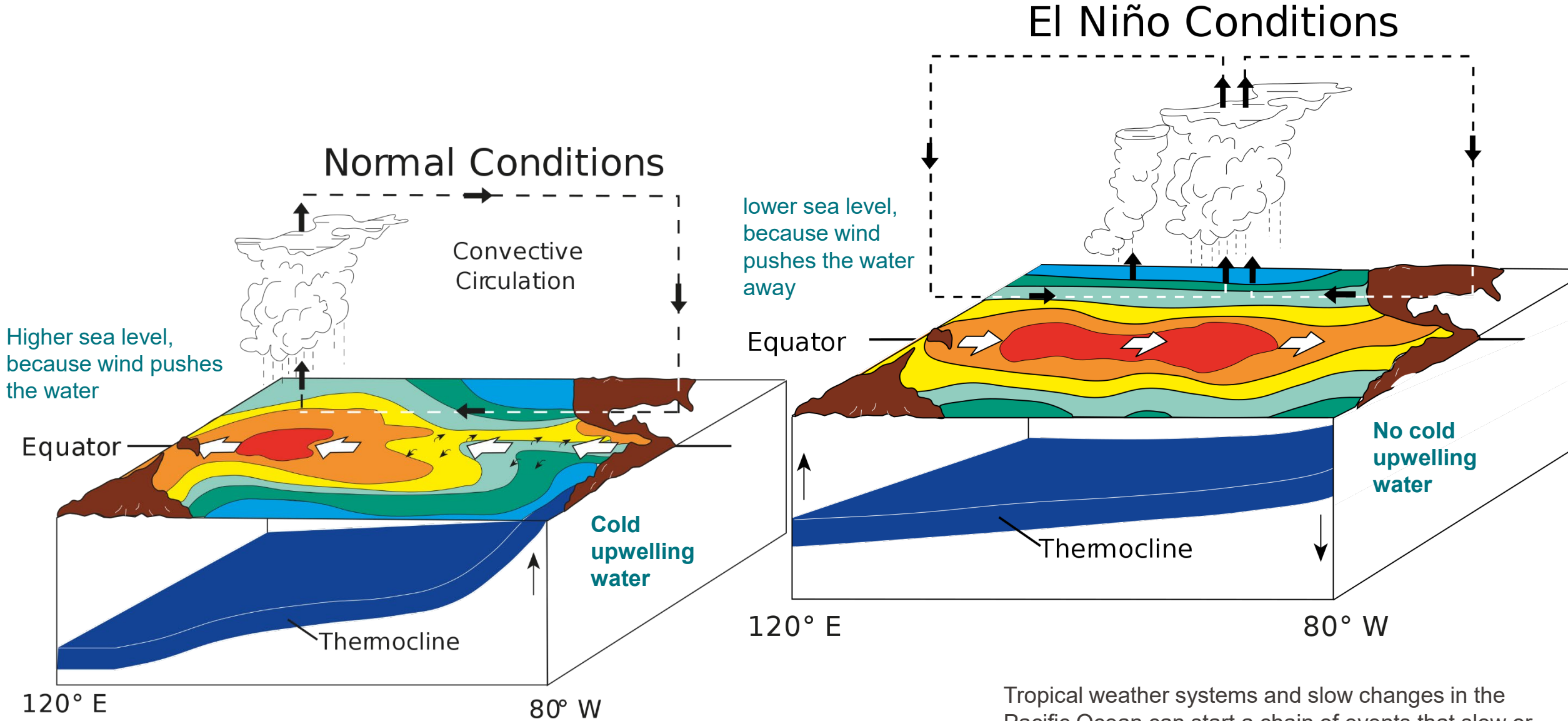
[https://en.wikipedia.org/wiki/El\\_Ni%C3%B1o](https://en.wikipedia.org/wiki/El_Ni%C3%B1o)  
o%E2%80%93Southern\_Oscillation

# El Niño sea level pressure anomaly (Southern Oscillation)



# Strong coupling between atmosphere and ocean





Tropical weather systems and slow changes in the Pacific Ocean can start a chain of events that slow or even reverse the trade winds and launch El Niño.

■ [https://en.wikipedia.org/wiki/El\\_Ni%C3%B1o%E2%80%93Southern\\_Oscillation](https://en.wikipedia.org/wiki/El_Ni%C3%B1o%E2%80%93Southern_Oscillation)

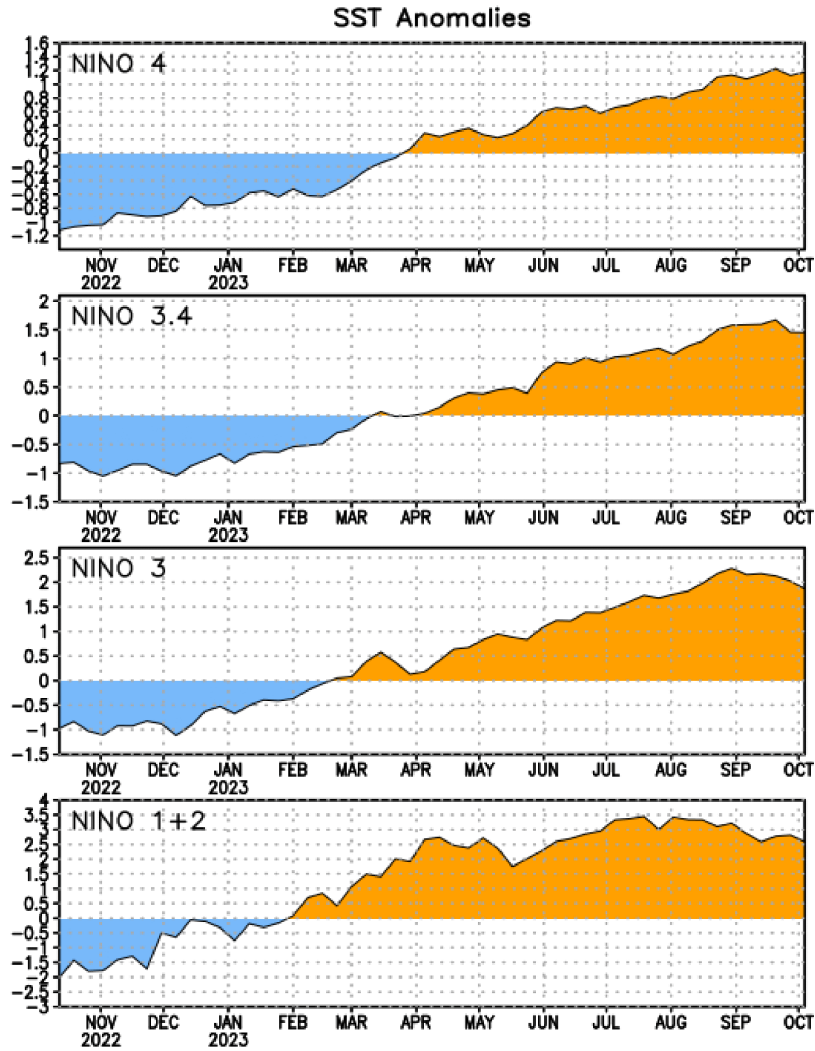


Figure 2. Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño regions [Niño-1+2 (0°-10°S, 90°W-80°W), Niño-3 (5°N-5°S, 150°W-90°W), Niño-3.4 (5°N-5°S, 170°W-120°W), Niño-4 (5°N-5°S, 150°W-160°E)]. SST anomalies are departures from the 1991-2020 base period weekly means.

Model Predictions of ENSO from Sep 2023

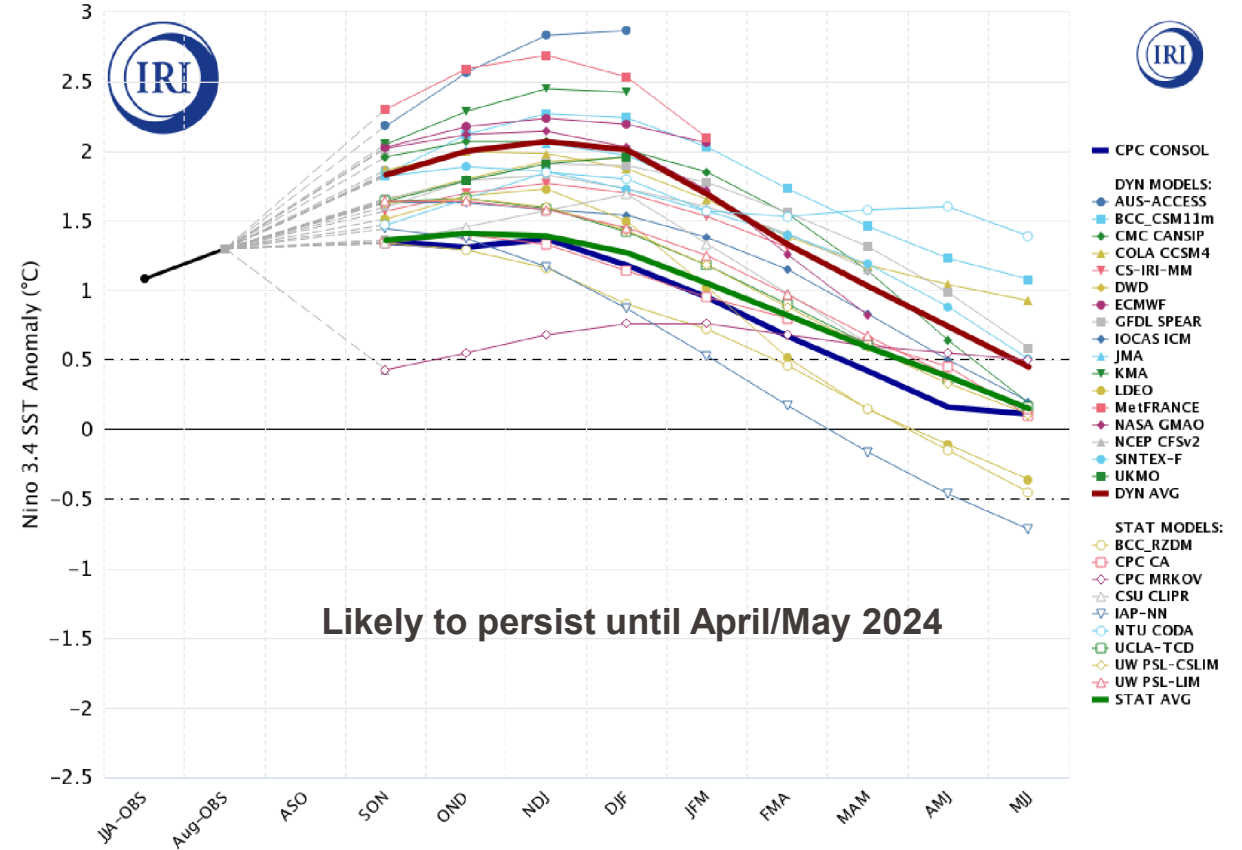
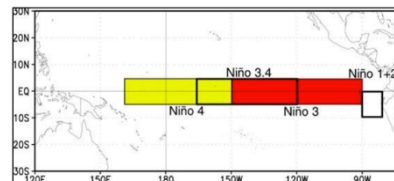


Figure 6. Forecasts of sea surface temperature (SST) anomalies for the Niño 3.4 region (5°N-5°S, 120°W-170°W). Figure updated 20 September 2023 by the International Research Institute (IRI) for Climate and Society.



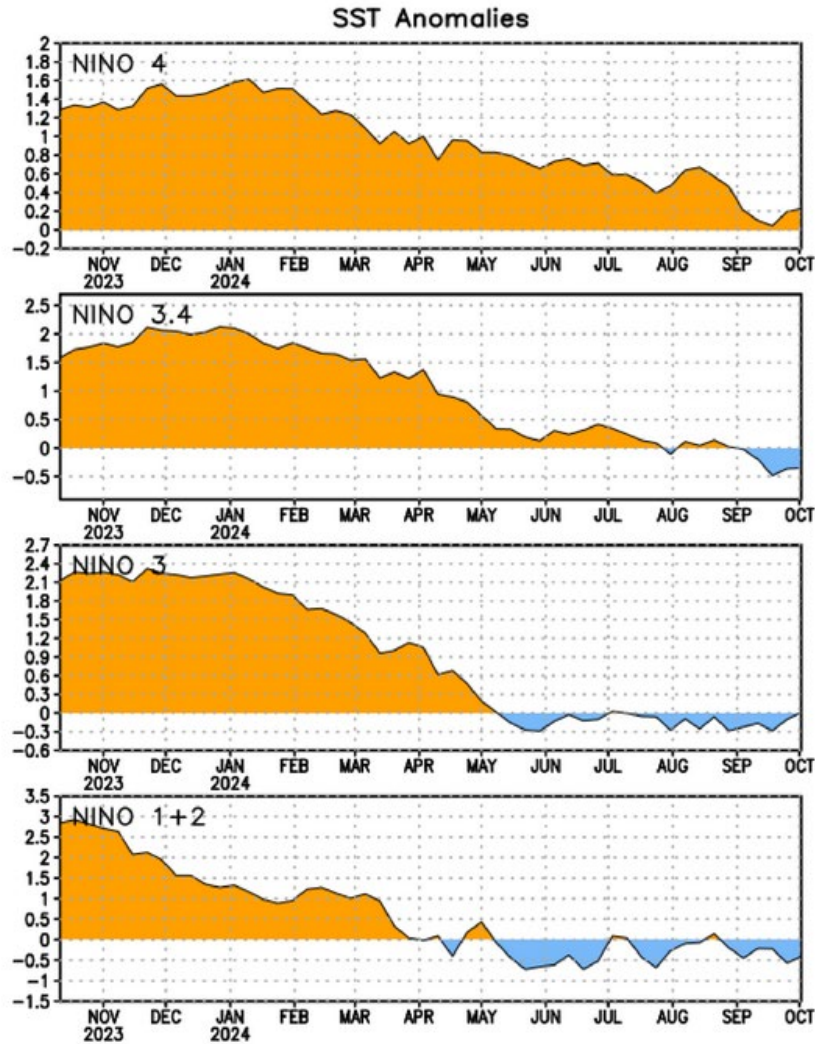


Figure 2. Time series of area-averaged sea surface temperature (SST) anomalies ( $^{\circ}\text{C}$ ) in the Niño regions [Niño-1+2 ( $0^{\circ}$ - $10^{\circ}\text{S}$ ,  $90^{\circ}\text{W}$ - $80^{\circ}\text{W}$ ), Niño-3 ( $5^{\circ}\text{N}$ - $5^{\circ}\text{S}$ ,  $150^{\circ}\text{W}$ - $90^{\circ}\text{W}$ ), Niño-3.4 ( $5^{\circ}\text{N}$ - $5^{\circ}\text{S}$ ,  $170^{\circ}\text{W}$ - $120^{\circ}\text{W}$ ), Niño-4 ( $5^{\circ}\text{N}$ - $5^{\circ}\text{S}$ ,  $150^{\circ}\text{W}$ - $160^{\circ}\text{E}$ )]. SST anomalies are departures from the 1991-2020 base period weekly means. Data credit: UKMet OSTIA.

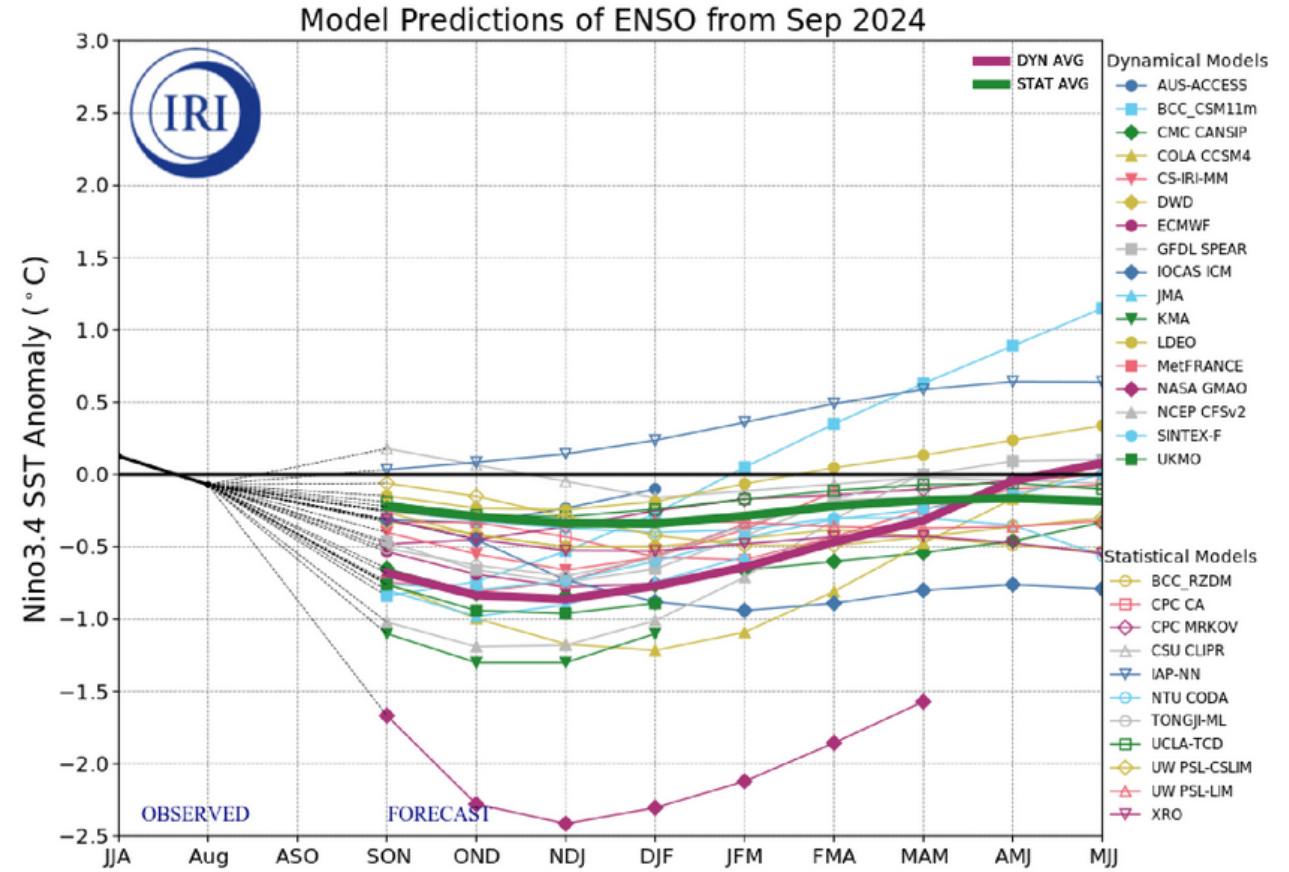
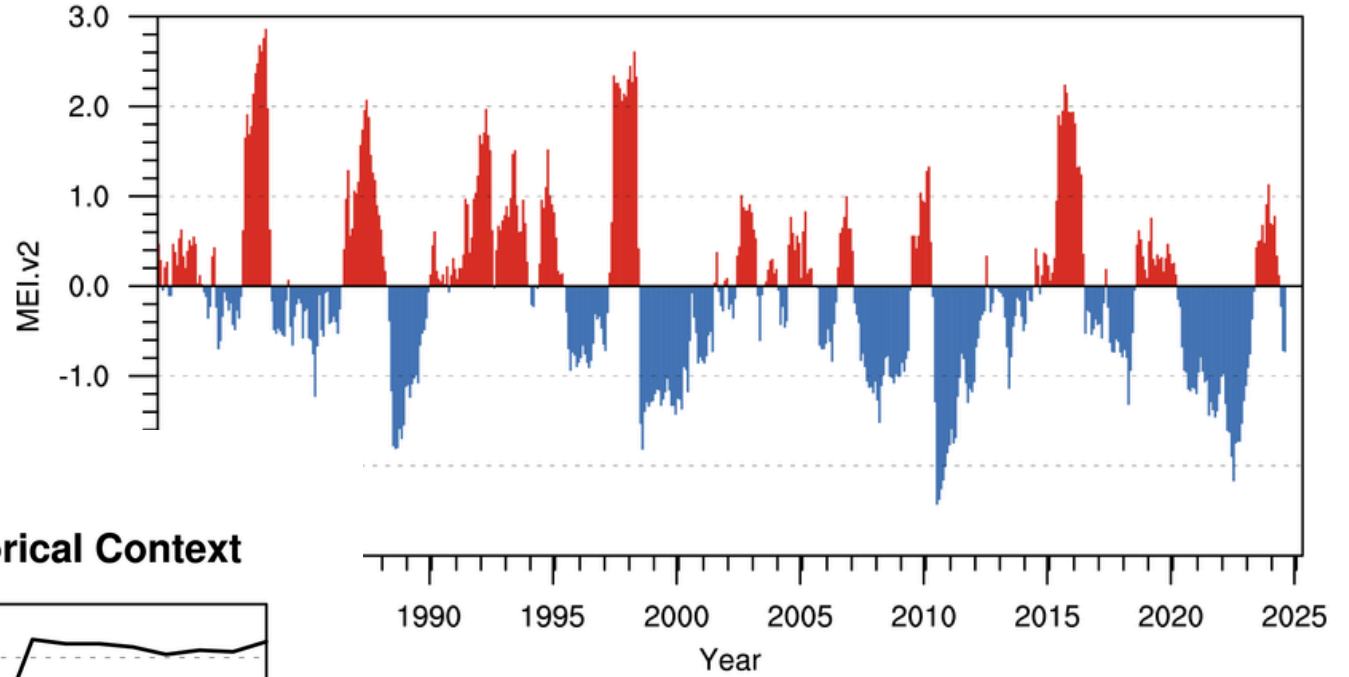


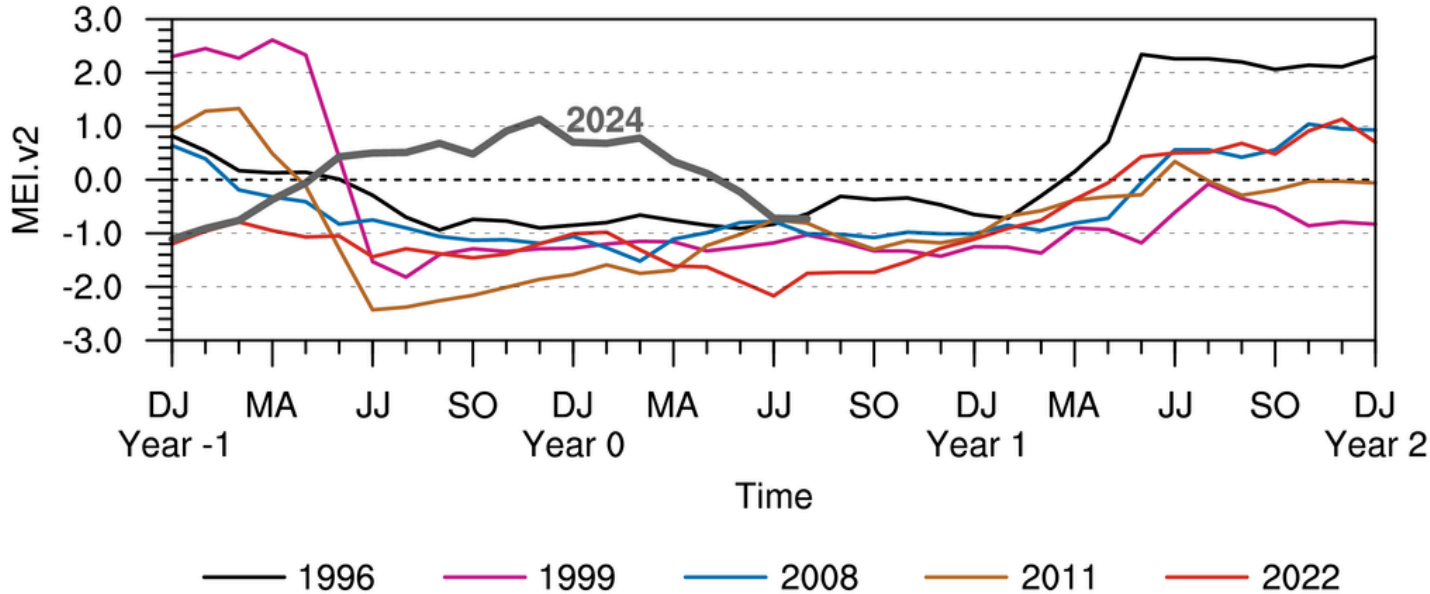
Figure 6. Forecasts of sea surface temperature (SST) anomalies for the Niño 3.4 region ( $5^{\circ}\text{N}$ - $5^{\circ}\text{S}$ ,  $120^{\circ}\text{W}$ - $170^{\circ}\text{W}$ ). Figure updated 19 September 2024 by the International Research Institute (IRI) for Climate and Society.

# ENSO status and forecast

Multivariate ENSO Index Version 2 using JRA3Q

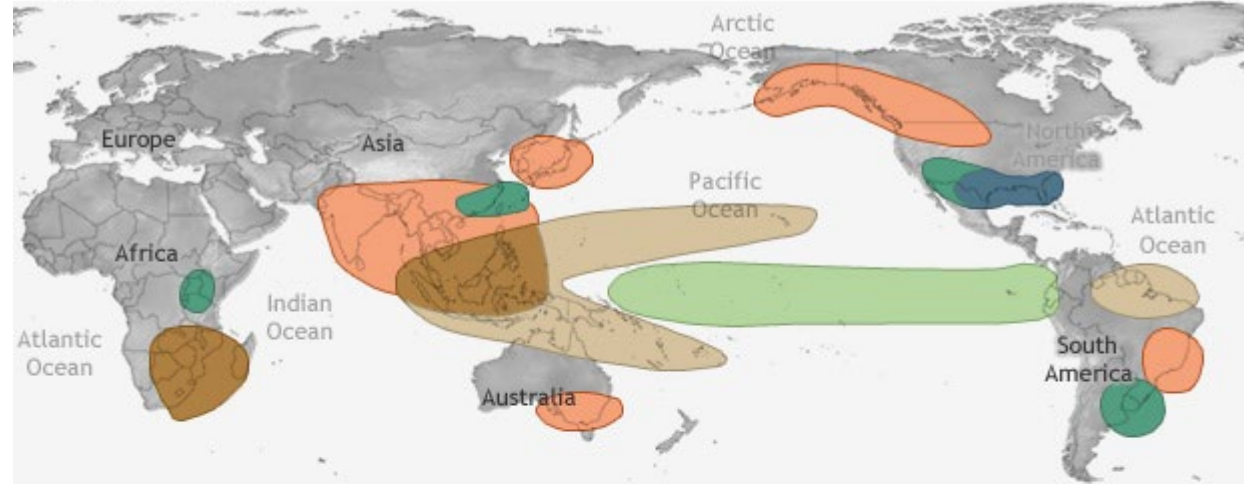


MEI.v2 Evolution of Current ENSO Event in Historical Context

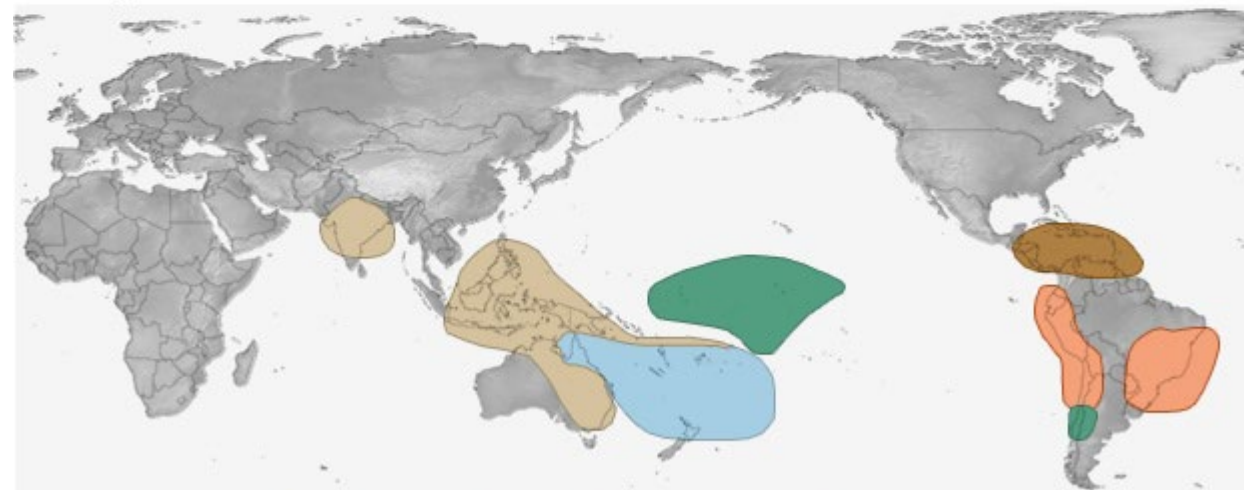


## EL NIÑO CLIMATE IMPACTS

December-February

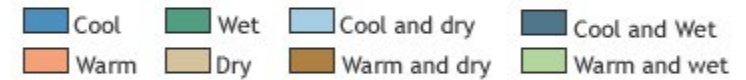
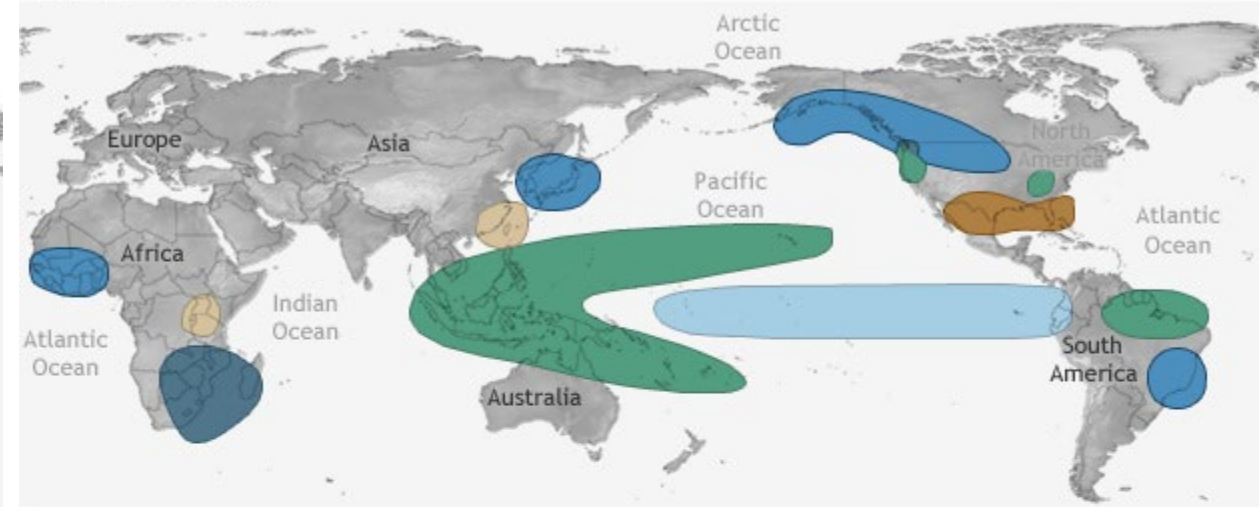


June-August

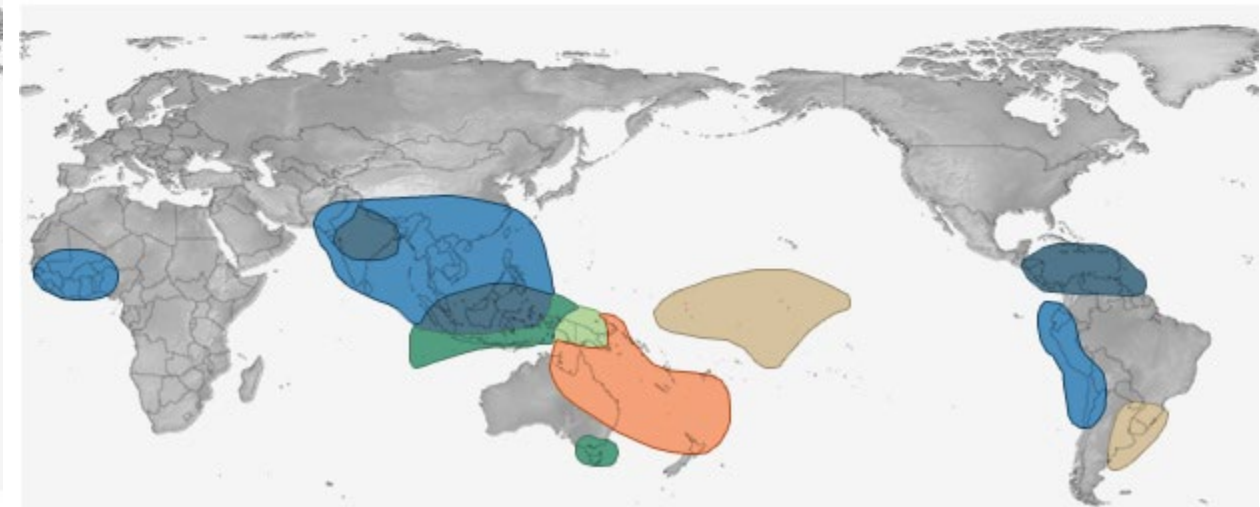


## LA NIÑA CLIMATE IMPACTS

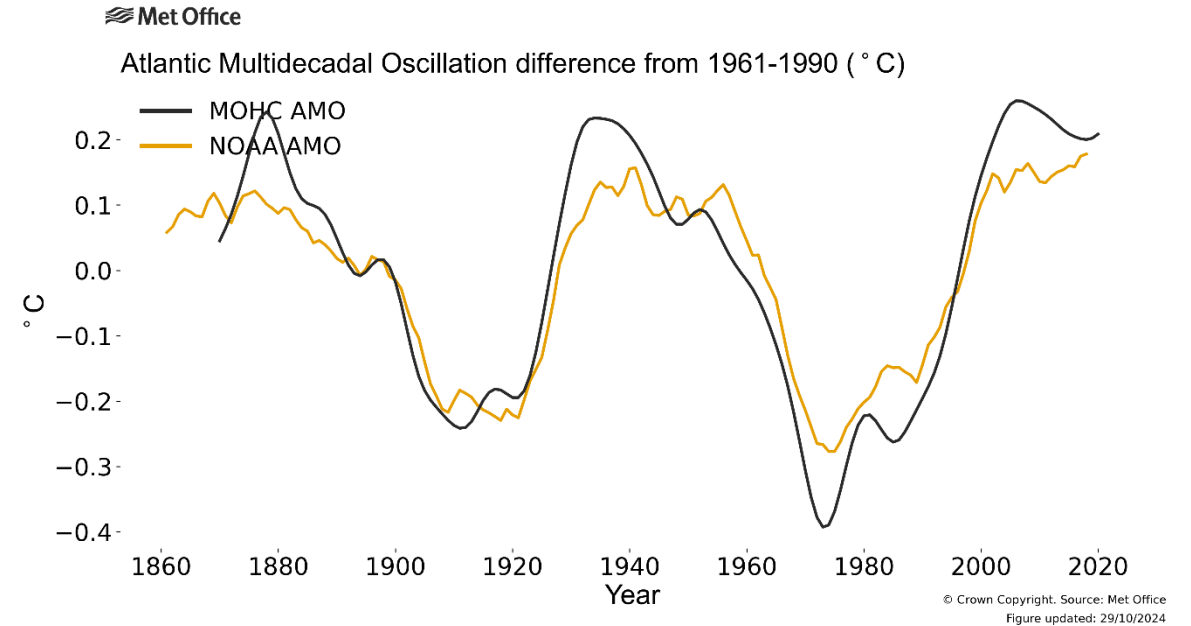
December-February



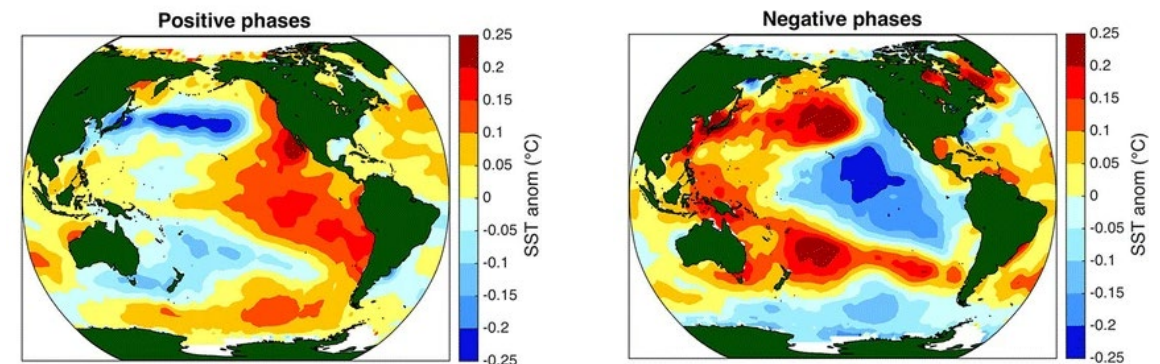
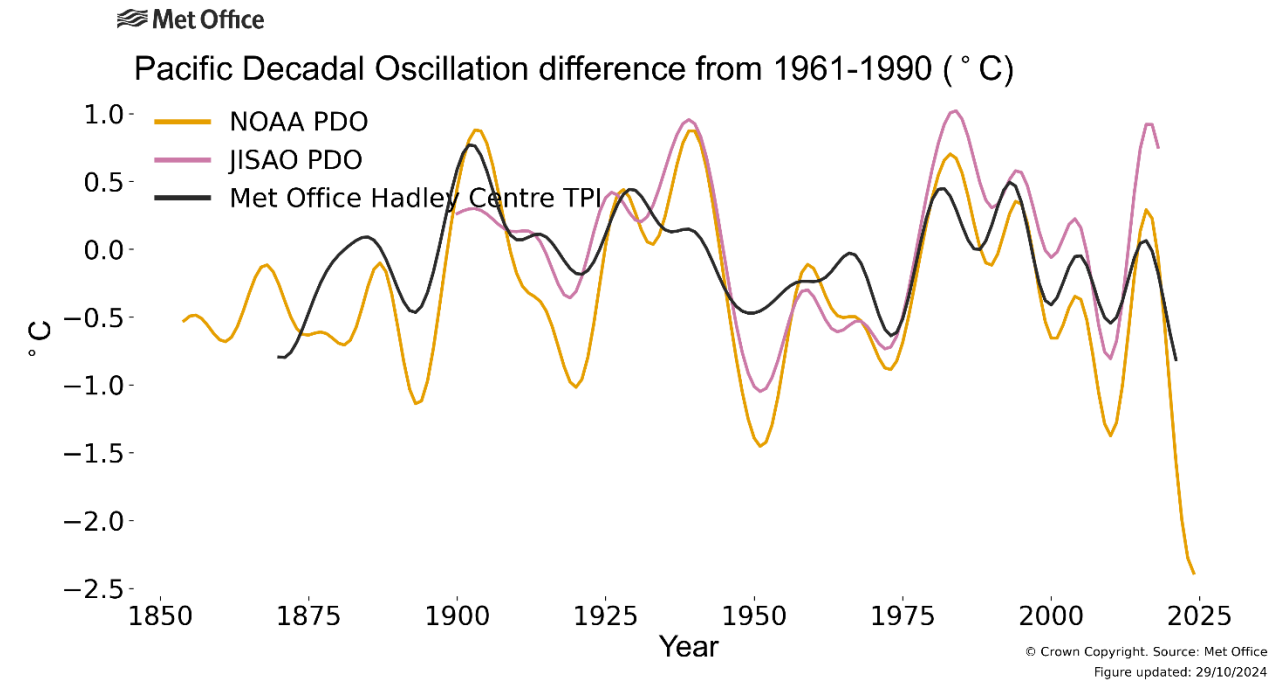
June-August



- The Atlantic Multidecadal Oscillation (or AMO for short) has two phases, a **positive phase** where **sea-surface waters** in the North Atlantic are **warmer than average** and a **negative phase** when they are **colder than average**.
- It is not entirely clear what **causes** changes in the AMO. Long records suggest that it is a long-lived natural fluctuation generated spontaneously within the ocean-atmosphere system. There is also evidence that switches in phase can be driven by changes in the output of anthropogenic pollution.
- The different phases of the AMO have been associated with a variety of **impacts**.
  - positive phase: associated with reduced Arctic sea ice, melting of the Greenland ice sheet, increased hurricane activity in the North Atlantic and increased rainfall over the Sahel region of sub-Saharan Africa.
  - negative phase: cooling at high latitudes, reduced hurricane activity and a drier Sahel.



- The Pacific Decadal Oscillation describes climatic variations over vast areas of the Pacific Ocean over periods of 20 to 30 years. At shorter time scales, there is some overlap between the PDO and other high-frequency variability such as ENSO. Therefore, the PDO series is typically smoothed to remove high-frequency variability and emphasise the slower changes.
- PDO has positive and negative phases.
- There are a number of apparent "shifts" in the PDO between the two phases, which occur around 1925, 1945, 1976 and 2000. The shift from the positive to negative phase around 2000 has been associated with a recent slowdown in the rate of global temperature change. The exact causes of the "shifts" are unknown and may be due to a combination of different mechanisms acting at different time scales.



- [https://climate.metoffice.cloud/climate\\_modes.html](https://climate.metoffice.cloud/climate_modes.html), <https://link.springer.com/article/10.1007/s00382-015-2525-1/figures/6>

# What are the main differences between NAO and ENSO?

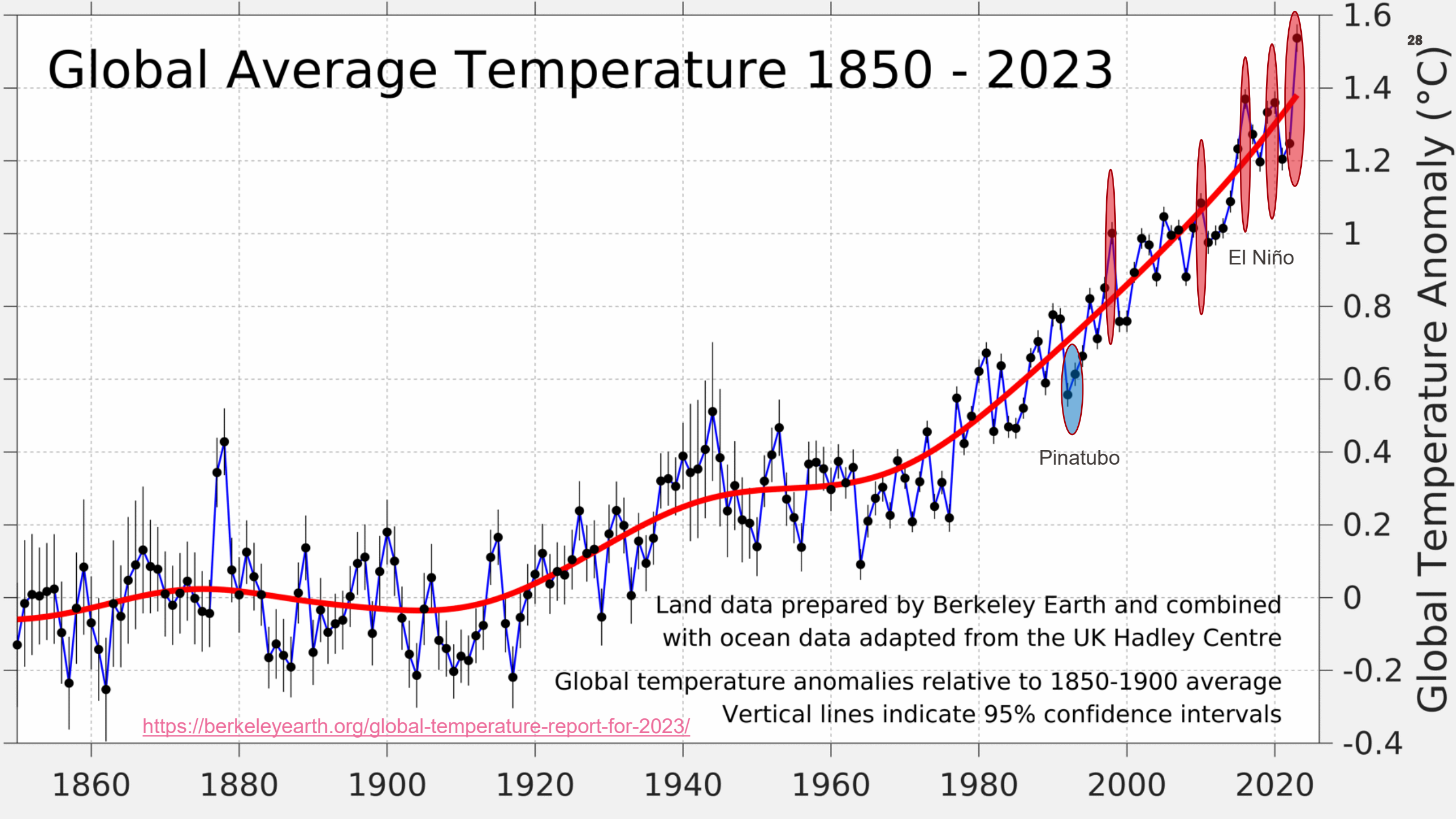
- There are several more modes.

---

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

- Von der Heydt et al. (2021), [10.1016/j.gloplacha.2020.103399](https://doi.org/10.1016/j.gloplacha.2020.103399)

# Global Average Temperature 1850 - 2023



# Why do we need to understand climate variability?

- Many modes of variability are **driven by internal climate processes** and are a **critical potential source of climate predictability** on sub-seasonal to decadal timescales.
- It is essential to understand the physical processes behind the past evolution of the modes of climate variability in order to **assess, with confidence**, their future changes.
- External forcing may affect their temporal (occurrence, variance, seasonality, persistence etc.) or spatial properties and associated teleconnections.
  - → meaning anthropogenic climate change can change natural climate variability.
  - → key research area for extremes

*“The **Paris Agreement** central aim is to [...] **keep global temperature rise [...] well below 2°C above pre-industrial levels and to pursue efforts to limit the [...] increase [...] to 1.5 °C.**”*

*<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>*



# Global Average Temperature 1850 - 2024

Exact numbers of warming vary slightly between data products.

**$1.62 \pm 0.06 \text{ }^\circ\text{C}$**   
Above average of 1850-1900

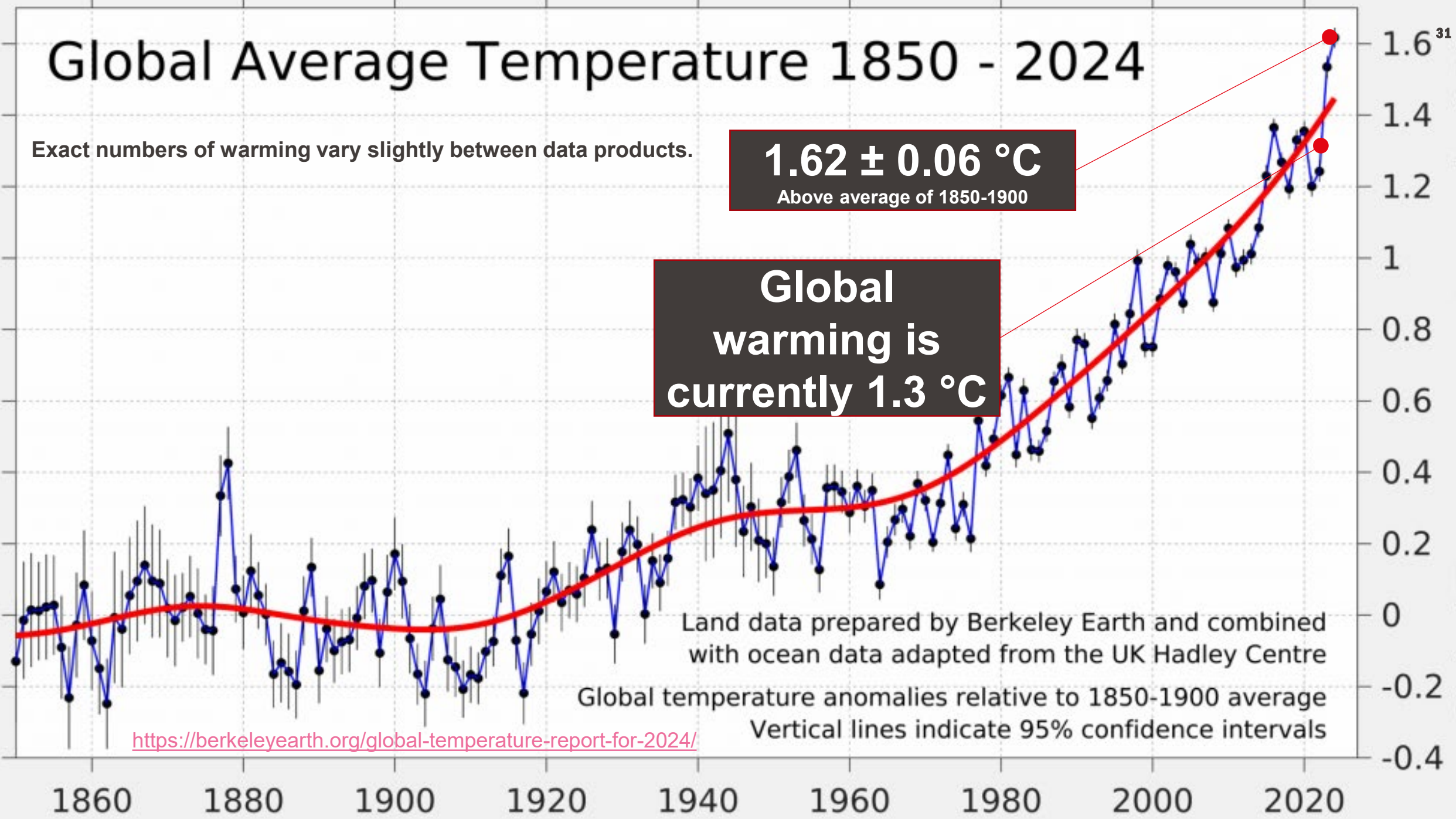
**Global  
warming is  
currently  $1.3 \text{ }^\circ\text{C}$**

Land data prepared by Berkeley Earth and combined  
with ocean data adapted from the UK Hadley Centre

Global temperature anomalies relative to 1850-1900 average  
Vertical lines indicate 95% confidence intervals

<https://berkeleearth.org/global-temperature-report-for-2024/>

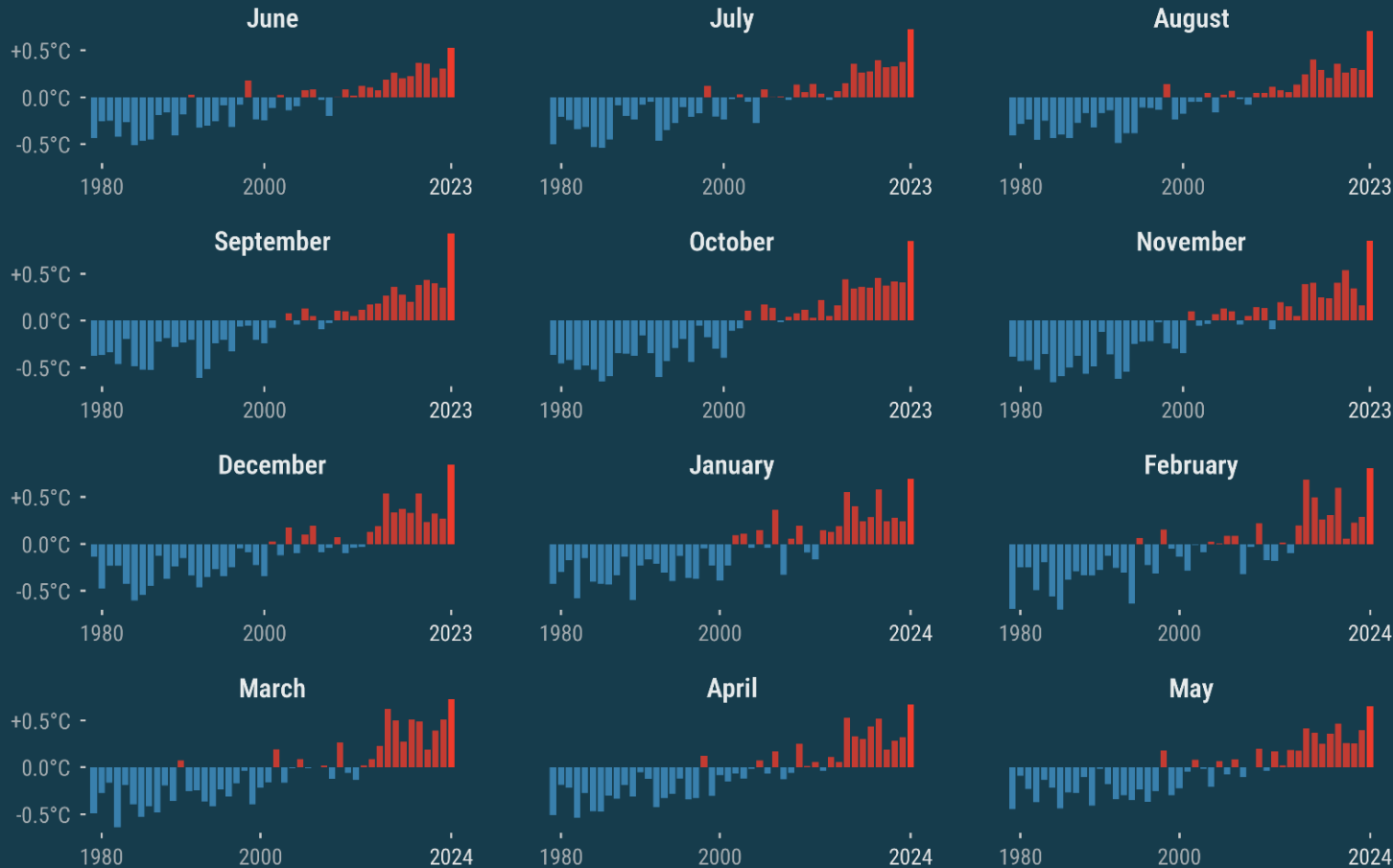
Global Temperature Anomaly ( $^\circ\text{C}$ )<sup>31</sup>



# Record temperatures since June 2023

## Each month since June 2023 was the warmest on record for the corresponding month

Global surface air temperature anomalies relative to 1991–2020 • Data: ERA5 1979–2024 • Credit: C3S/ECMWF



- Each month since June 2023 has been a record warm month globally averaged
- The record series continued through July 2024.



PROGRAMME OF THE  
EUROPEAN UNION



IMPLEMENTED BY  
ECMWF



# Breaching 1.5°C much faster than expected?

- 66% chance that at least one full year between 2023 and 2027 will be above 1.5°C above preindustrial temperatures (WMO, fall 2023). → 2023 was > 1.5°C
- 2024 was the hottest year on record, and that in La Niña conditions
- Not the same consideration: one year vs. long-term average
- BUT  
we are extremely close to the 1.5°C target and heading towards 2-3°C warming by 2100 with 2 main implications:
  - More vigorous emissions reduction needed.
  - The most climate sensitive regions and related tipping points might cause drastic impacts sooner than anticipated.



## Scientific body

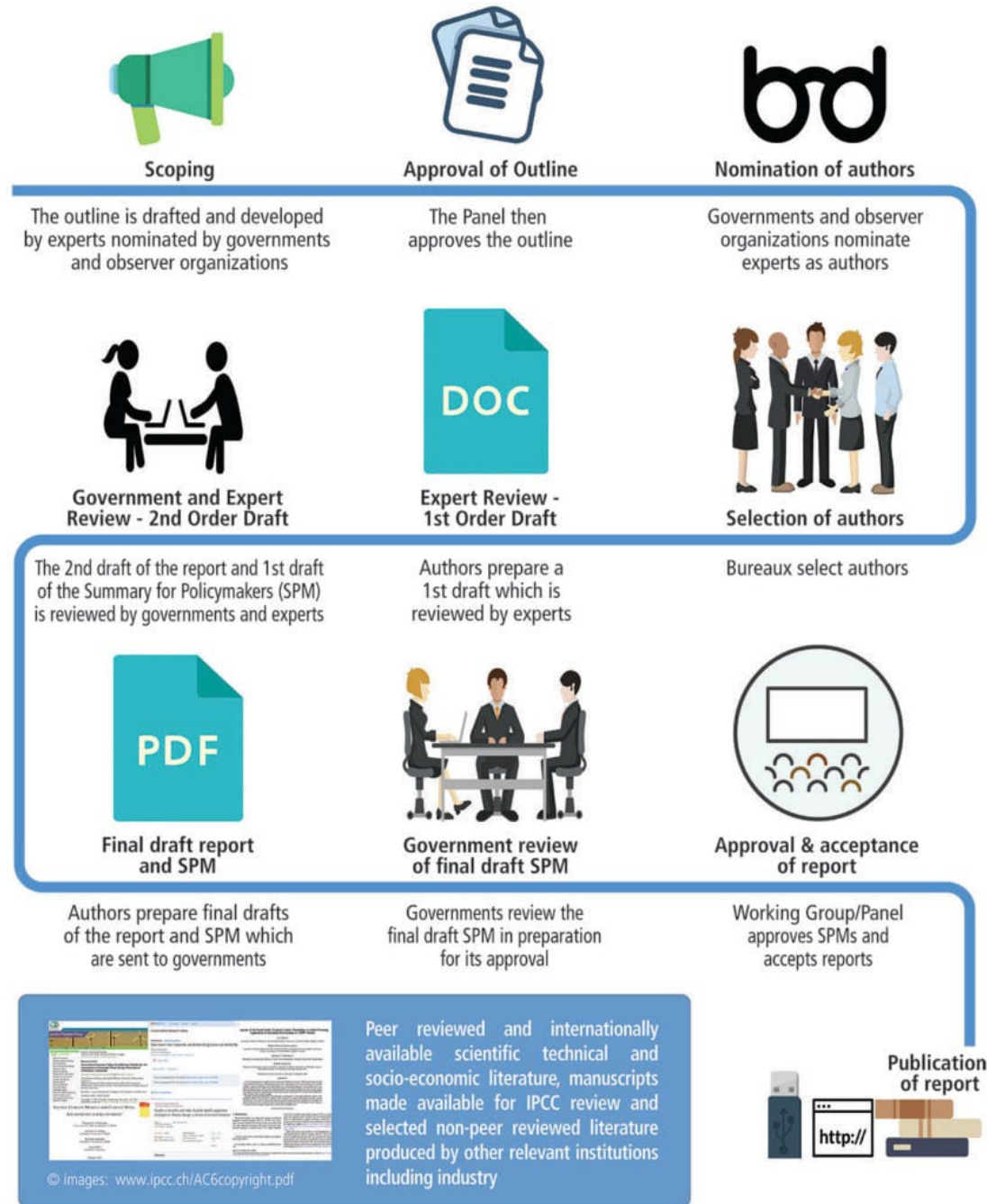
Objectives of the assessments:

- determine the current state of climate
- estimate the environmental consequences
- estimate the socio-economic consequences

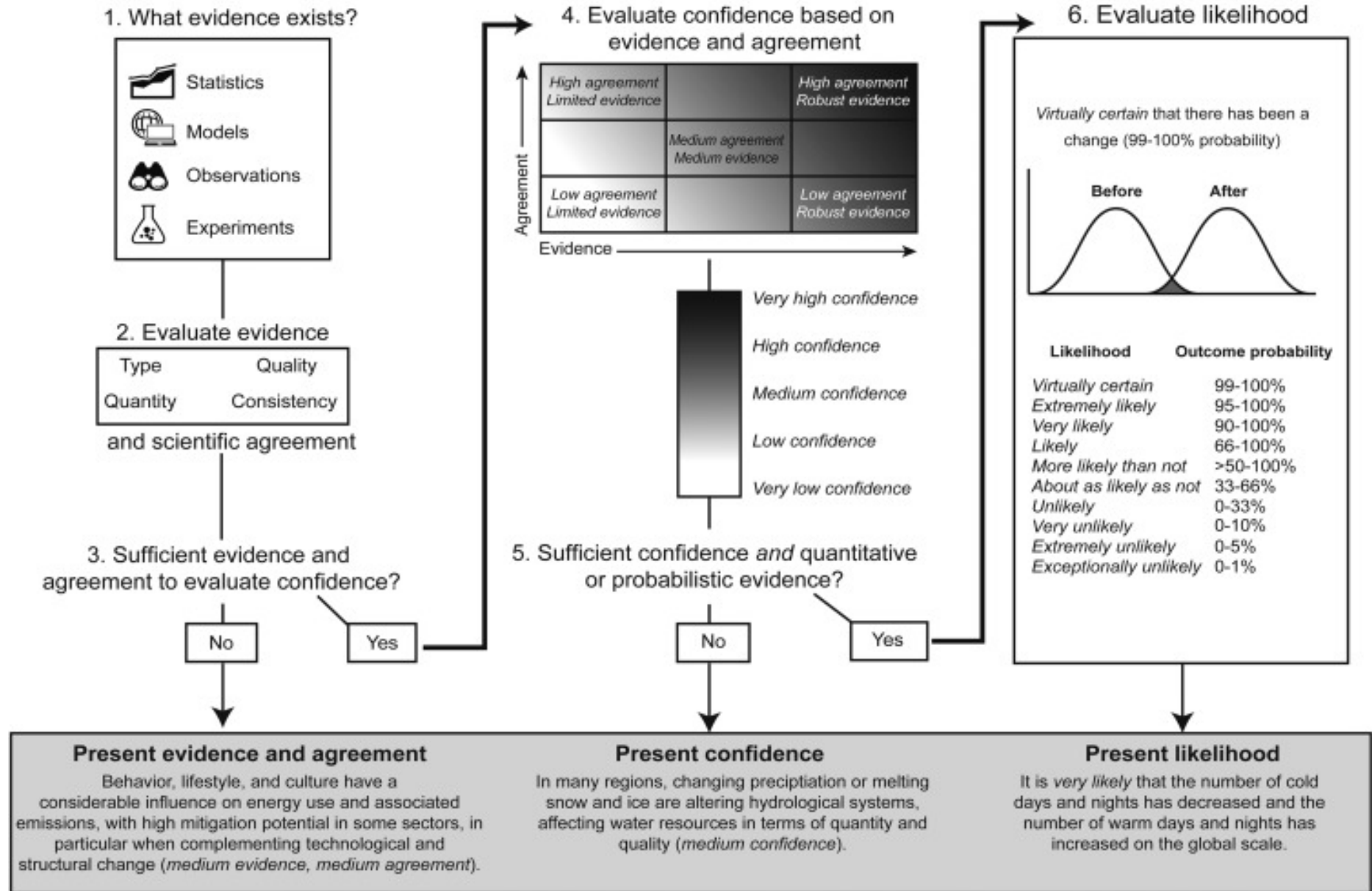
The **Intergovernmental Panel on Climate Change (IPCC)** was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and later endorsed by the United Nations General Assembly. It is based in Geneva, Switzerland, and is composed of 195 member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

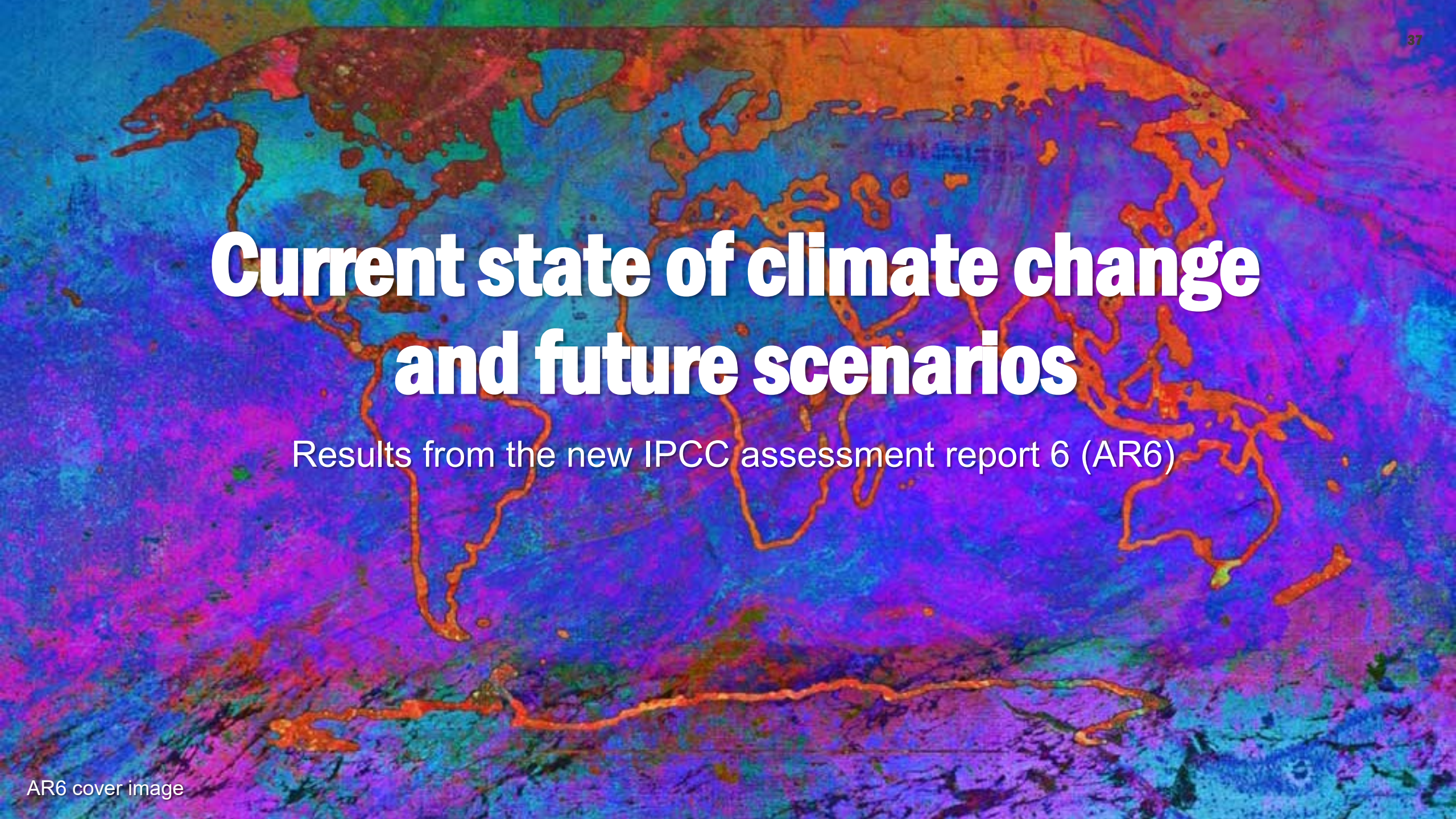
It issues scientific assessments every 5-8 years since 1990.

# From literature to the report



# IPCC confidence and likelihood (calibrated language)





# Current state of climate change and future scenarios

Results from the new IPCC assessment report 6 (AR6)

# 3 working groups of the IPCC

- **Working Group I The Physical Science Basis**

- WGI aims at assessing the physical scientific basis of the climate system and climate change.

- **Working Group II Impacts, Adaptation and Vulnerability**

- Working Group II assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting to it.

- **Working Group III Mitigation of Climate Change**

- WG III focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere.



## Headline Statements from the Summary for Policymakers

9 August 2021 (subject to final copy-editing)

### A. The Current State of the Climate

- A.1** It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.
- A.2** The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.
- A.3** Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the Fifth Assessment Report (AR5).
- A.4** Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of equilibrium climate sensitivity of 3°C, with a narrower range compared to AR5.

**Scientific  
consensus**

**Reference to  
paleoclimate**

**First time linking  
to extremes**

**ECS ~ 3°C**

## B. Possible Climate Futures

- B.1** Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO<sub>2</sub>) and other greenhouse gas emissions occur in the coming decades.
- B.2** Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, and proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover and permafrost.
- B.3** Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events.
- B.4** Under scenarios with increasing CO<sub>2</sub> emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO<sub>2</sub> in the atmosphere.
- B.5** Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.

**Currently heading for 2-3 °C, see emission scenarios**

**Intensification, extreme events, challenge to quantify and predict → can make impacts worse**

**Climate system is dynamic**

**Tipping points**

## C. Climate Information for Risk Assessment and Regional Adaptation

- C.1 Natural drivers and internal variability will modulate human-caused changes, especially at regional scales and in the near term, with little effect on centennial global warming. These modulations are important to consider in planning for the full range of possible changes.
- C.2 With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels.
- C.3 Low-likelihood outcomes, such as ice sheet collapse, abrupt ocean circulation changes, some compound extreme events and warming substantially larger than the assessed very likely range of future warming cannot be ruled out and are part of risk assessment.

## D. Limiting Future Climate Change

- D.1 From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO<sub>2</sub> emissions, reaching at least net zero CO<sub>2</sub> emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH<sub>4</sub> emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.
- D.2 Scenarios with low or very low greenhouse gas (GHG) emissions (SSP1-1.9 and SSP1-2.6) lead within years to discernible effects on greenhouse gas and aerosol concentrations, and air quality, relative to high and very high GHG emissions scenarios (SSP3-7.0 or SSP5-8.5). Under these contrasting scenarios, discernible differences in trends of global surface temperature would begin to emerge from natural variability within around 20 years, and over longer time periods for many other climatic impact-drivers (*high confidence*).

e.g. ENSO

Each decimal degree makes a difference.

There are potential dramatic changes that cannot be ruled out.

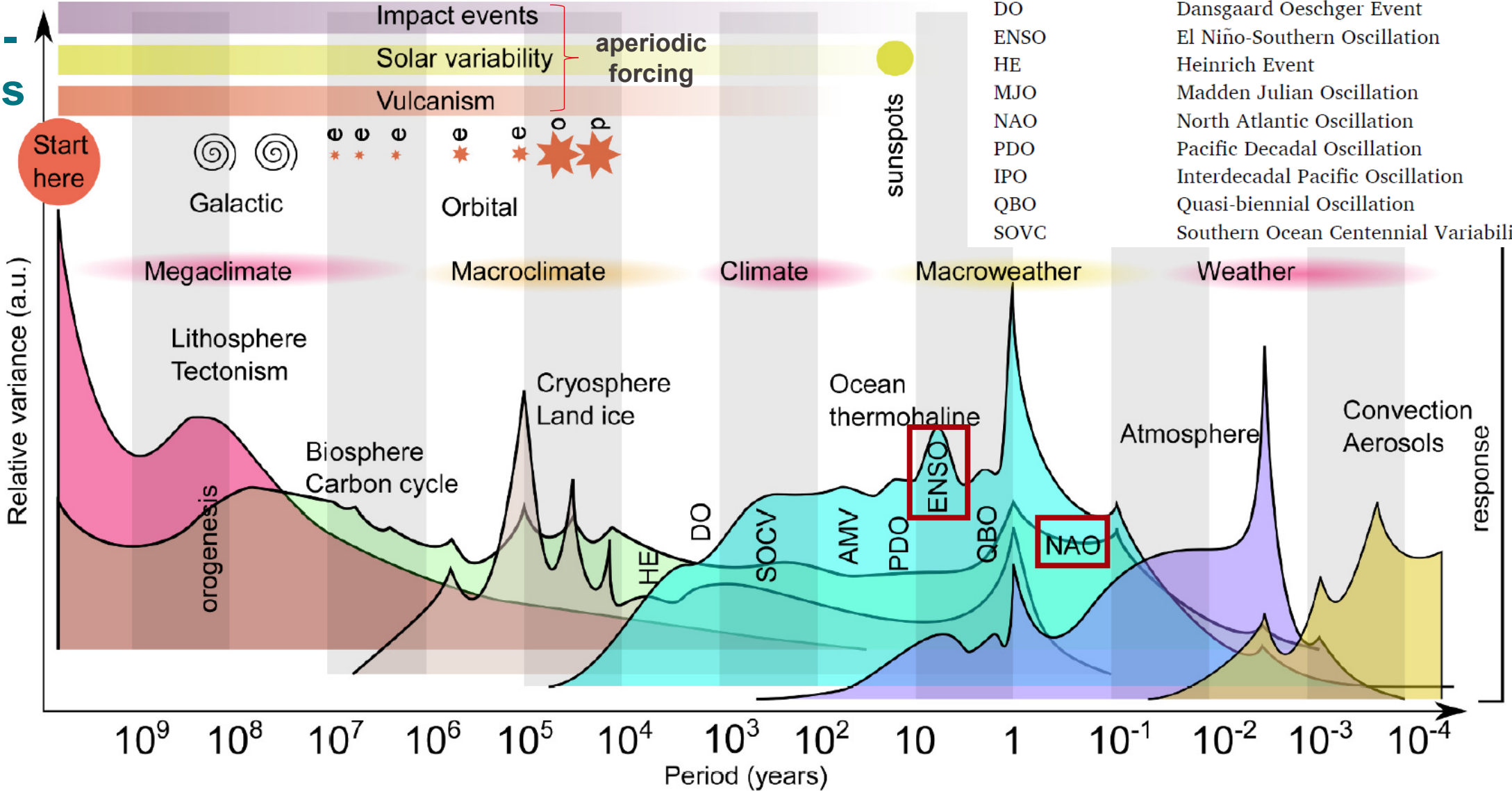
Net-zero CO<sub>2</sub>, and reduce CH<sub>4</sub> and air pollution

First changes visible in 2 decades if vigorous action occurred now.



# Climate Variability

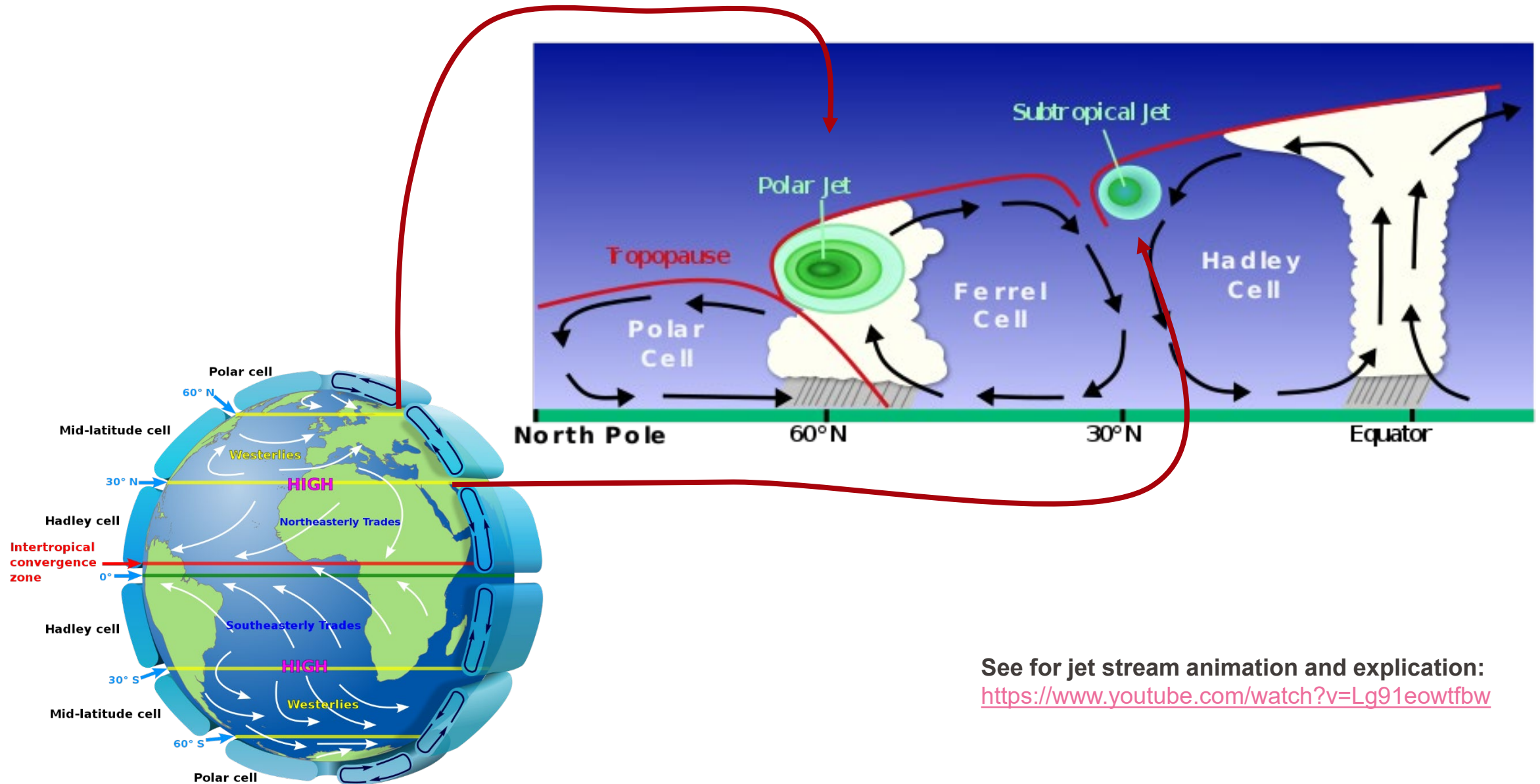
Time-scales !



■ Von der Heydt et al. (2021), [10.1016/j.gloplacha.2020.103399](https://doi.org/10.1016/j.gloplacha.2020.103399)

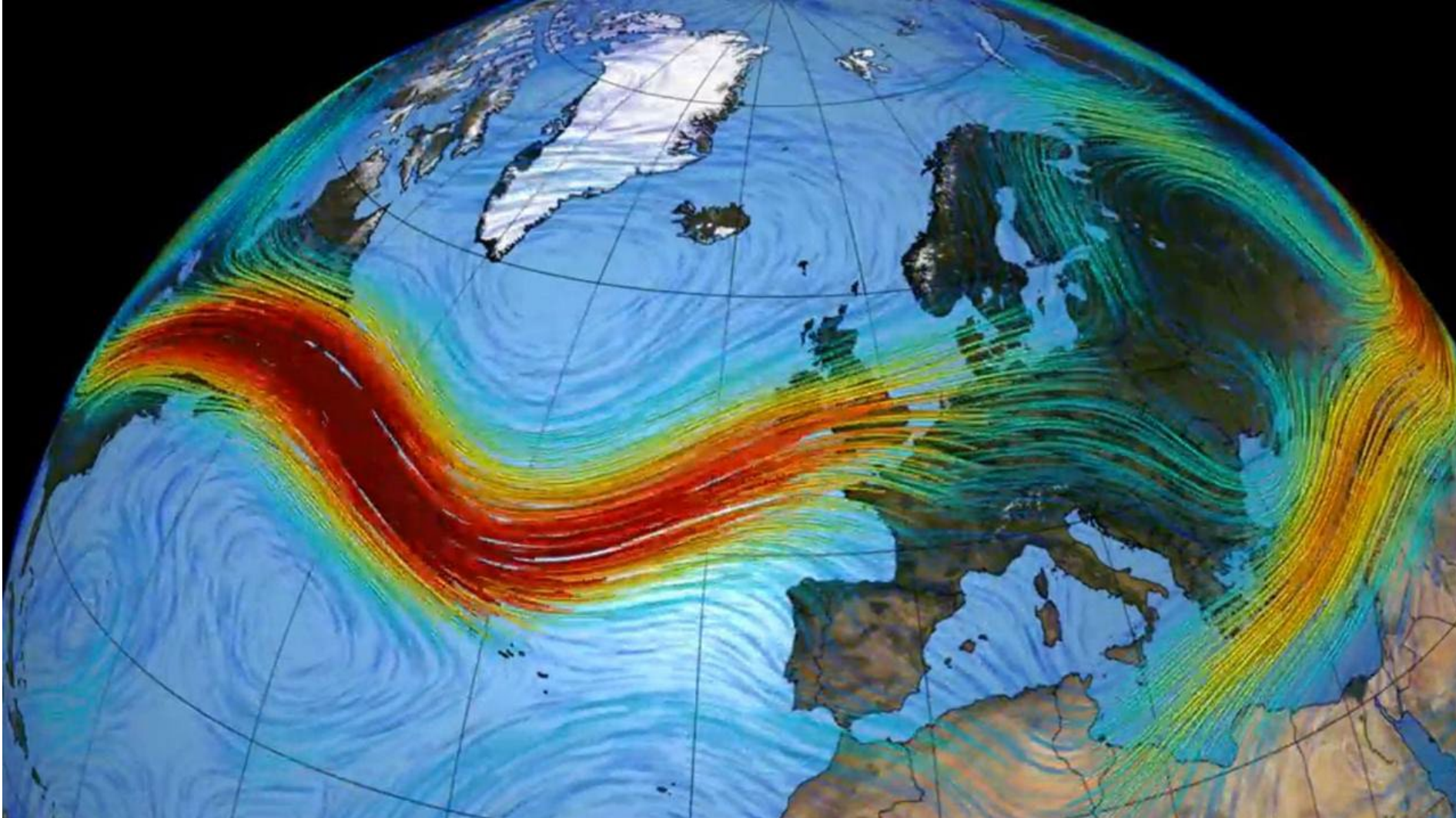
Orbital variability due to eccentricity (e), obliquity (o) and precession (p)

# Global circulation patterns

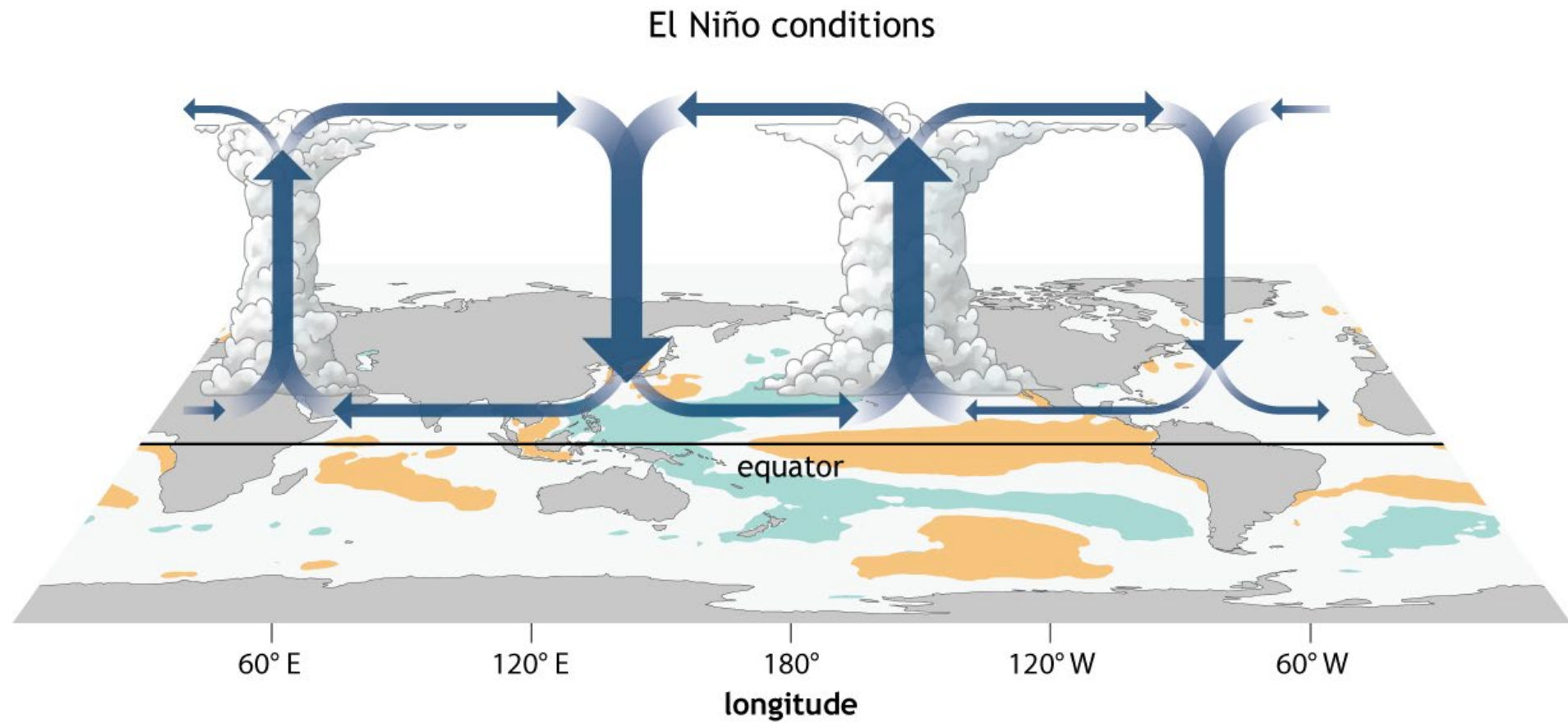


See for jet stream animation and explication:  
<https://www.youtube.com/watch?v=Lg91eowtfbw>

# Ondulating jet stream



- <https://weather.com/de-DE/wissen/klima/news/2018-08-20-nicht-nur-natuerliche-ursachen-verlangsamter-jetstream-befeuert>



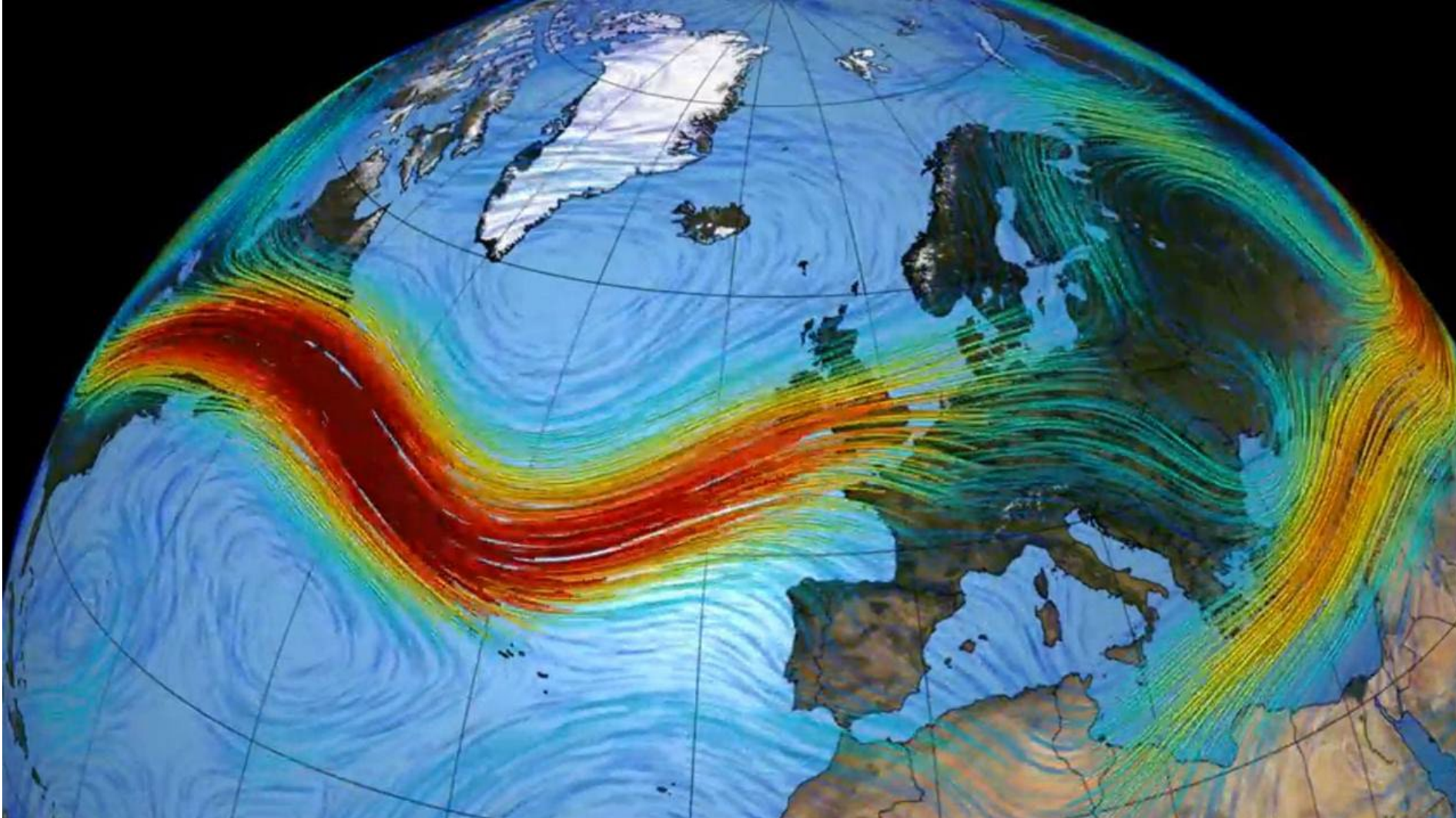
NOAA Climate.gov

## Current debate:

# Will the 2023/24 El Niño push Earth beyond the 1.5 °C warming target?

- <https://www.noaa.gov/news/topping-charts-september-2023-was-earths-warmest-september-in-174-year-record>
- <https://climate.copernicus.eu/copernicus-september-2023-unprecedented-temperature-anomalies>
- <https://www.theguardian.com/environment/commentisfree/2023/oct/05/global-heating-weather-temperatures-climate-impact>
- <https://www.theguardian.com/environment/commentisfree/2023/oct/19/will-the-earth-breach-its-15c-guardrail-sooner-than-we-thought>
- Figures and facts
- Summary of debate

# Ondulating jet stream



- <https://weather.com/de-DE/wissen/klima/news/2018-08-20-nicht-nur-natuerliche-ursachen-verlangsamter-jetstream-befeuert>