Climate change in the Arctic: From regional warming to global impacts

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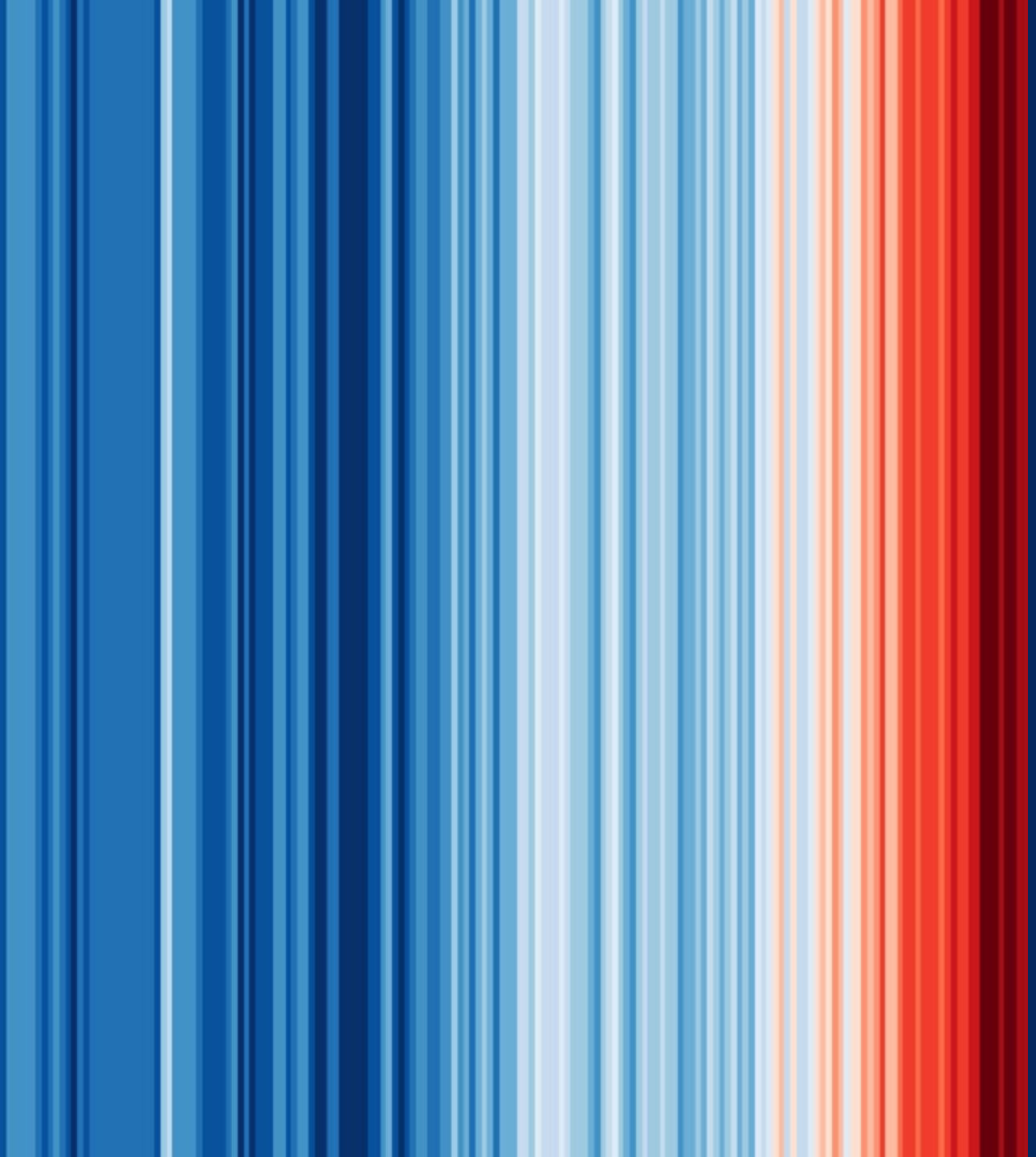

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Climate Change in Context

Climate Change

- “It is unequivocal that human influence has warmed the atmosphere, ocean and land. 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.” (IPCC, 2023, p.46).

- Climate change: “A change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and / or the variability of its properties and that persists for an extended period, typically decades or longer.” (IPCC, 2021)

- We can see the impact of our changing climate on the land surface.
- For example **rapid glacier retreat** in the last decade:

Briskdal Glacier, Norway:

FAQ 1.2: **Where is climate change most apparent?**

Temperature changes are most apparent in regions with smaller natural variations.

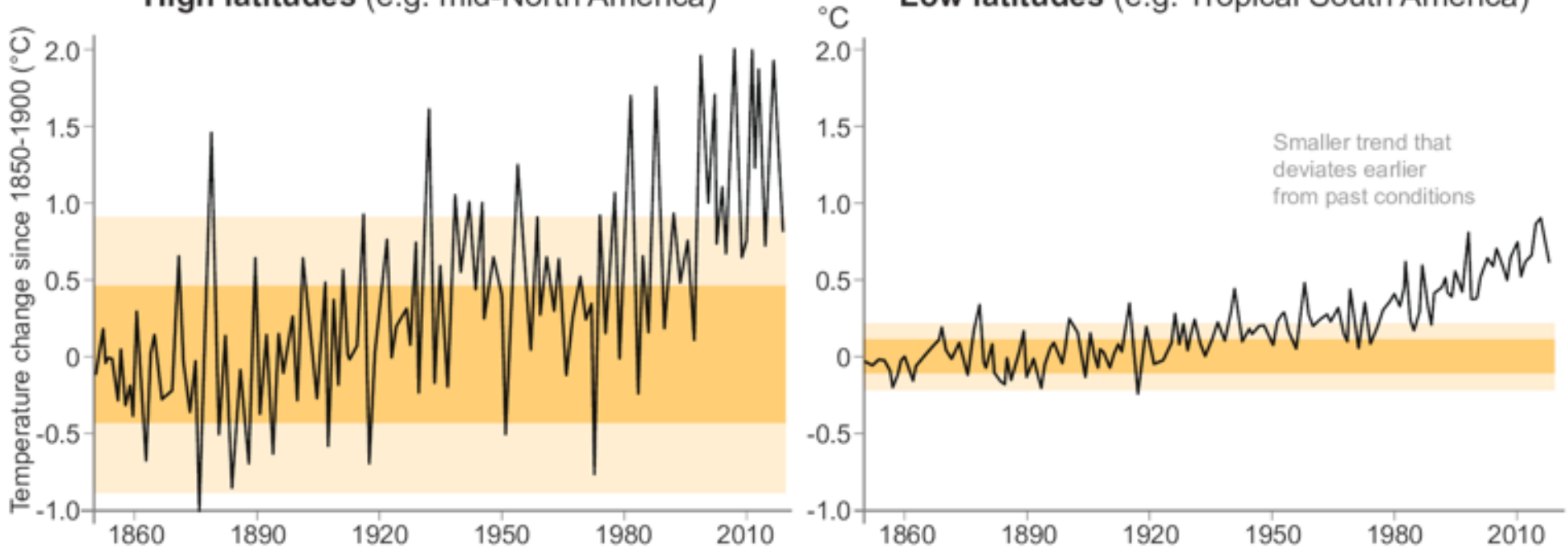
Estimation of:

2 standard deviations of natural year-to-year variations

1 standard deviation of natural year-to-year variations

High latitudes (e.g. mid-North America)

Low latitudes (e.g. Tropical South America)

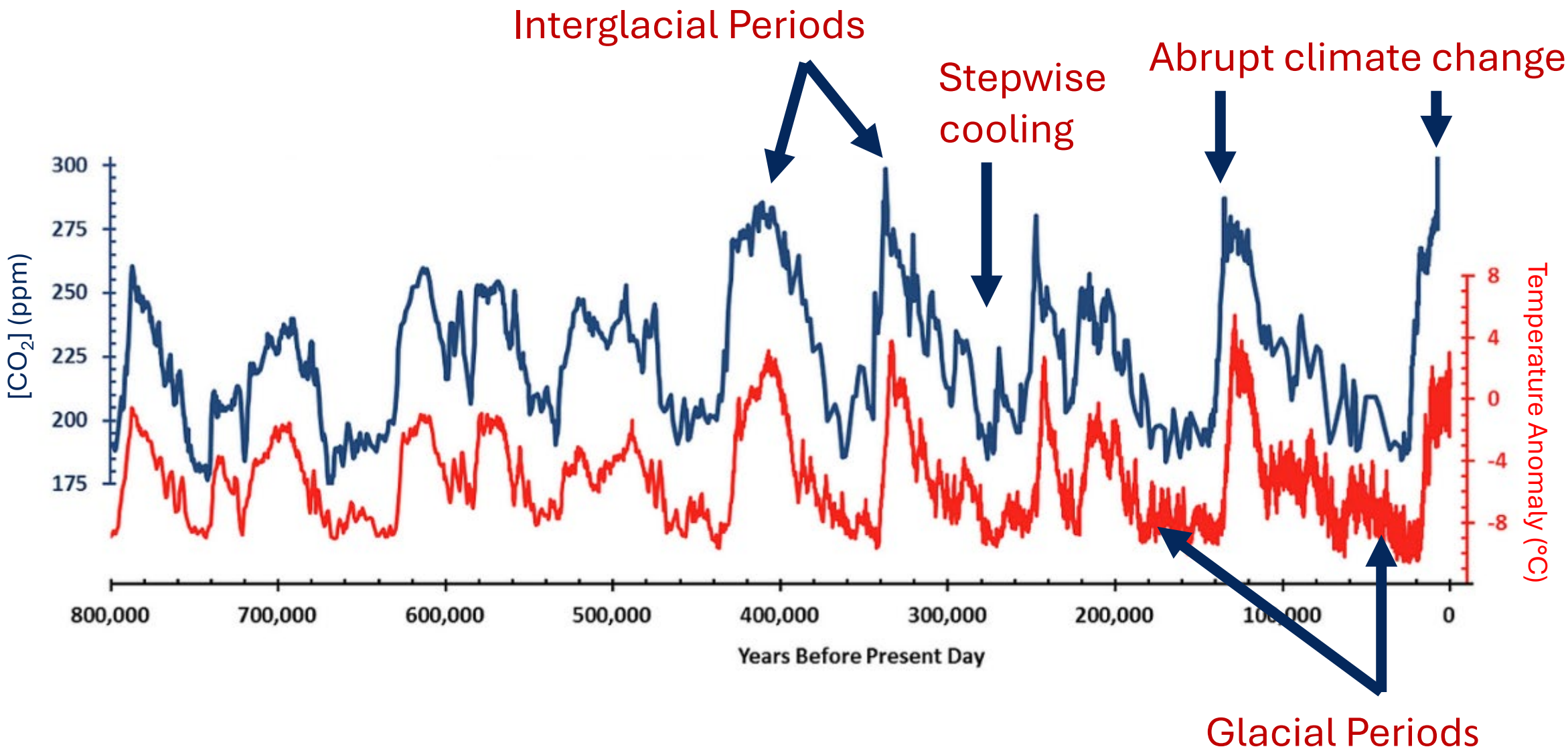


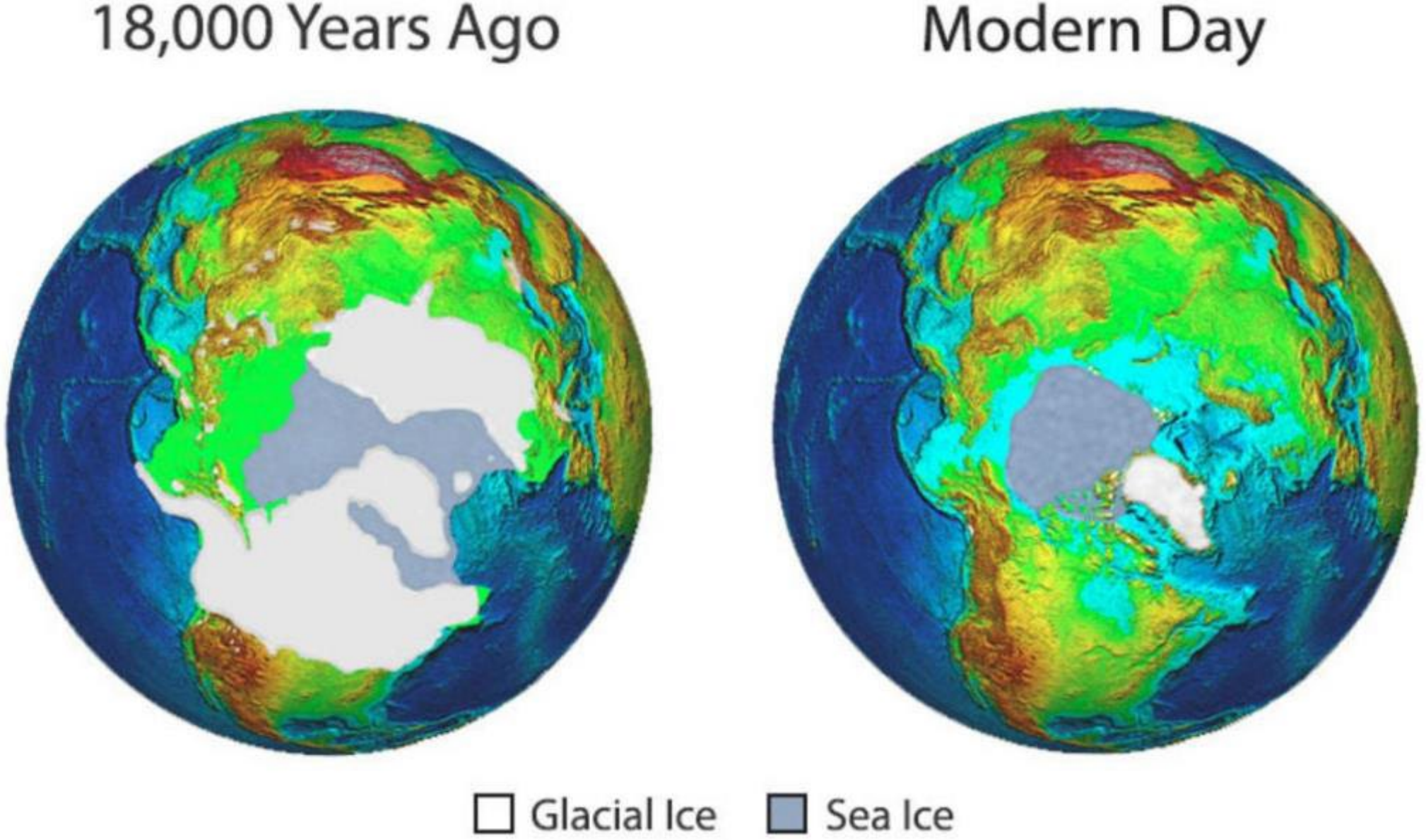
Natural Climate Change

- A key question for scientists is how far has anthropogenic activity taken us away from Earth's **natural pattern of climate change**?

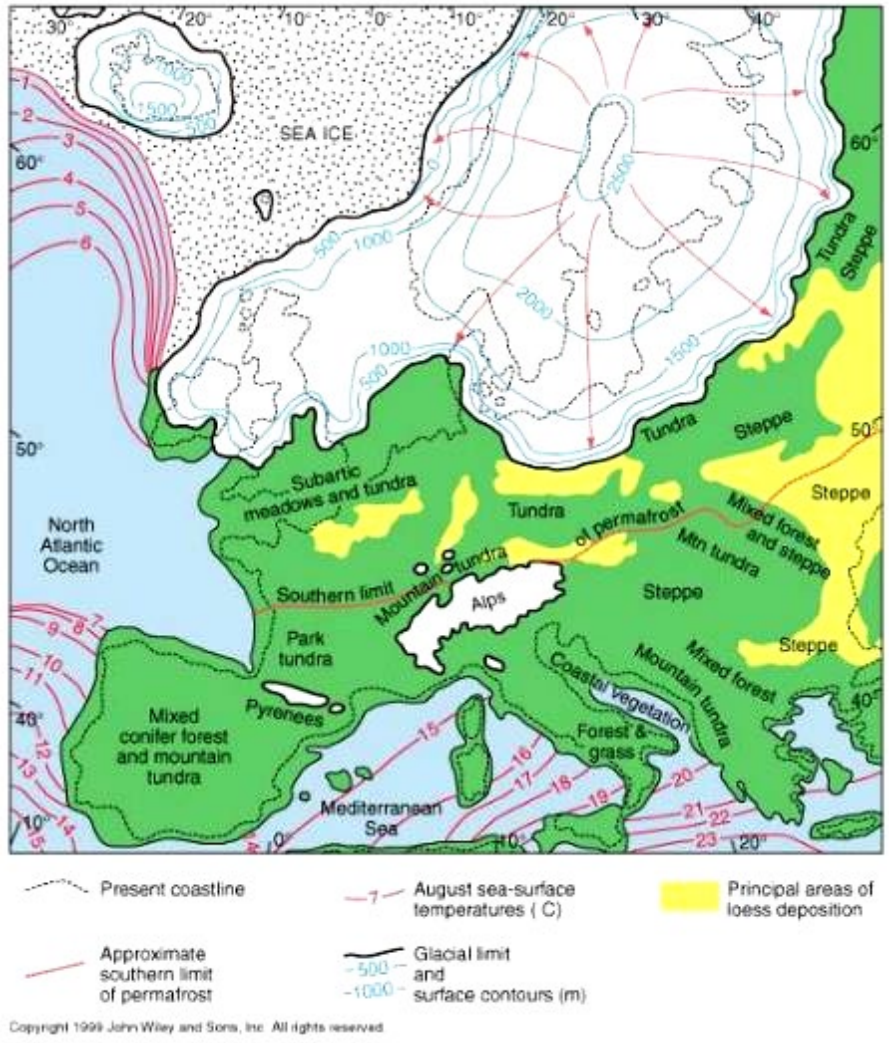
- Air bubbles trapped in polar ice sheets reveal the past 800,000 years of Earth's climate under **natural forcing** and a natural greenhouse effect.

- Evidence suggests **repeated episodes** of natural climate change and fluctuations of greenhouse gases.

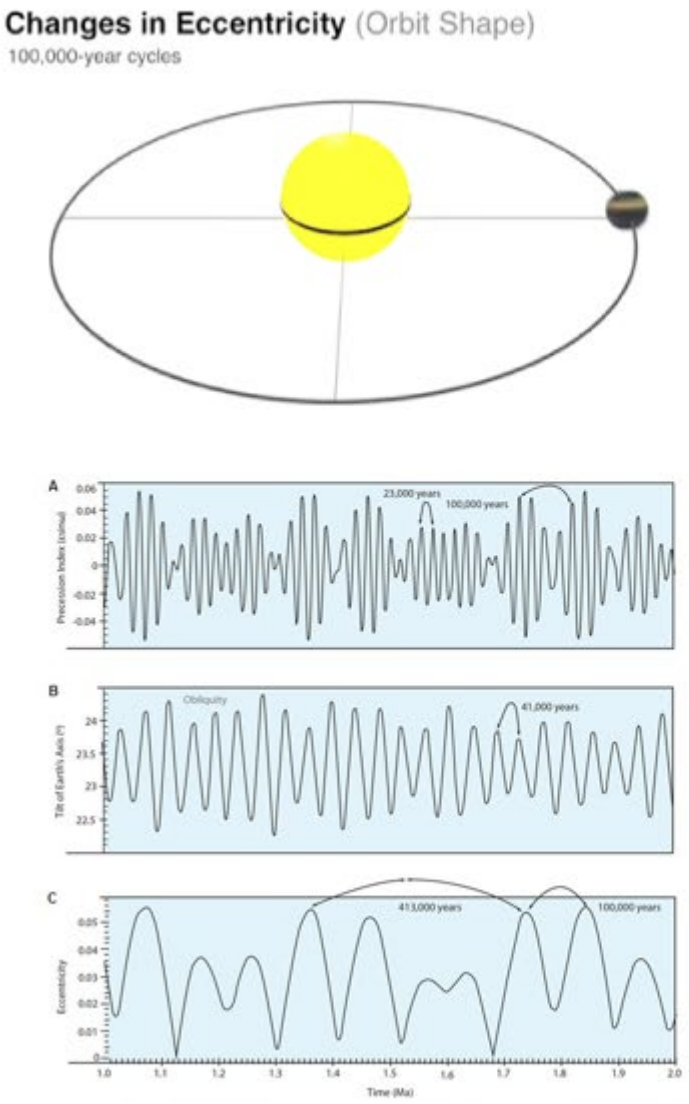

Interglacial Periods
Stepwise cooling
Abrupt climate change
[CO2] (ppm)
300
275
250
225
200
175
800,000
700,000
600,000
500,000
400,000
300,000
200,000
0
Years Before Present Day
8
4
0
-4
-8
Temperature Anomaly (°C)
Glacial Periods

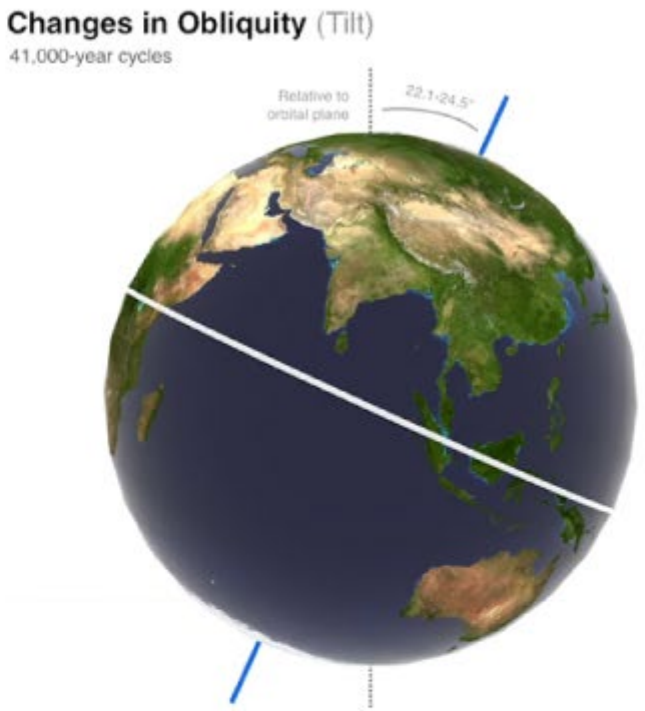

18,000 Years Ago
Modern Day
Glacial Ice
Sea Ice

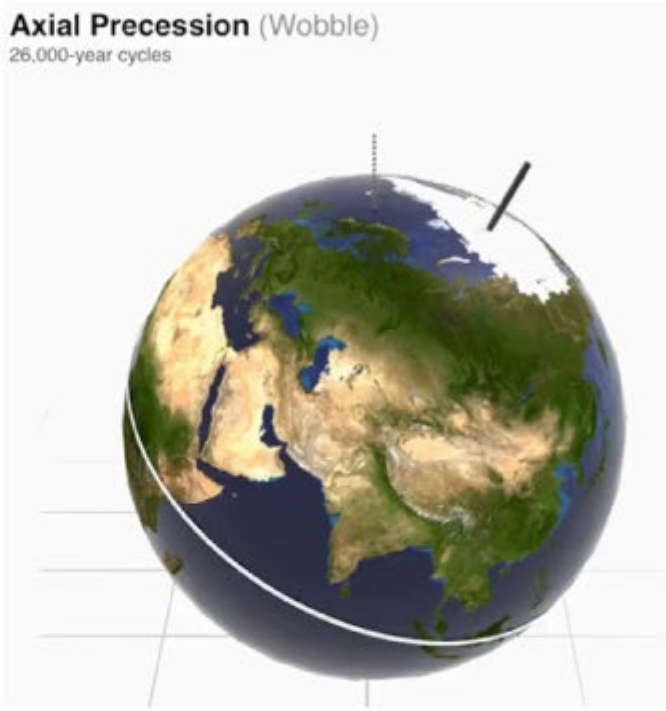
During the Devensian glacial (11,700 years ago), the Bristol region looked liked this:



- Driven by the Croll-Milankovitch pacemaker:

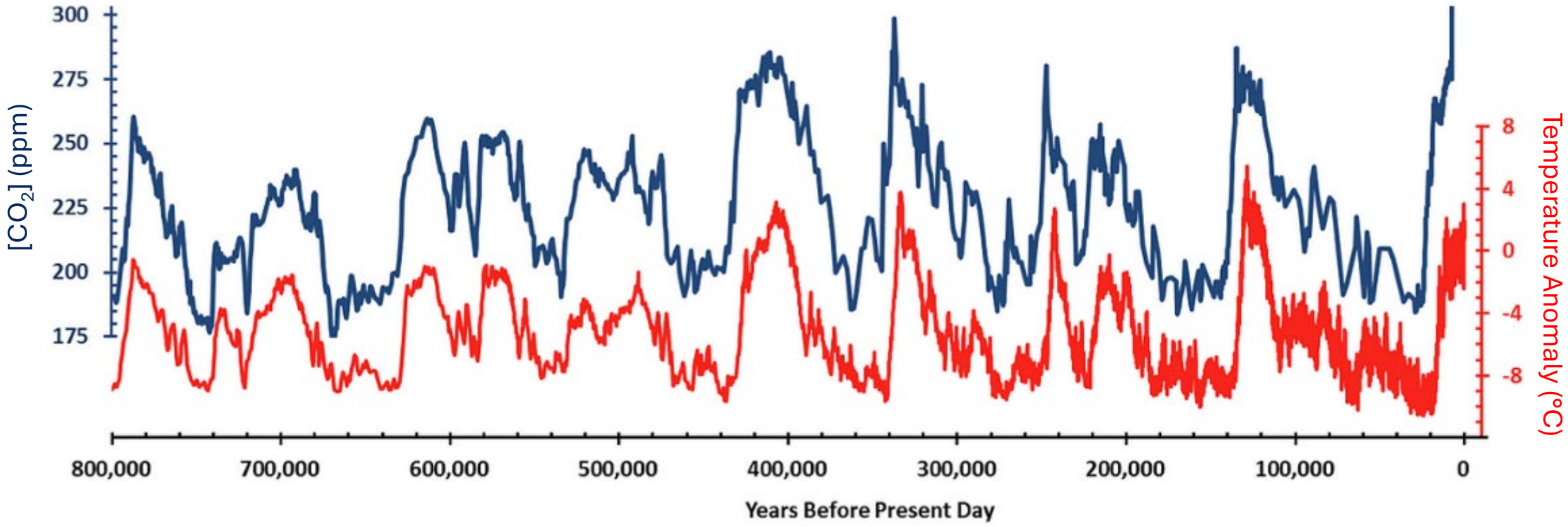






For animated versions of these images, see link below

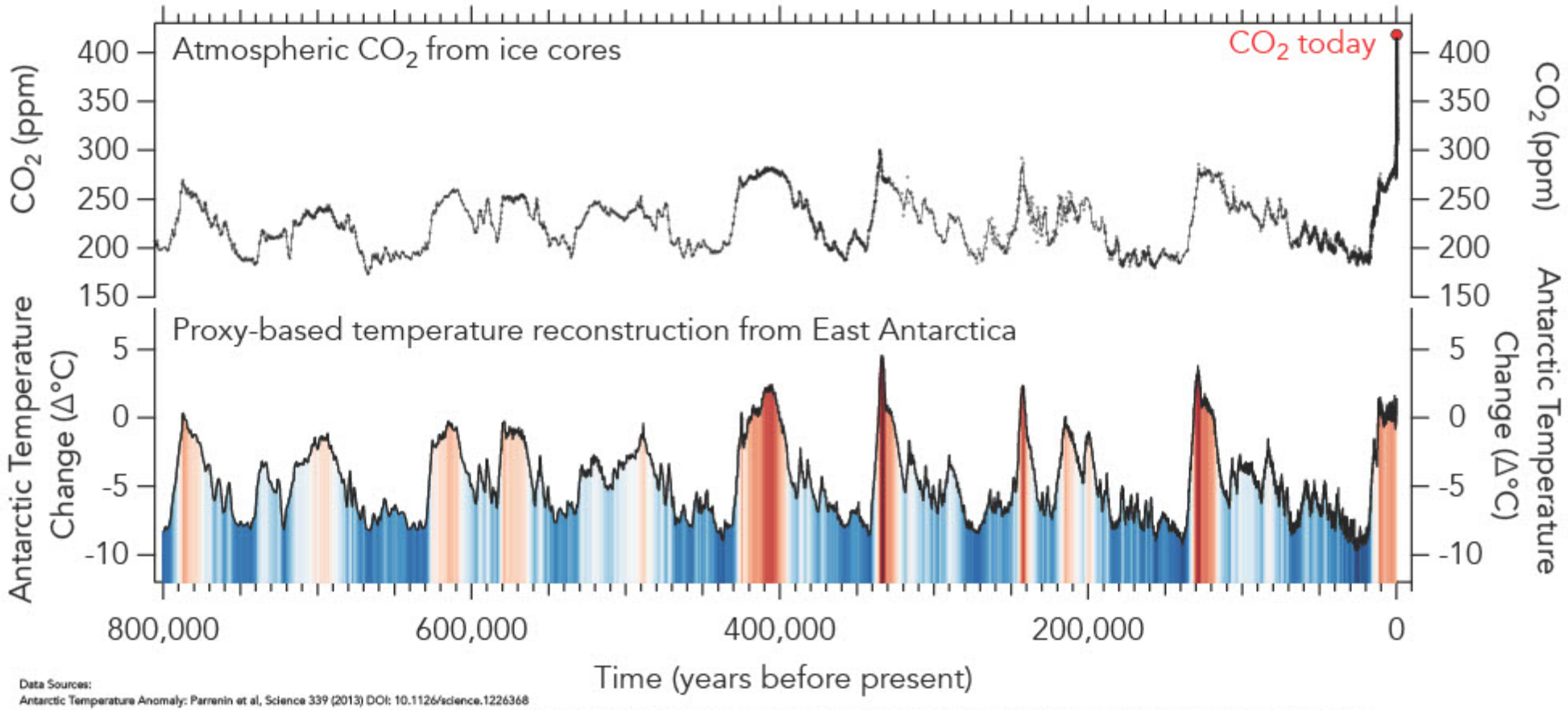
https://science.nasa.gov/science-research/earth-science/milankovitch-orbital-cycles-and-their-role-in-earths-climate/



Based on this graph what should happen next to global temperatures? Should they cool down or warm up?

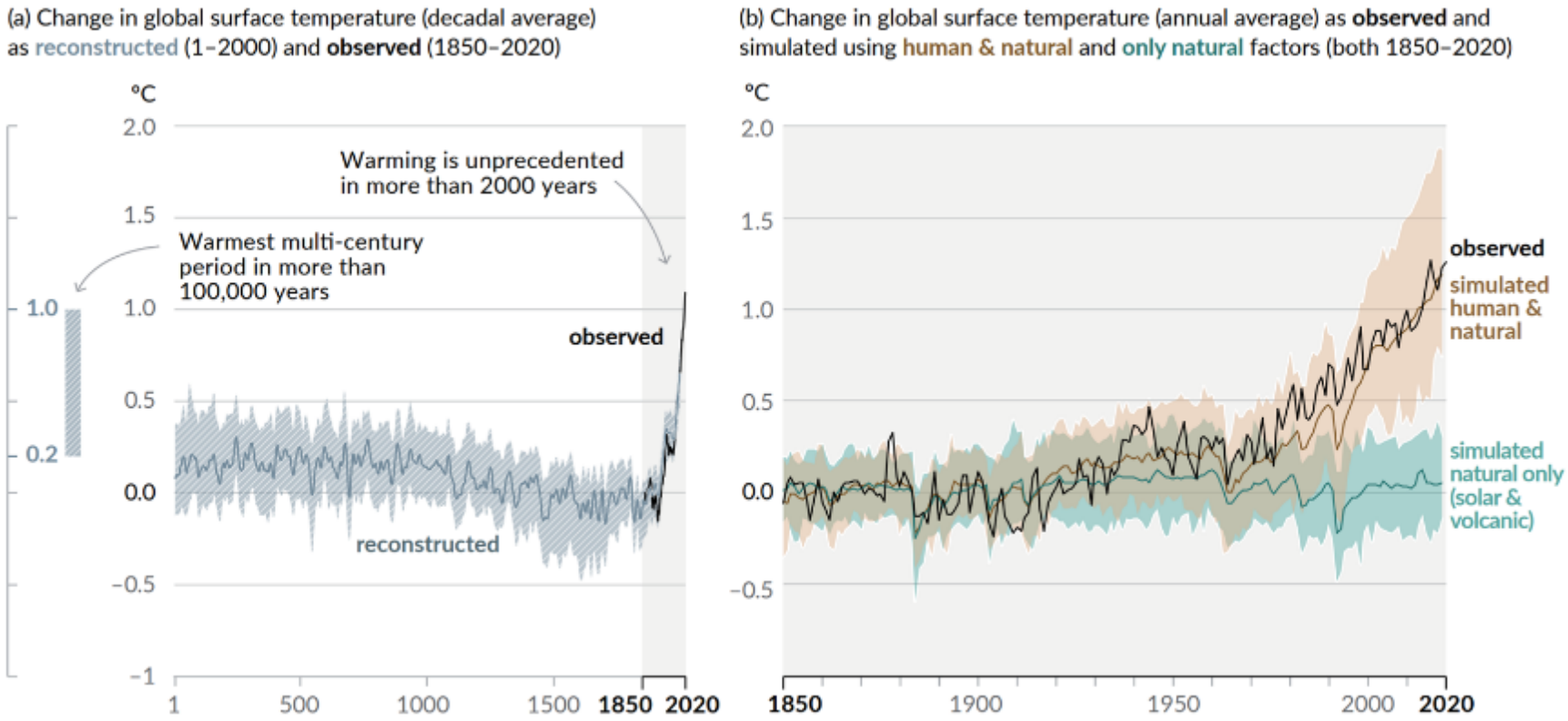
- Polar ice core records confirm that present-day atmospheric greenhouse gas concentrations are **anomalously high**

Figure 3: The oldest ice core records for atmospheric CO_2 and temperature change in Antarctica



Data Sources:
Antarctic Temperature Anomaly: Parrenin et al, Science 339 (2013) DOI: 10.1126/science.1226368
Atmospheric CO_2: Petit et al., Nature 399, 429 (1999); Fischer et al., Science 283, 1712 (1999); Monnin et al., EPSL 224 (2004); Siegenthaler et al., Science 310, 5752 (2005); Lüthi et al., Nature 453, 379–382 (2008) Loulergue et al., Nature 453, 383–386 (2008); Bereiter et al., PNAS 109, 9755–9760 (2012); Ahn et al., Global Biogeochem. Cycles, 26 (2012); Mitchell et al., Science 342, 6161 (2013); Marcott et al., Nature 514, 616–619 (2014); Bauska et al., Nature Geoscience 8, 383–387 (2015); Rubino et al., Earth Syst. Sci. Data, 11, 473–492 (2019); Nehrbass-Ahles et al., Science 369, 6506 (2020); Shin et al., Clim. Past 16, 2203–2219 (2020) Lee et al., Clim. Past 16, 1691–1713 (2020);Bauska et al., Nature Geoscience 14, 91–96 (2021); NOAA/GML (gml.noaa.gov/ccgg/trends/)
Figure made by Thomas Bauska

- The Earth's climate has gone through periods of warming and cooling.
- Human activity and increasing GHG concentrations in the atmosphere is taking the planetary system outside of the **natural climate variability** we have seen in the geological past.
- I.e. we are experiencing **unnatural or anthropogenic climate change**.



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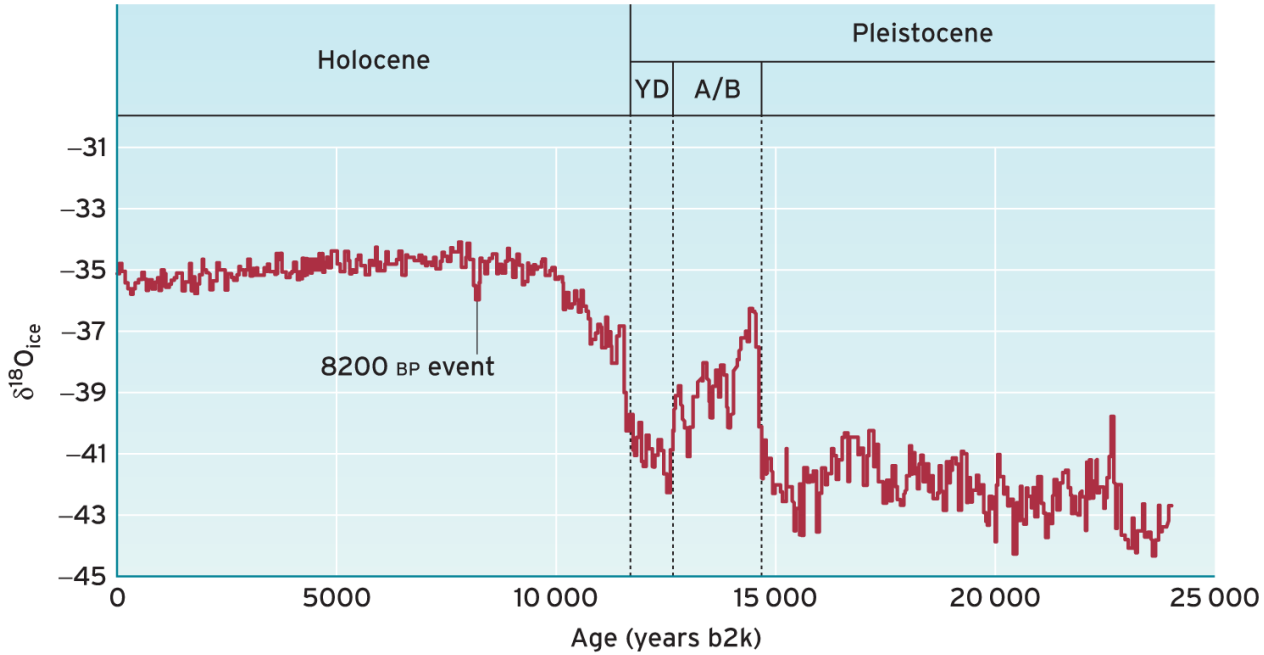
Internal Feedback

Does Orbital Forcing Explain Everything?

- The orbitally-driven changes in insolation are too small to have caused the major glacials and interglacials.
- There is a **4-6 degree shortfall.**
- The pacemaker does not explain why we can see **abrupt or non-linear** changes in past climate.

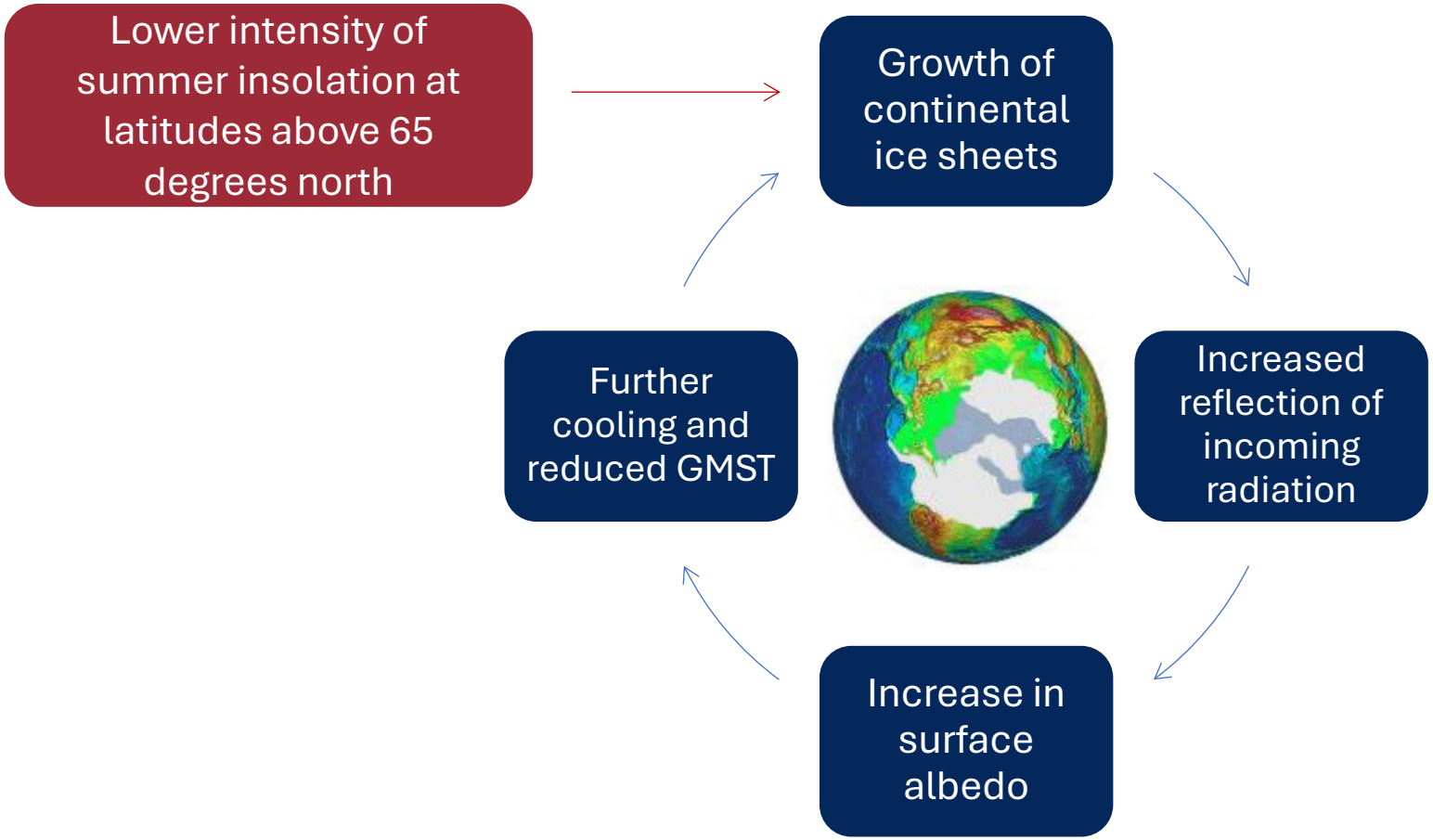


The Answer: Feedbacks

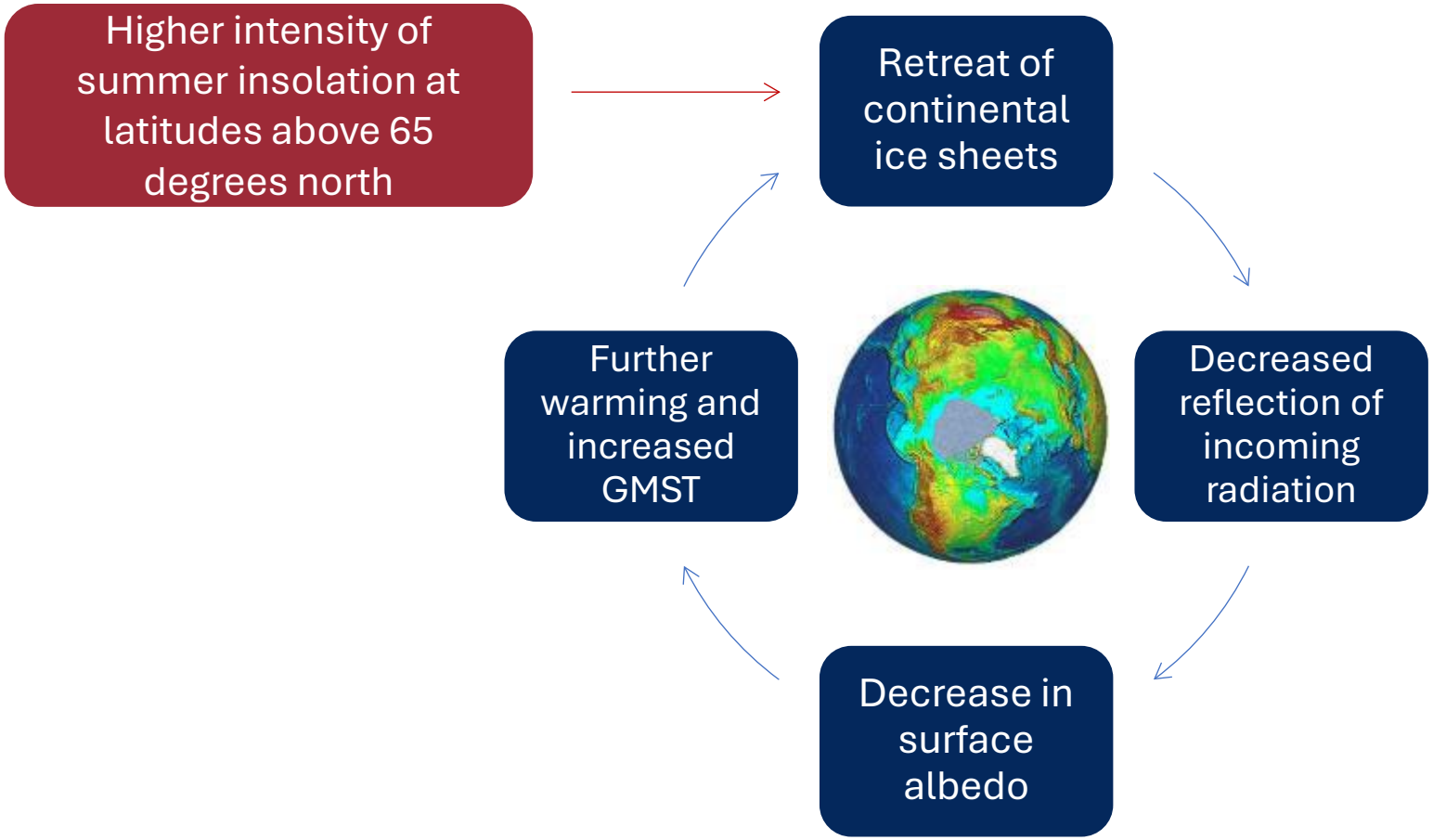
- Feedbacks are processes within components of the Earth system act to dampen or enhance the impacts of orbital forcing (Davis and Nagle, 2018)

- Positive feedbacks: enhance the effect of orbital forcing as the initial trigger. So a change in incoming radiation can be enhanced by a +ve mechanism.
- Negative feedbacks: dampen the effect of orbital forcing as the initial trigger. So a change in incoming radiation can be dampened by a –ve mechanism.

- Example 1: Changes in orbital forcing result in an initial decrease in incoming solar radiation resulting in cooling. This is then enhanced by internal positive feedback.

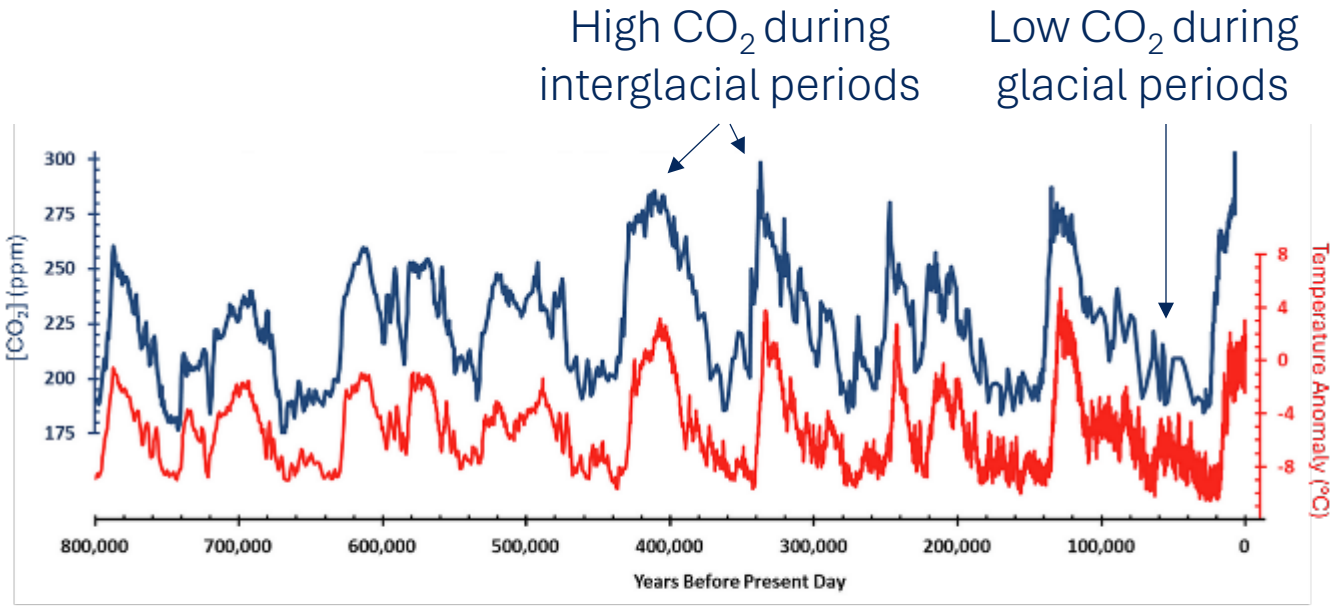


- Example 2: Changes in orbital forcing result in an initial increase in incoming solar radiation resulting in warming. This is then enhanced by internal positive feedback.



Greenhouse Gases & Feedback

- GHGs will also generate and contribute to positive and negative feedbacks within the earth system.
- Concentrations of these gases in the atmosphere is an important factor in bringing about warming and cooling periods.



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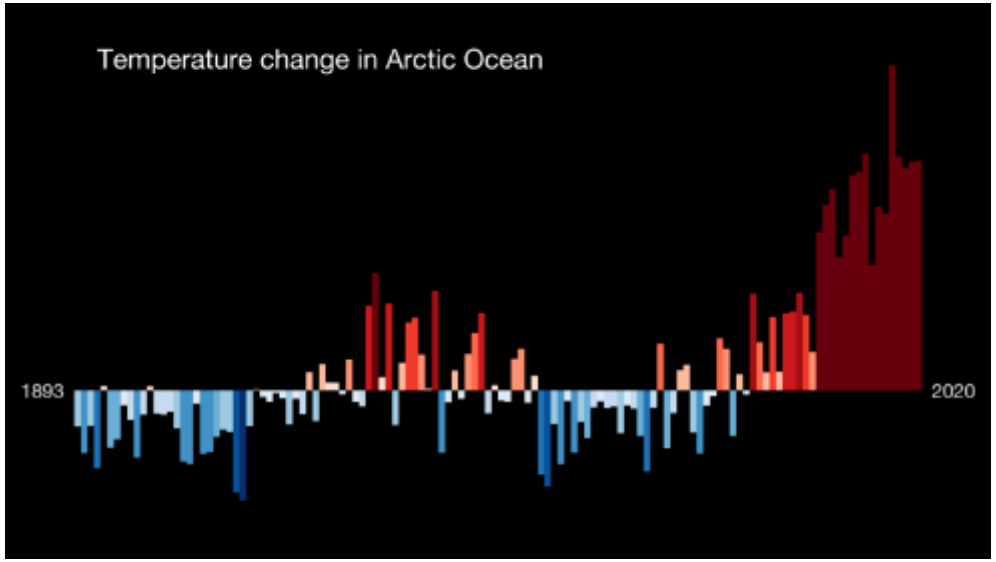
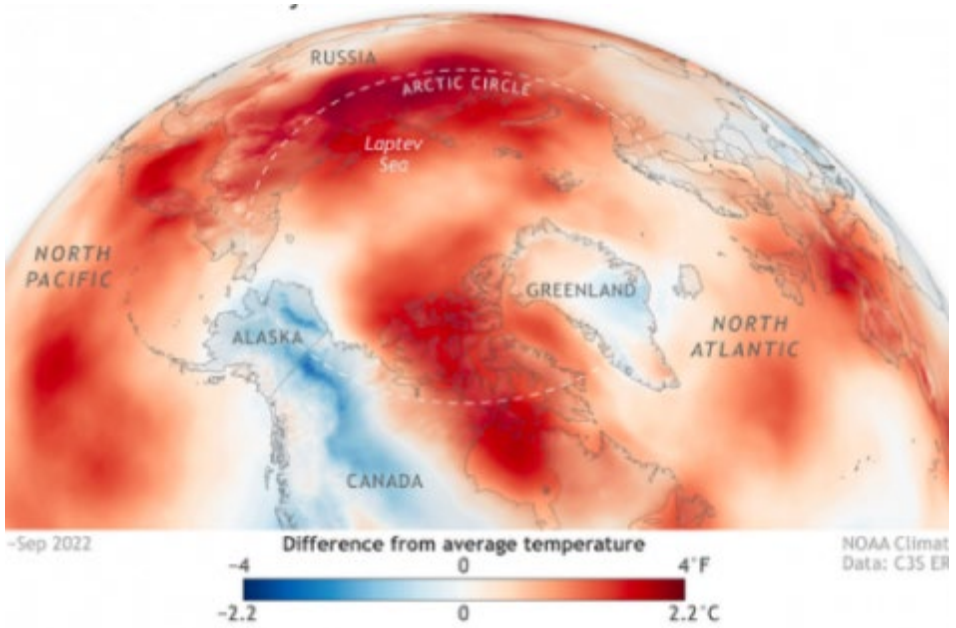
Arctic Amplification

The Arctic

- The Arctic is an important area for climate science research:



1. Climate Sensitivity: The Arctic is warming at about twice the global average. This makes it a sensitive indicator of broader climate trends. Studying this region helps scientists understand how and why climate changes can accelerate in certain areas.



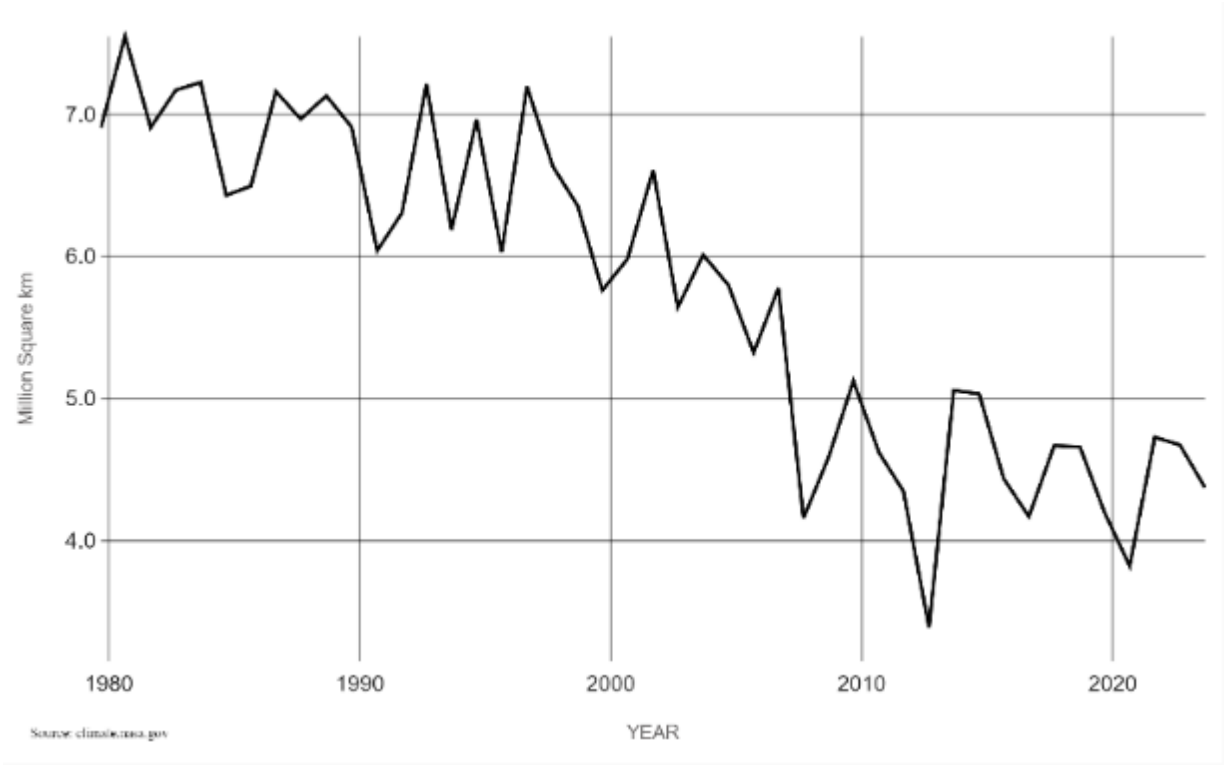
- Modelling changing temperatures in the Arctic region is a challenge for climate scientists.

- Many models do not accurately capture the scale of the observed temperature change (Sweeney et al. 2023).

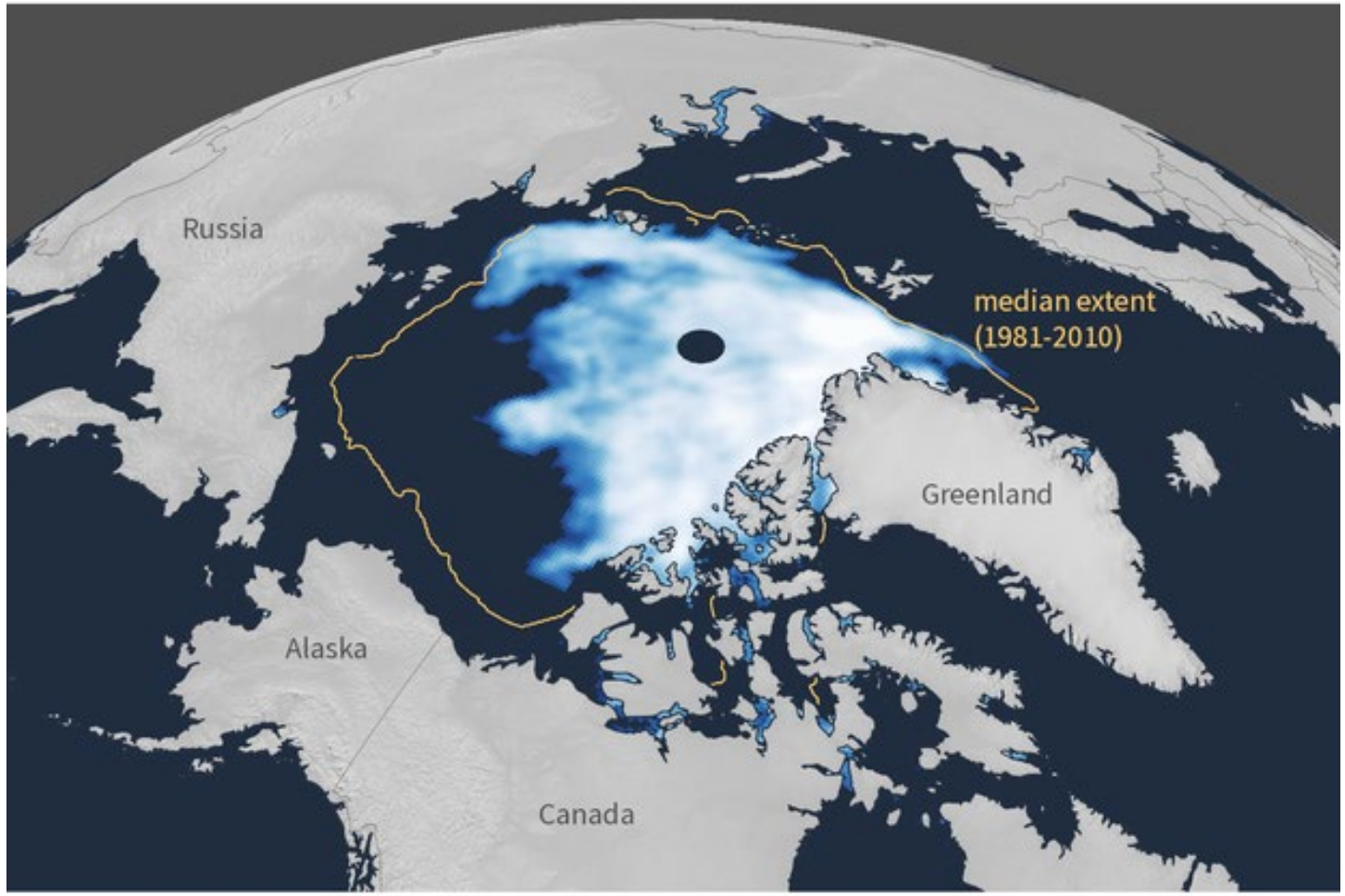
- New concerns that natural variability within the earth system (natural changes in climactic conditions) have been masking the full extent of rising temperatures in the Arctic.

- The Arctic might actually be warming **3-4 times faster** than the rest of the Earth (Zhou et al. 2024)

- 2. **Sea Ice Loss**: The Arctic's sea ice is shrinking rapidly, which has both regional and global impacts. Sea ice **reflects** sunlight, keeping the region cool. As it melts, darker ocean water **absorbs** more heat, further accelerating warming.



2023 SUMMER MINIMUM

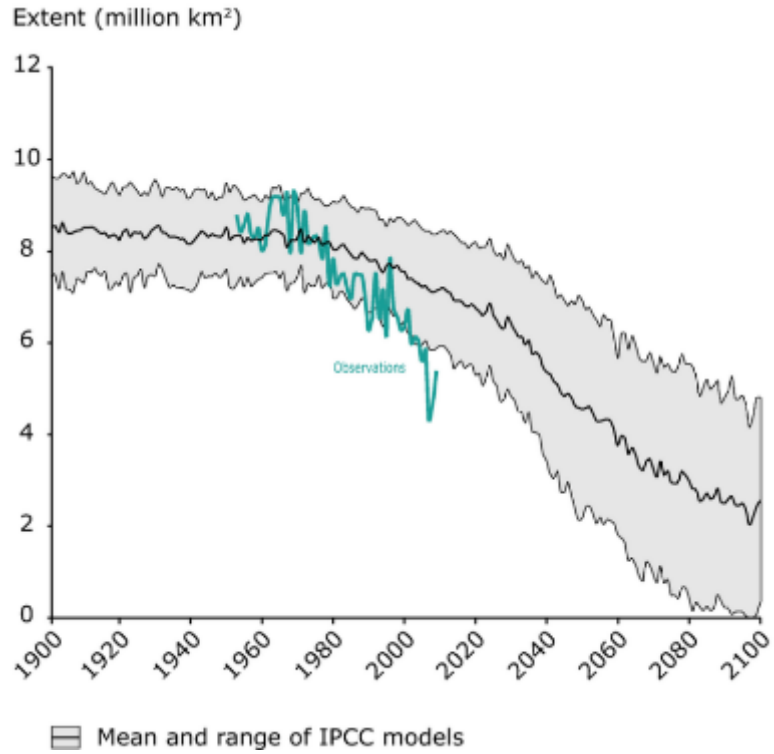


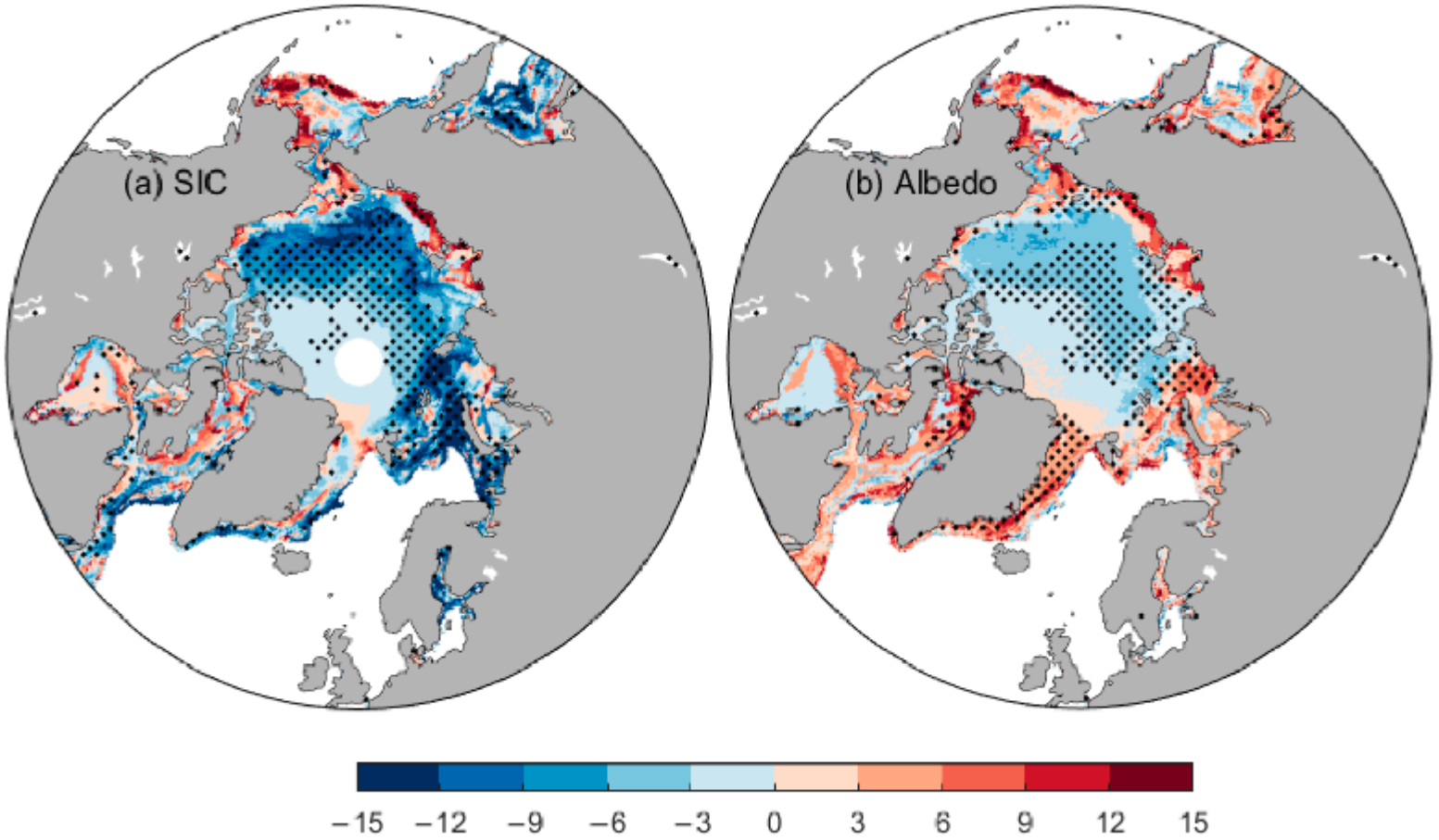
September 19, 2023

Sea ice concentration (percent)

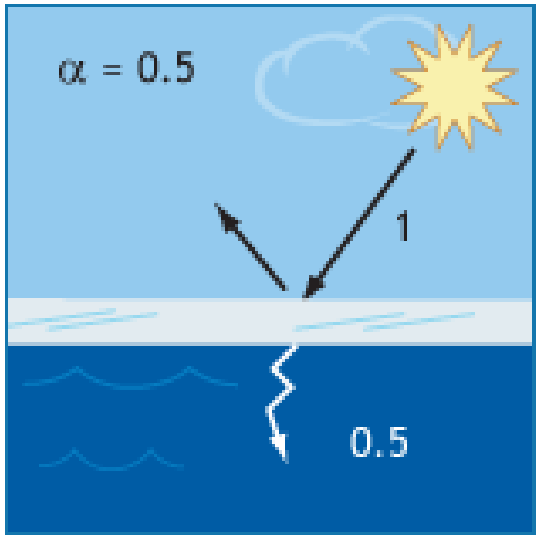
15 100

NOAA Climate.gov
Data: NSIDC

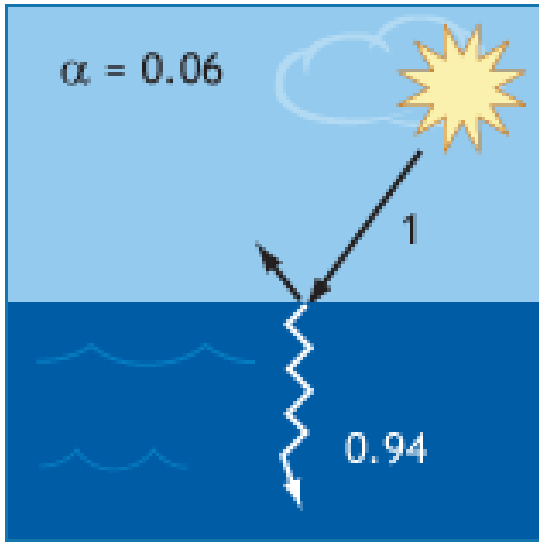




Bare Ice



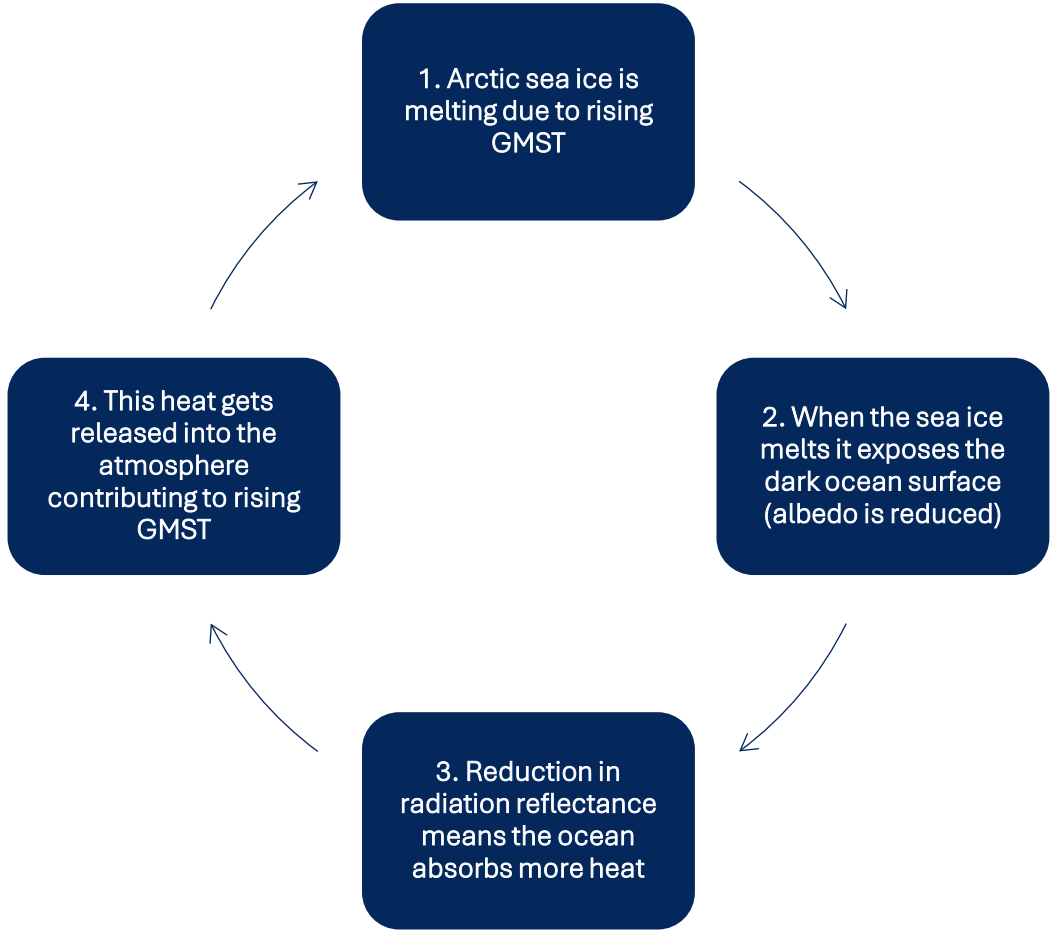
Open Ocean



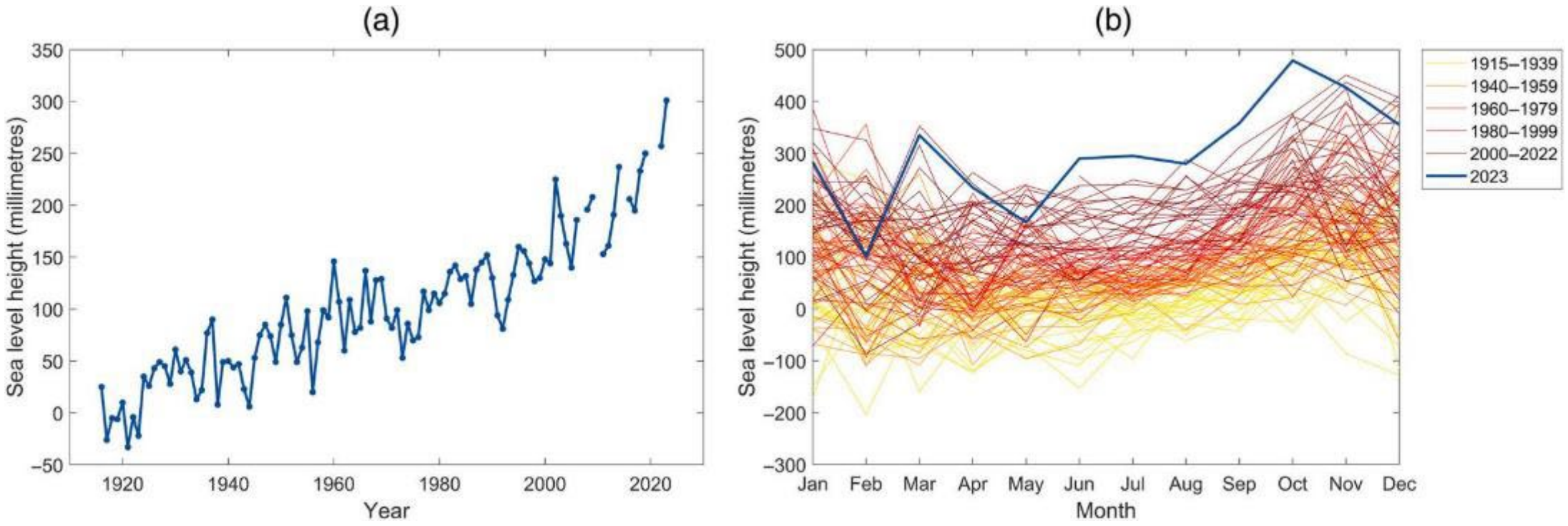
Arctic Amplification

- What we are seeing in terms of changing Arctic temperatures and sea ice loss is a positive feedback developing enhancing the impacts of climate change.

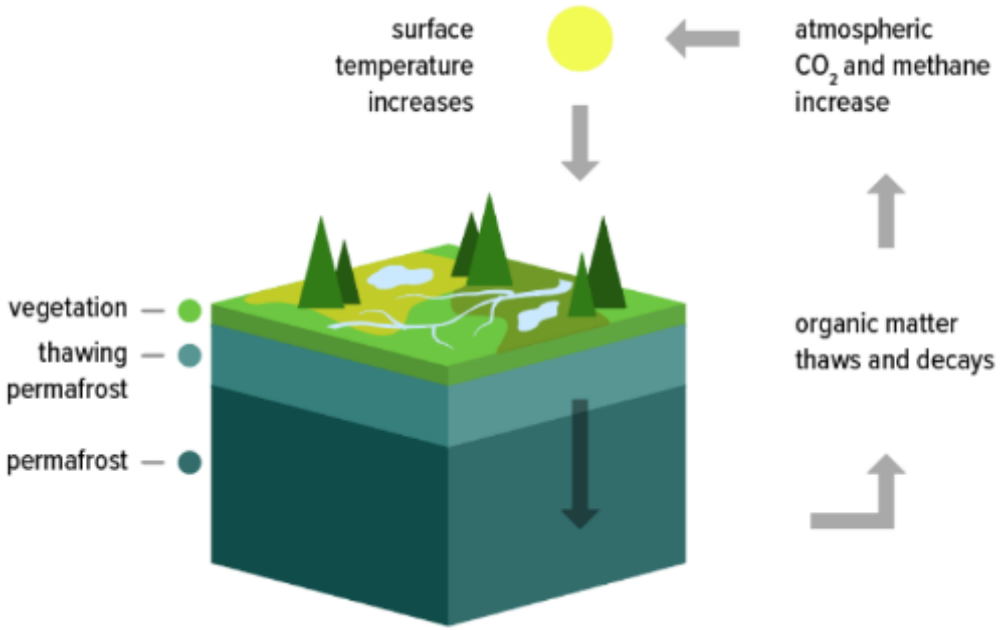
- This could have far reaching impacts…



- 1. **Rising Sea Levels**: Melting glaciers and ice sheets in the Arctic contribute to rising sea levels, which threaten coastal communities and ecosystems worldwide.



- 2. **Permafrost Thaw**: Large areas of the Arctic are covered by permafrost, which **stores** vast amounts of carbon. As the Arctic warms, permafrost thaws, releasing carbon dioxide and methane, potent greenhouse gases. This could significantly **accelerate** global climate change.

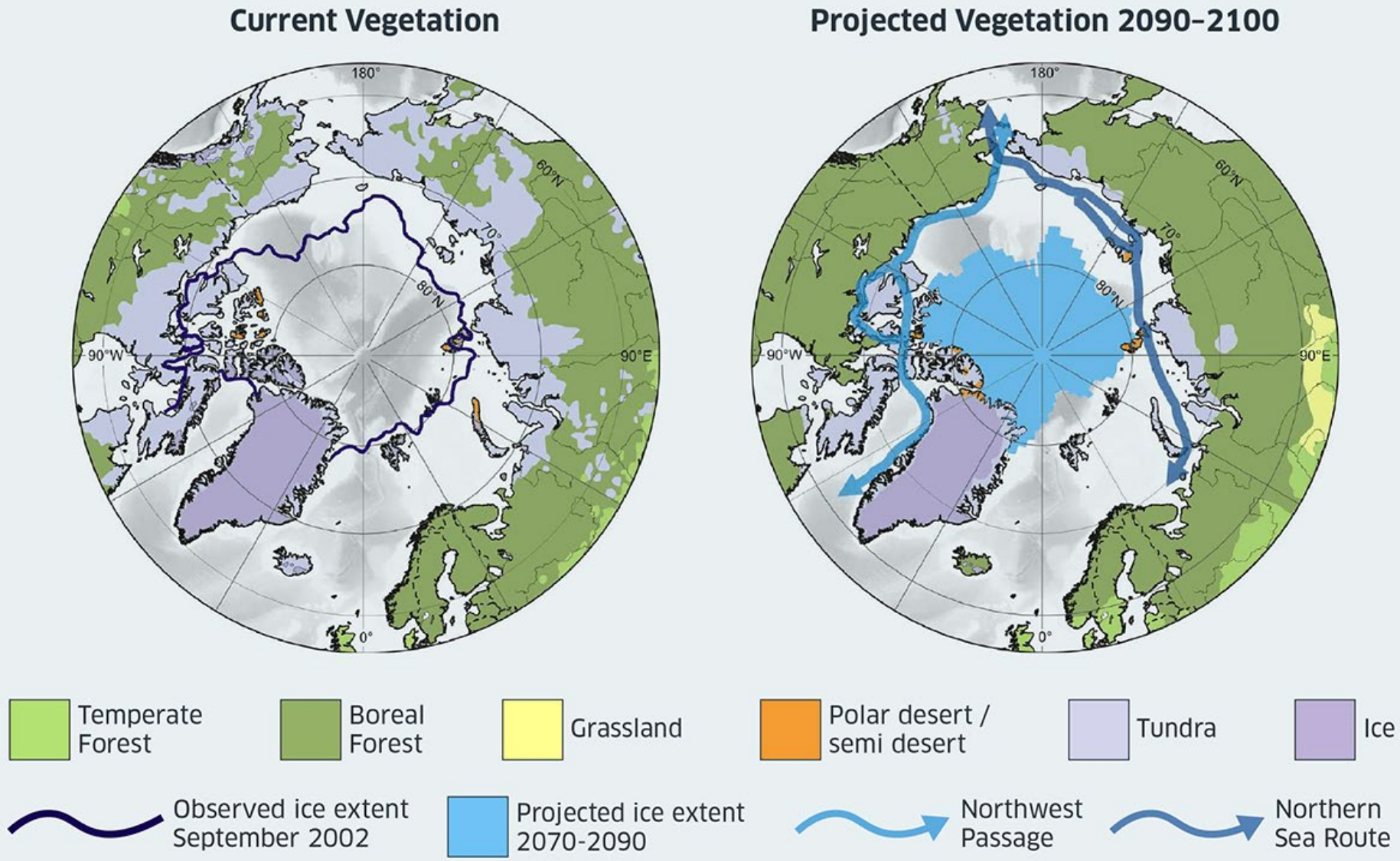


- 3. Both changing sea ice extent and tundra climatic conditions will likely have significant impacts on **ecosystems**.

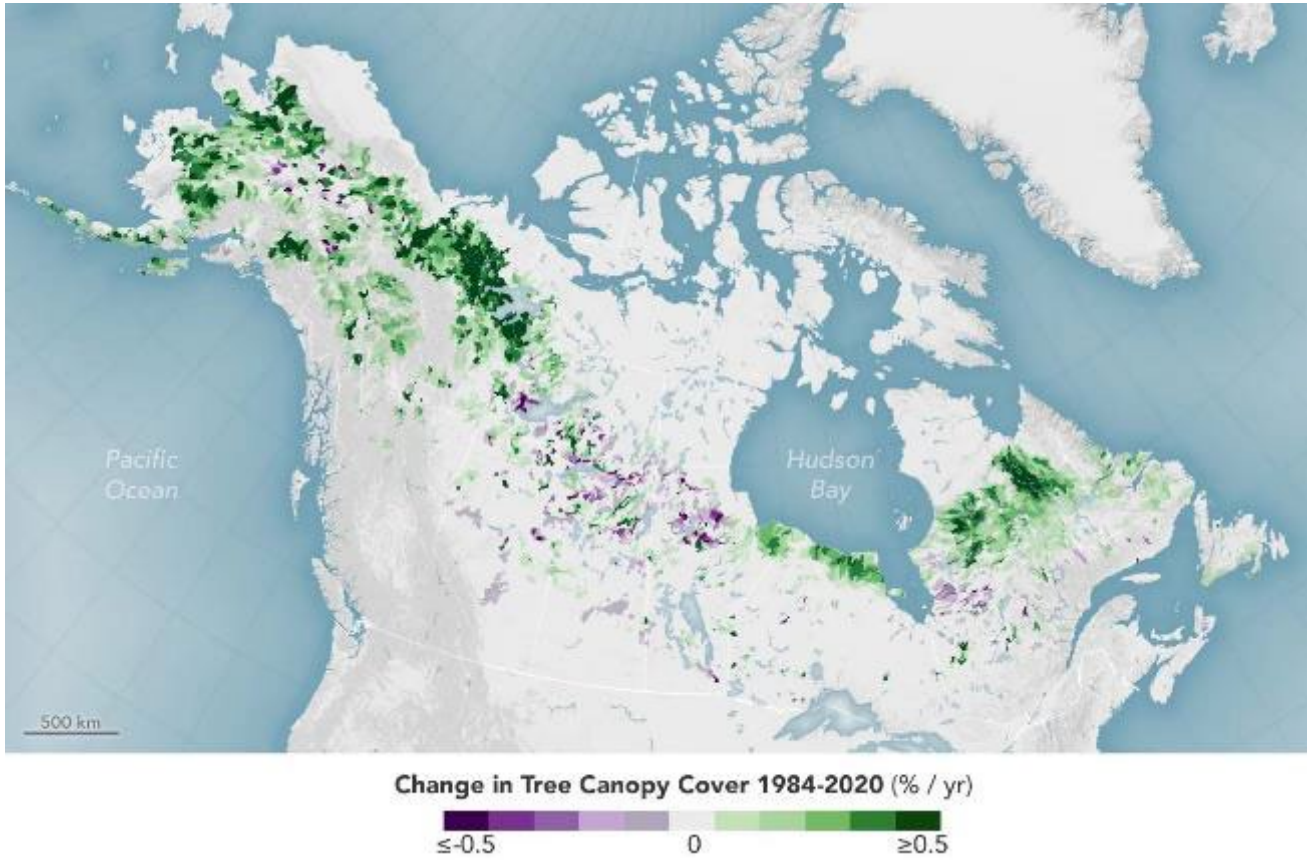
- **For example: Polar Bears**
- Polar bears rely on sea ice to hunt seals. As ice retreats, bears have to travel longer distances or are forced to hunt on land, where food is scarce.
- Seals breed on sea ice, so the loss of ice affects their abundance and availability as prey for polar bears.
- Longer Fasting Periods: With the sea ice melting earlier in the spring and freezing later in the fall, polar bears face longer fasting periods, leading to malnutrition.

- Polar bear populations are declining in many areas, particularly in regions where sea ice loss is most pronounced.
- A 2020 study projected that if current trends in greenhouse gas emissions continue, many polar bear populations could become extinct by the end of the century due to the loss of their sea ice habitat.

Changes in Arctic vegetation patterns



- Rising GMST is changing the vegetation structure of forests in the far north.
- Increased presence of **trees and shrubs** in the tundra.
- The change in forest structure could **absorb** more of the greenhouse gas carbon dioxide (CO_2) from the atmosphere.
- The change in forest structure may also cause **permafrost areas to thaw** as more sunlight is absorbed by darker vegetation. This could **release** CO_2 and methane.

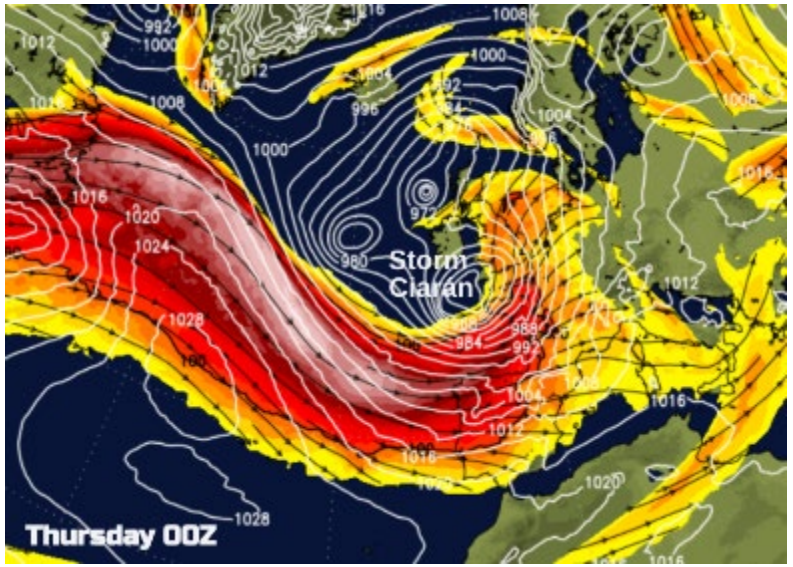


Montesano et al (2024)

- 4. And also **global weather patterns** as changing temperatures and sea ice extent in the Arctic can have significant impacts on the strength and position of the **jet stream.**

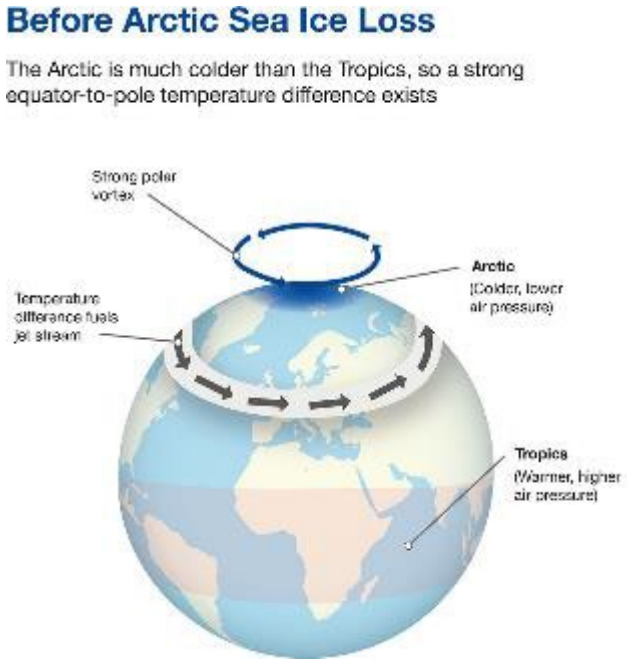
- Models generally agree sea ice loss results in a more **southerly jet stream** (a southerly jet stream can be linked to stronger winter storms in the UK) (Ye et al 2023).

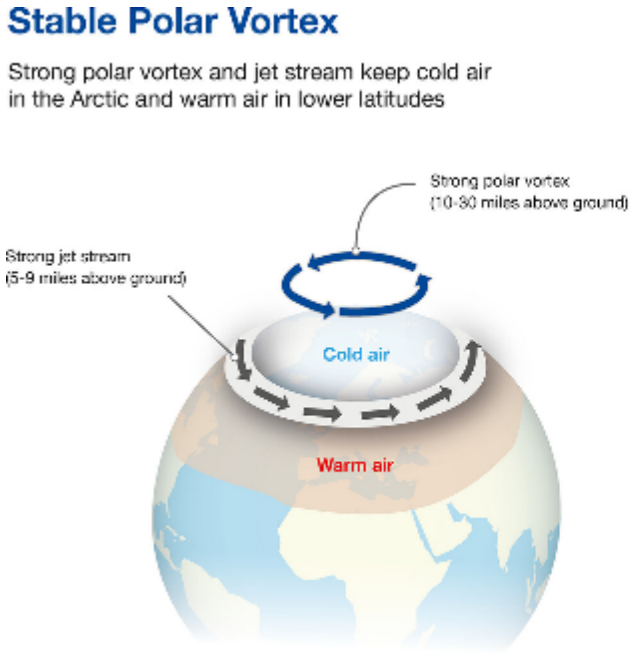
- Storm Ciaran 2023 was an example of a major storm driven by a southerly jet stream.

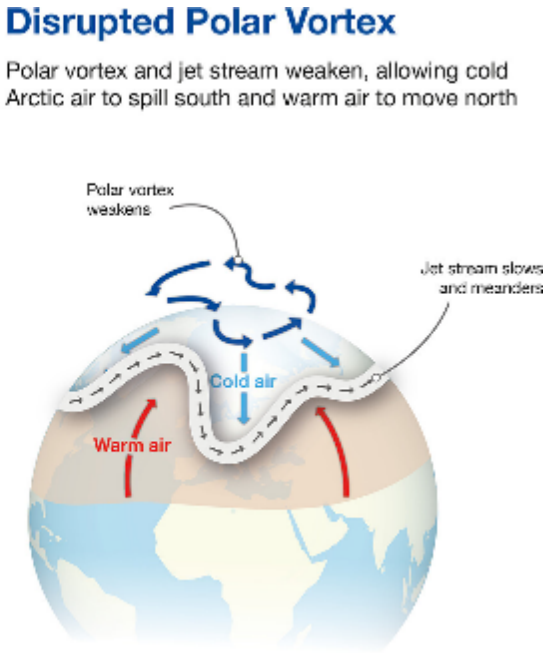


- As well as the jet stream sea ice might also affect the polar vortex – if the vortex is weakened this could weaken the jet stream and might lead to extreme cold conditions in the UK (Screen 2021)

- E.g. Beast from the East (2018)

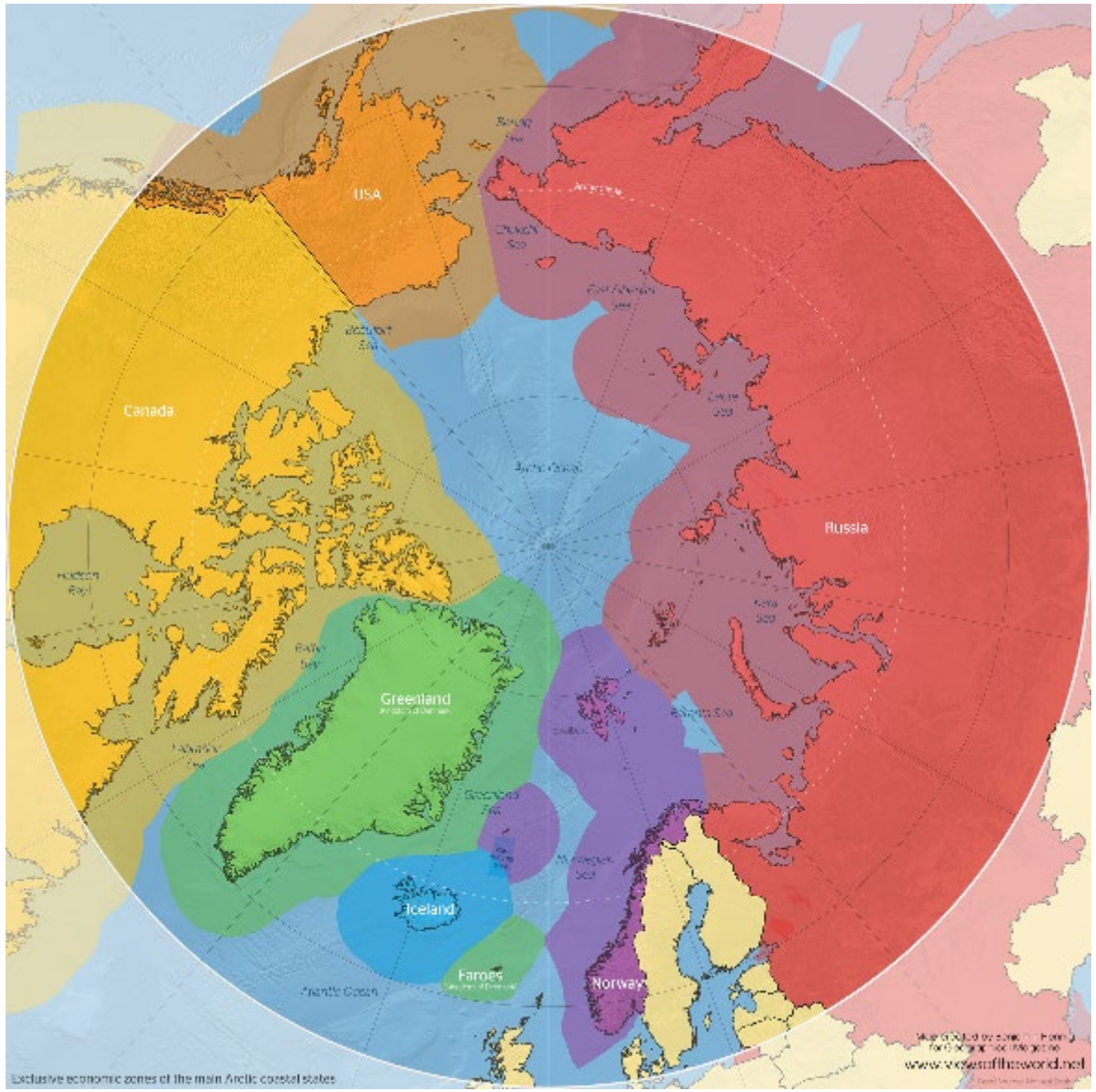




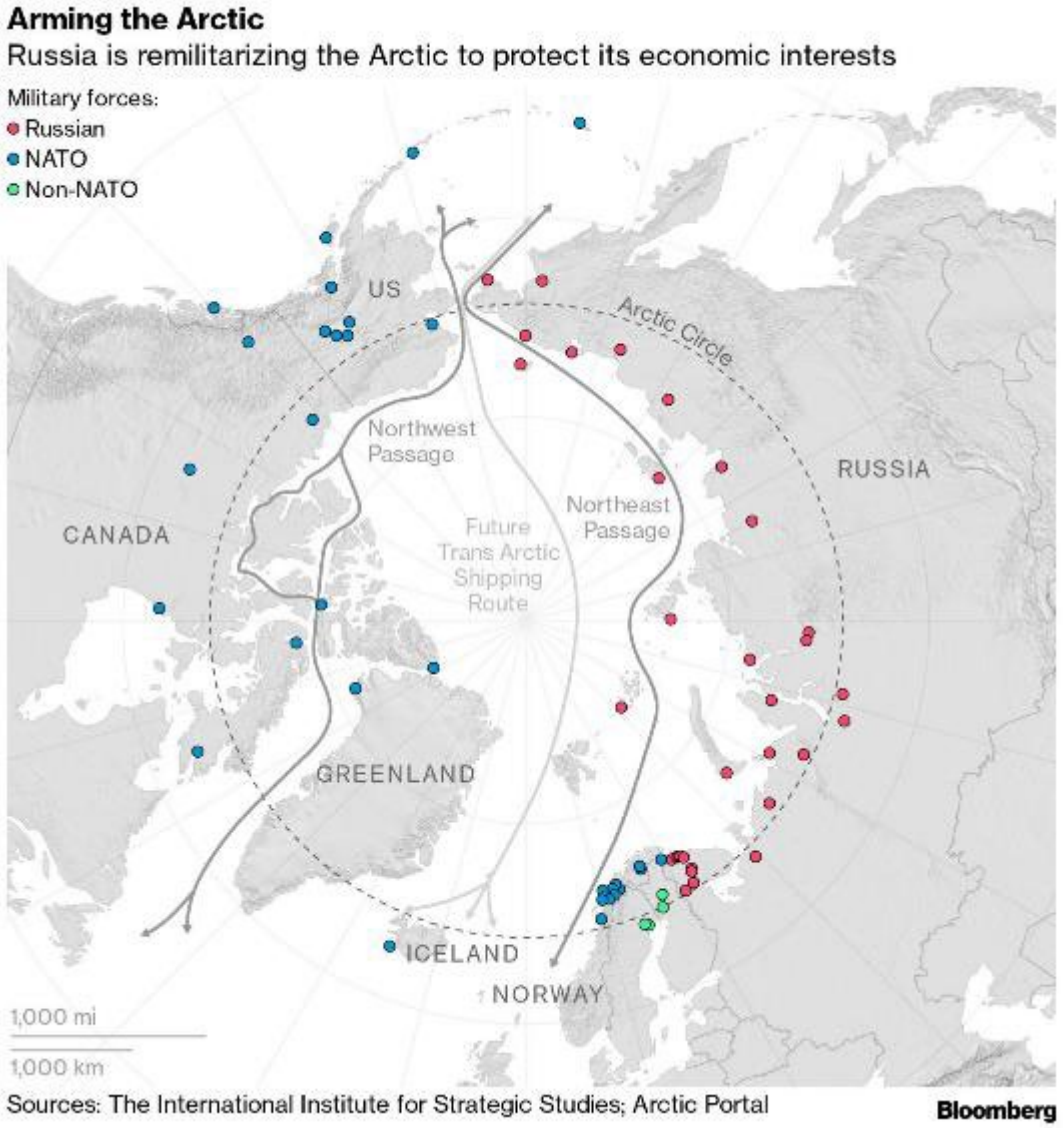


- 5. Geopolitical and Economic Implications.

- The Arctic is rich in natural resources, including oil, gas, and minerals. With ice **retreating**, access to these resources is becoming **easier**.
- Arctic nations, particularly Russia, the United States, Canada, Denmark (via Greenland), and Norway, are reinforcing **territorial claims**.

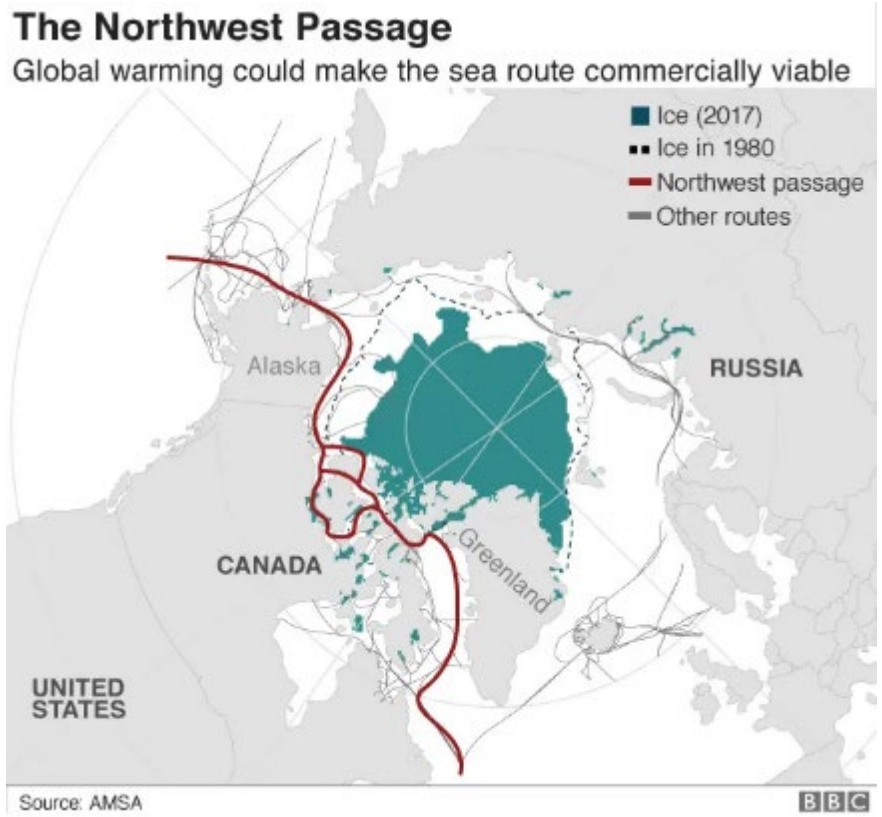


- Nations are expanding their **military presence** in the Arctic due to increased accessibility.
- Russia has reopened Soviet-era bases and is modernising its Arctic fleet.
- The United States and NATO are also enhancing their Arctic capabilities.
- This raises concerns about the potential for military confrontations in the region, especially in disputed waters and resource-rich areas.



- Reduced sea ice is shortening the navigation along the Northern Sea Route (NSR) and Northwest Passage (NWP).
- The NSR could reduce travel time between Europe and Asia by up to 40%.

- This shift offers economic benefits, such as reduced fuel consumption and faster shipping times, but also raises strategic concerns.
- Russia controls much of the NSR, and its policies regarding access, tolls, and security influence global trade dynamics.
- The NWP, primarily controlled by Canada, also offers new possibilities for global shipping.



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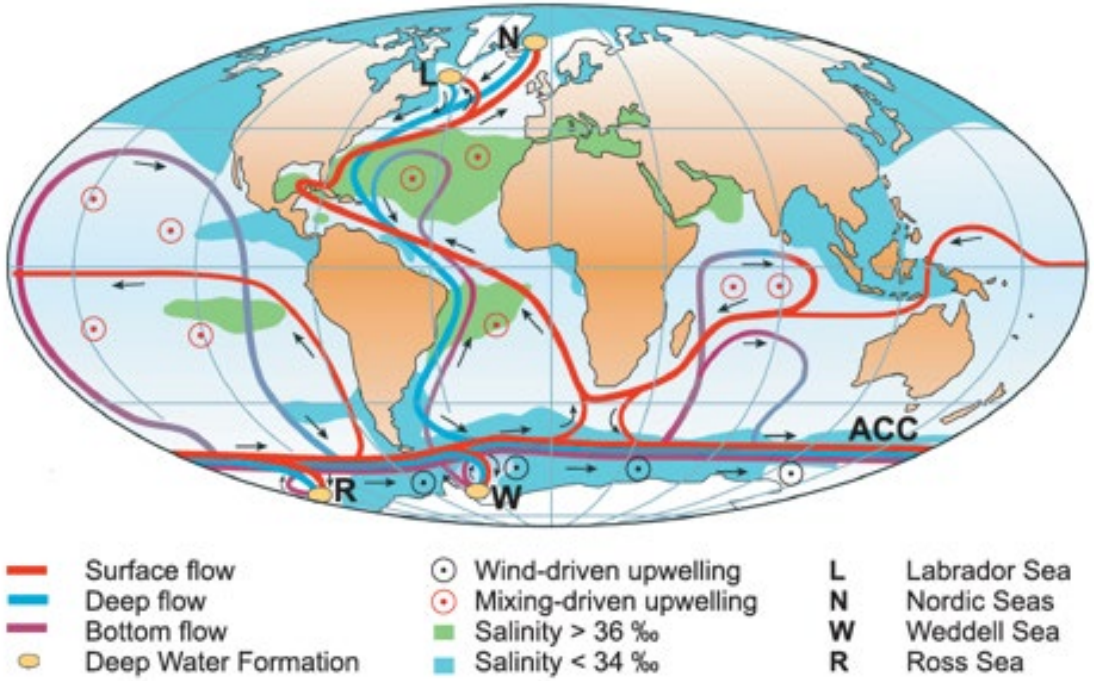
The Atlantic Meridional Overturning Circulation

The AMOC & Internal Feedback

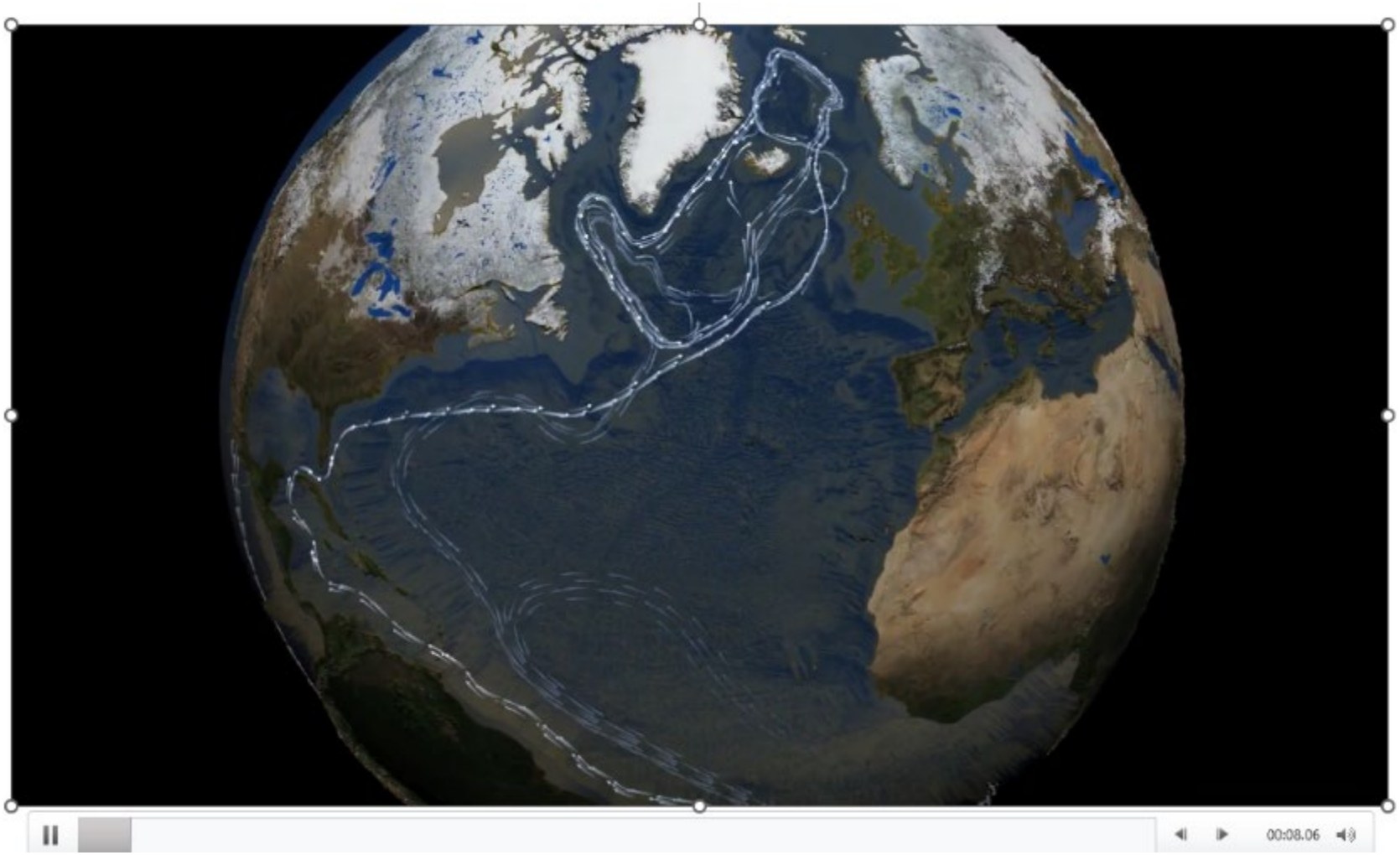
- We also rely on the oceans to perform negative feedback roles.
- Ocean circulations can help to dampen the effects of orbital forcing and rising temperatures by redistributing heat within the earth system.
- A key feature of the global oceanic conveyor belt is the Atlantic Meridional Overturning Circulation.

Overturning Circulation

- Overturning circulation is one of the ‘engines’ which power the global thermohaline circulation (the global conveyor belt).
- These engines are only found in a small number of places.
- These overturning locations connect surface ocean and the atmosphere with deep ocean.
- Two key engines in the North Atlantic: Labrador and Nordic Seas.
- South Atlantic: Ross and Weddell Seas



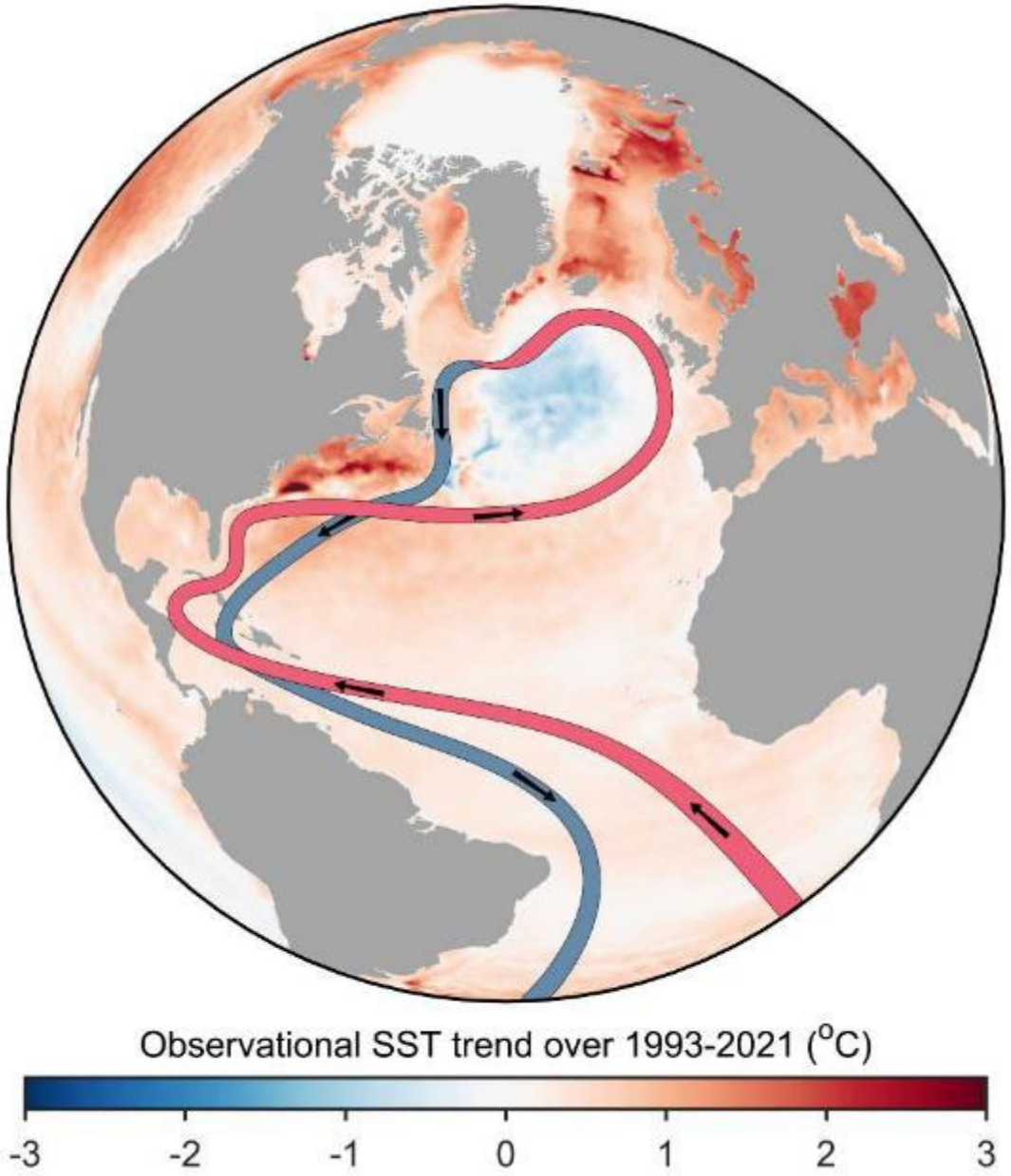
- AMOC Animation



See Thermohaline Circulation in Our Oceans [1080p] on Youtube and original visualisations at NASA SVS | The Thermohaline Circulation - The Great Ocean Conveyor Belt - Stereoscopic Version

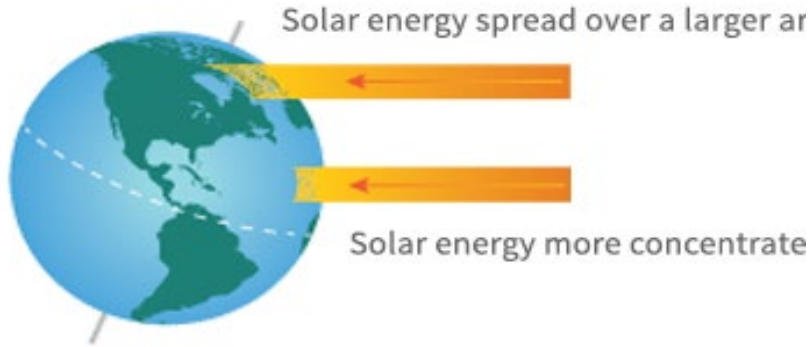
- AMOC: Atlantic Meridional Overturning Circulation.
- Specifically, the portion of the thermohaline circulation with overturning in the NA.

- Where warm surface water travels northwards
- Overturns…
- Resulting in cold North Atlantic Deep Water travelled southwards



Internal Feedback

- The AMOC is currently performing a **negative feedback role**.
- It redistributes heat from the equator towards the pole preventing **unlimited heating at the equator** and **cooling in the high latitudes**.
- Heat is transferred from the ocean to the **atmosphere** warming surface climate.
- Strong influence on UK and NW Europe climate.



AMOC Variability & Concerns

- The AMOC shows **variability** over the observational record.
- However, events which have happened in the geological record show the potential of a "**collapse**" of the AMOC which acts as a **tipping point** and generates **abrupt cooling** in North Atlantic region
- In the past this has been associated with major **melting events** as we move into interglacials.
- With the rapid melting of glaciers and icesheets today could this happen again?

Melting of the Greenland Ice Sheet

- Lenton et al (2019) identify the GIS as a major potential source of freshwater input into the North Atlantic.
- In the last 20 years there has been observed loss of mass of GIS.
- Significant ablation: represents the ensemble of processes that lead to ice and snow mass loss – e.g. surface melt, sublimation.
- Loss is driven by +ve: “Arctic Amplification”

North Atlantic Freshening

- Low salinity meltwater from a thawing GIS could inhibit densification (Rahmstorf, 2016).
- The influx of freshwater into these systems is called "freshening".

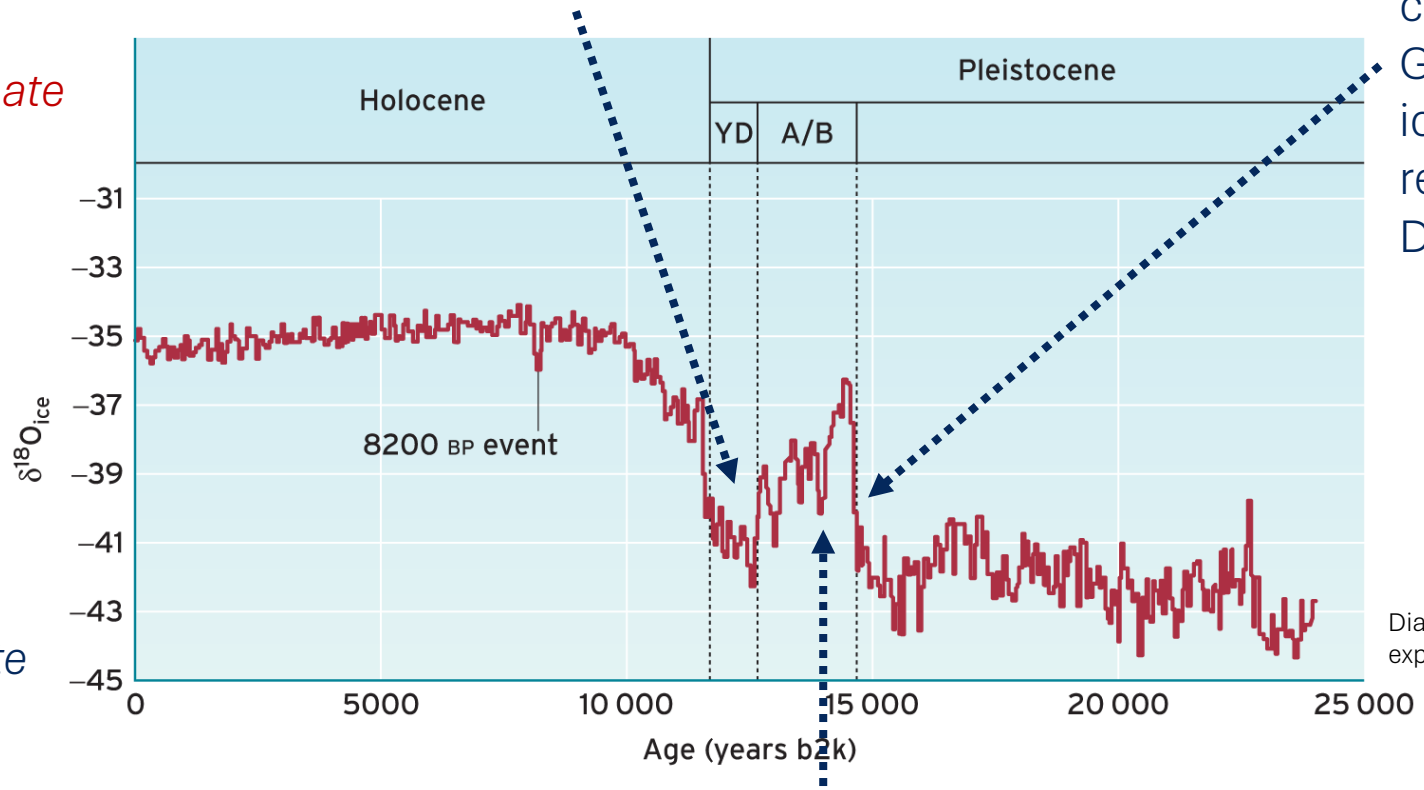
- The temperature of the meltwater is less significant.
- It's the freshening effect on the key downwelling location which is a concern.
- As soon as the surface water starts to be diluted by freshwater it will no longer be dense enough to sink.
- If densification was stopped the AMOC would switch from an "on" stable state to an "off" stable state (Rahmstorf 2016)

- This has happened before – resulting in an abrupt episode of **non-linear climate change** at the end of the Devensian glaciation (13,000 years before present).

3. Warmer waters no longer reach northerly latitudes, causing an abrupt cold episode (the "Younger Dryas").

1. Increased insolation in northerly latitudes caused increase in GMST and continental ice sheets to melt and retreat at the end of the Devensian glaciation.

Warm Climate



Cold Climate

Diagram source and full explanation: Holden (2017)

2. Meltwater from the Laurentide ice sheet in N. America entered the N. Atlantic ocean, exceeded critical density threshold in AMOC downwelling locations and weakened the overturning circulation

How Close is AMOC to Turning Off?

- Attention is turning to understanding where we are in this process today.
- How close are we to the critical tipping point which will see the AMOC weaken or stop?

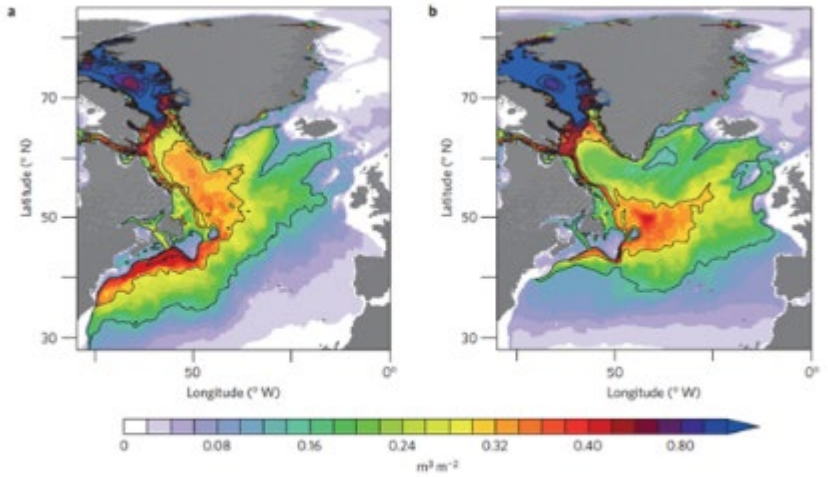
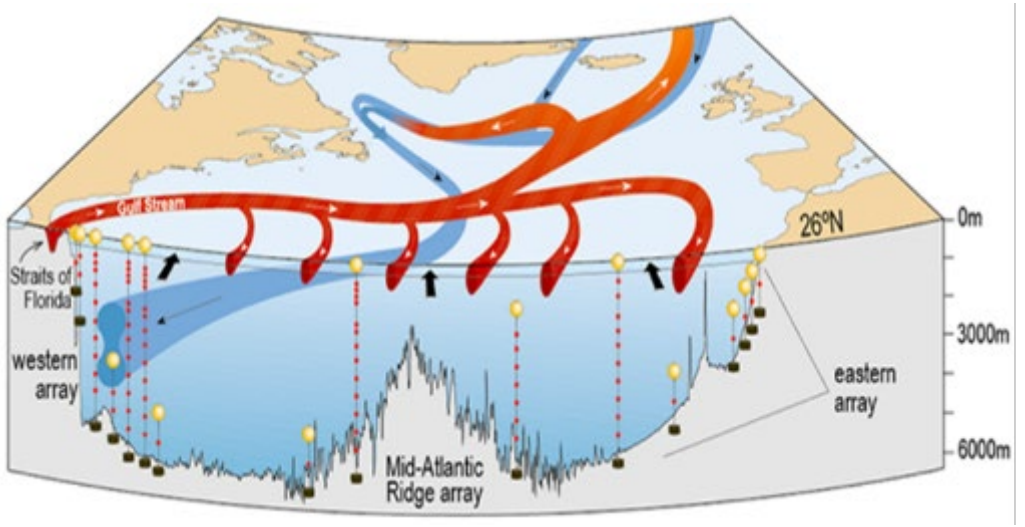


Figure 2 | Fate of the additional Greenland runoff. a,b, Distribution of vertically integrated passive tracer content in the last year of MELT in the 0.05° simulation (VIKING20) (**a**) and the 0.25° simulation (ORCA025) (**b**).



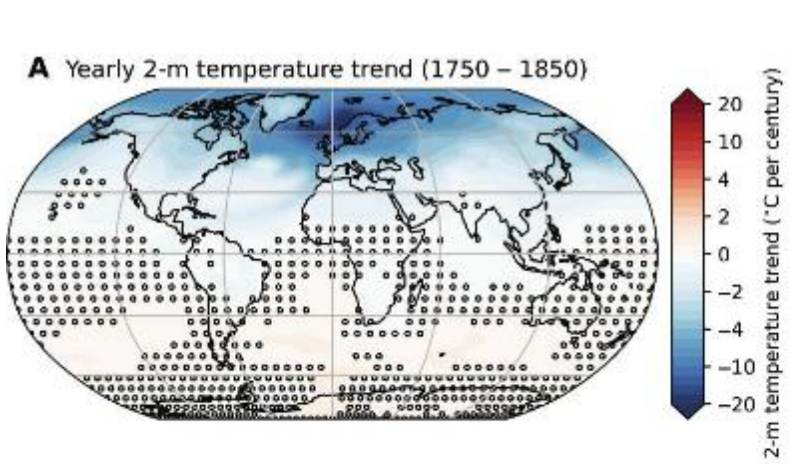
Can we Detect a Trend?

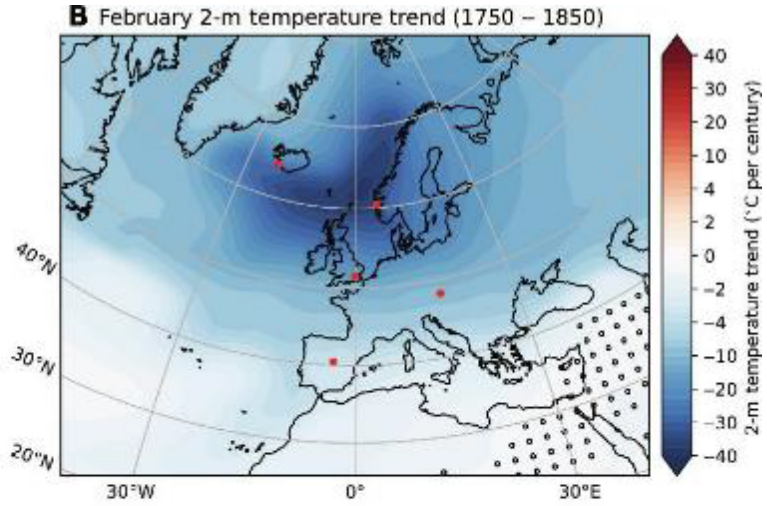
- This is currently a key area of debate amongst researchers (see also Armstrong McKay et al. (2022) for a recent summary).

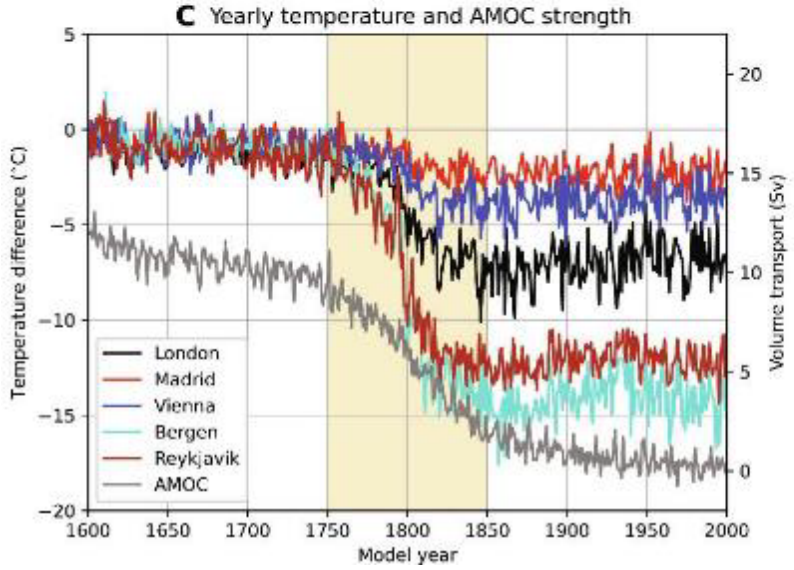
- There are some scientists that think they can identify a decreasing trend in the strength of AMOC.
- And an alternative group who think that what we can see in the instrumental record is just natural variability within the system itself.

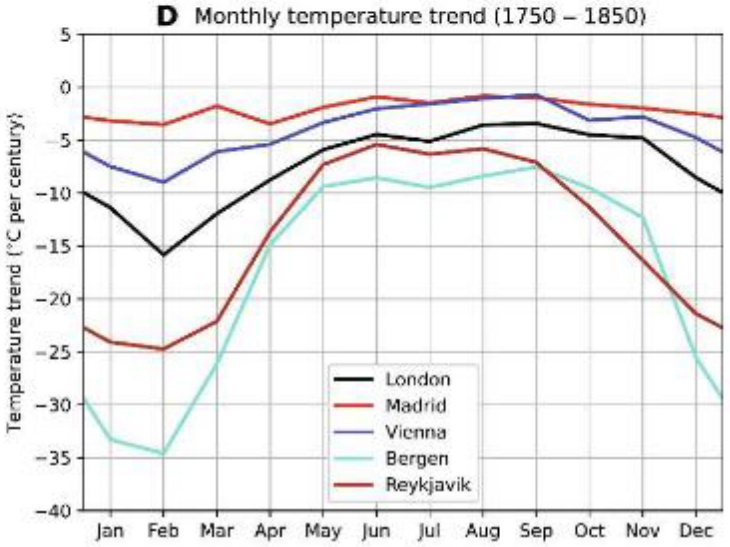
- This is example of why climate change is a wicked problem.
- There is a large amount of uncertainty and contested data and knowledge about whether the AMOC is weakened and what could happen in the event of a collapse.

What Could Happen?

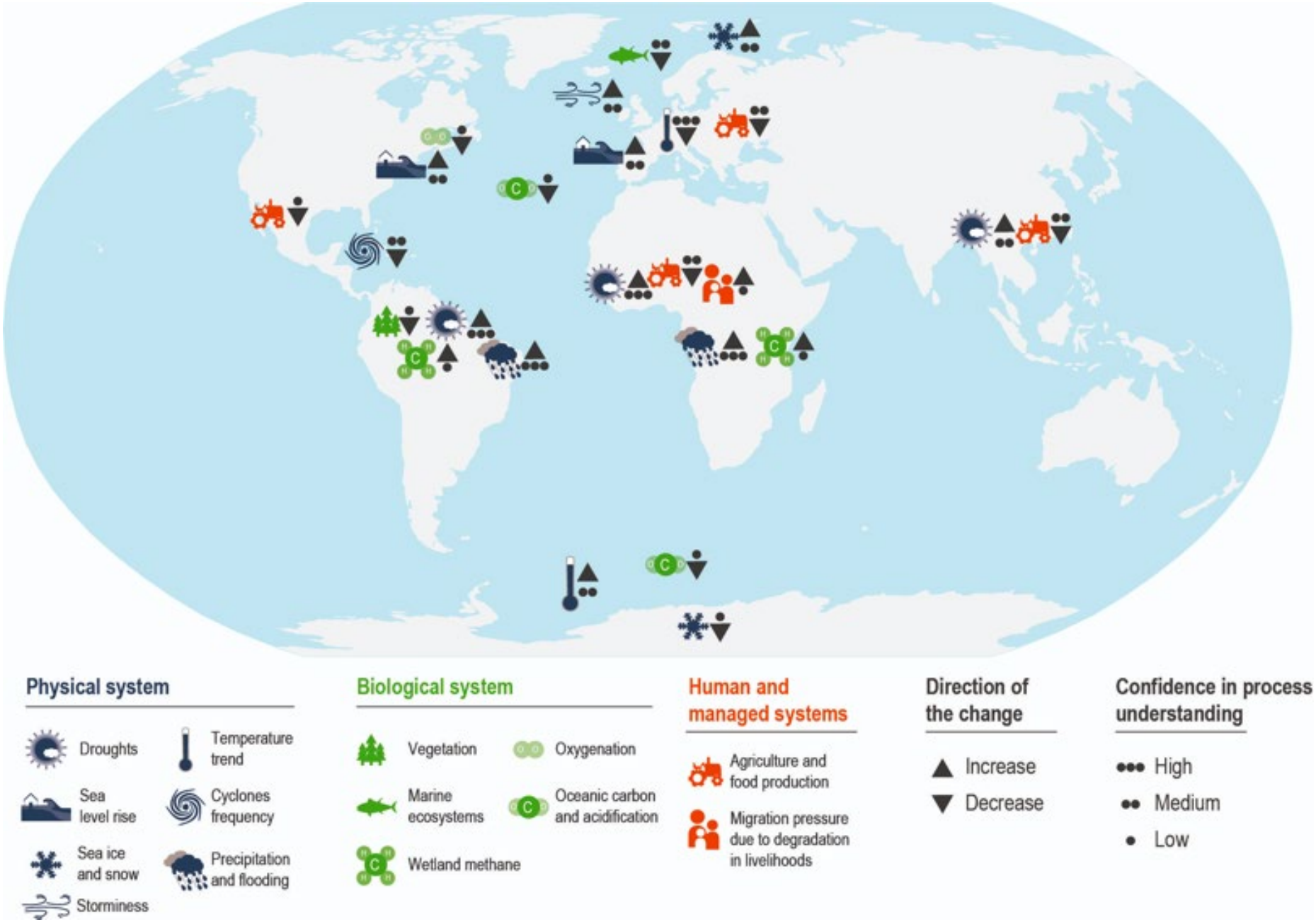








Westen et al (2024)


Physical system
Droughts
Temperature trend
Sea level rise
Cyclones frequency
Sea ice and snow
Precipitation and flooding
Storminess
Biological system
Vegetation
Oxygenation
Marine ecosystems
Oceanic carbon and acidification
Wetland methane
Human and managed systems
Agriculture and food production
Migration pressure due to degradation in livelihoods
Direction of the change
Increase
Decrease
Confidence in process understanding
High
Medium
Low

Summary

- Earth has experienced regular episodes of natural climate change in the past which we can reconstruct using ice cores.
- This has been driven by external orbital forcing.
- However internal feedbacks play an important role as well.
- GHGs and increasing concentrations in the atmosphere can change and create new feedback loops.
- Arctic amplification is a concerning positive feedback loop for many reasons.
- The AMOC which currently regulates temperatures and has a negative feedback role might suddenly change in the future as a result of climate change.