Lecture 9

The Science of Climate Change (II): Natural Factors influencing Temperature Variability

KEY QUESTION:

Can natural factors fully account for contemporary climate change?

With the completion of this lecture, attached readings and tutorial, you should be able to understand the:

- Natural factors influencing temperature variability in the Quaternary period
- Influence of these natural factors on temperatures through feedback mechanisms

Lecture Outline

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9.1 Introduction

- As we have seen in **Lect. 8**, Earth's climate has undergone significant variation over the course of its existence. The Quaternary Period, for instance, consisted of a cold Pleistocene epoch, and a warm Holocene epoch.
- Since human activity associated with the modern human (*homo sapiens*) only arose about 200,000 years ago, the factors that caused temperature variability prior to that are likely natural. (But in **Lect. 10**, we will learn that humans play a bigger role today.)
- While examining the list of factors affecting temperature variability, it is important to understand that they do not operate independently but simultaneously. This might therefore mean that while one factor leads to warming, another might counteract or enhance that warming.

9.2 Natural Factors influencing Temperature Variability in the Quaternary period

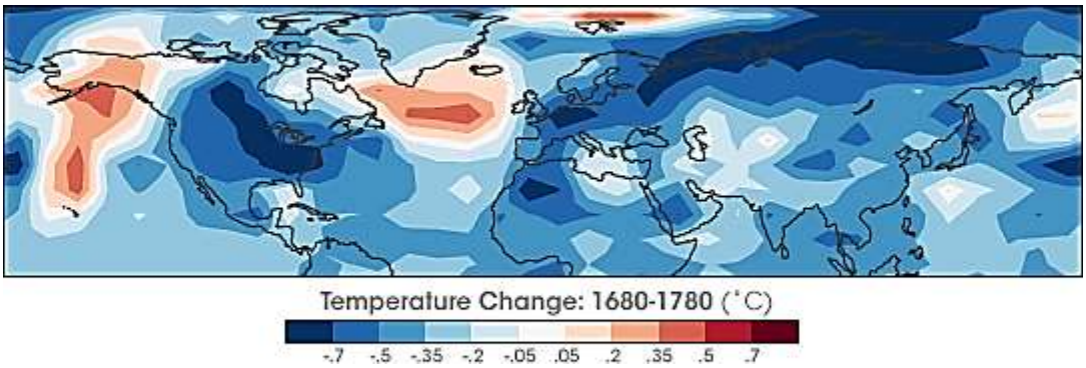
9.2.1 Changes in Solar Output

- The sun is Earth's only source of heat and light, so it is natural to assume that changes in the global temperature must be related to changes in the solar output.
- For centuries now, scientists have known that the solar output (irradiance) varies over time. Periods of **slightly higher solar output** are associated with the **appearance of sunspots**, and astronomers have been recording the number of sunspots since the 1600s. The abundance of sunspots rises and falls usually in a 11-year cycle.
- The so-called "Little Ice Age" (see **Lect. 8 Fig. 1**) that affected parts of Europe and North America for several centuries ending in the 1800s is thought to have been caused (at least in part) by a **decrease in solar output**. A more recent example is presented in **Box 1**.

Box 1: The Maunder Minimum

- Between 1650 and 1710, a period known as the Maunder Minimum, past climate data showed that Europe was colder than most other areas.
- **Reduced solar output** led to **lower temperatures** in much of the Northern Hemisphere during the Maunder Minimum.
- The map in **Fig. 1** represents the temperature difference between 1680 (during the Maunder Minimum) and 1780 (a period of normal solar activity) calculated by a general circulation model. Blue areas were colder than normal, and red areas were warmer.

Fig. 1



9.2.2 Changes in Thermohaline Circulation

- Thermohaline circulation refers to *the large-scale circulation of the world's oceans*, involving the localised vertical movement of large bodies of water, driven by variation in **temperature** (*thermo*) and **salt** (*halite*) content. Thus, the **thermohaline circulation is important in transporting heat between the low latitudes and the higher latitudes**.
- We describe the **Thermohaline Circulation** in **Fig. 2** starting from the North Atlantic:
  - The Gulf Stream carry warm and less salty water from the Caribbean north-eastward to the seas between Greenland, Iceland and Norway. As this water moves to the higher latitudes it becomes **cold, salty and dense**. It becomes dense enough to sink in **'downwelling zones'** particularly at high latitudes in the North Atlantic into the deep ocean.
  - This descending dense water helps to 'pull' the warm waters from the southwest in the lower latitudes, maintaining the flow north-eastwards as well as the **transfer of heat from water to the atmosphere**. (Note: This is an important stage influencing the Arctic temperature and discouraging the growth of ice sheets there.)
  - Cold water that sinks to the bottom of the Atlantic Ocean, flows far southward as the **North Atlantic Deep Water** (NADW), crossing the equator and eventually joining deep waters flowing around Antarctica as **Antarctic Bottom Water** (ABW) and beyond. Other branches of deep cold water flow northward into the Indian and Pacific oceans, eventually rising in an **'upwelling zone'** of western South and Central America.
  - The warm and less saline upwelled water again moves back towards the high latitudes to transfer heat to the atmosphere in the North Atlantic only to sink again.

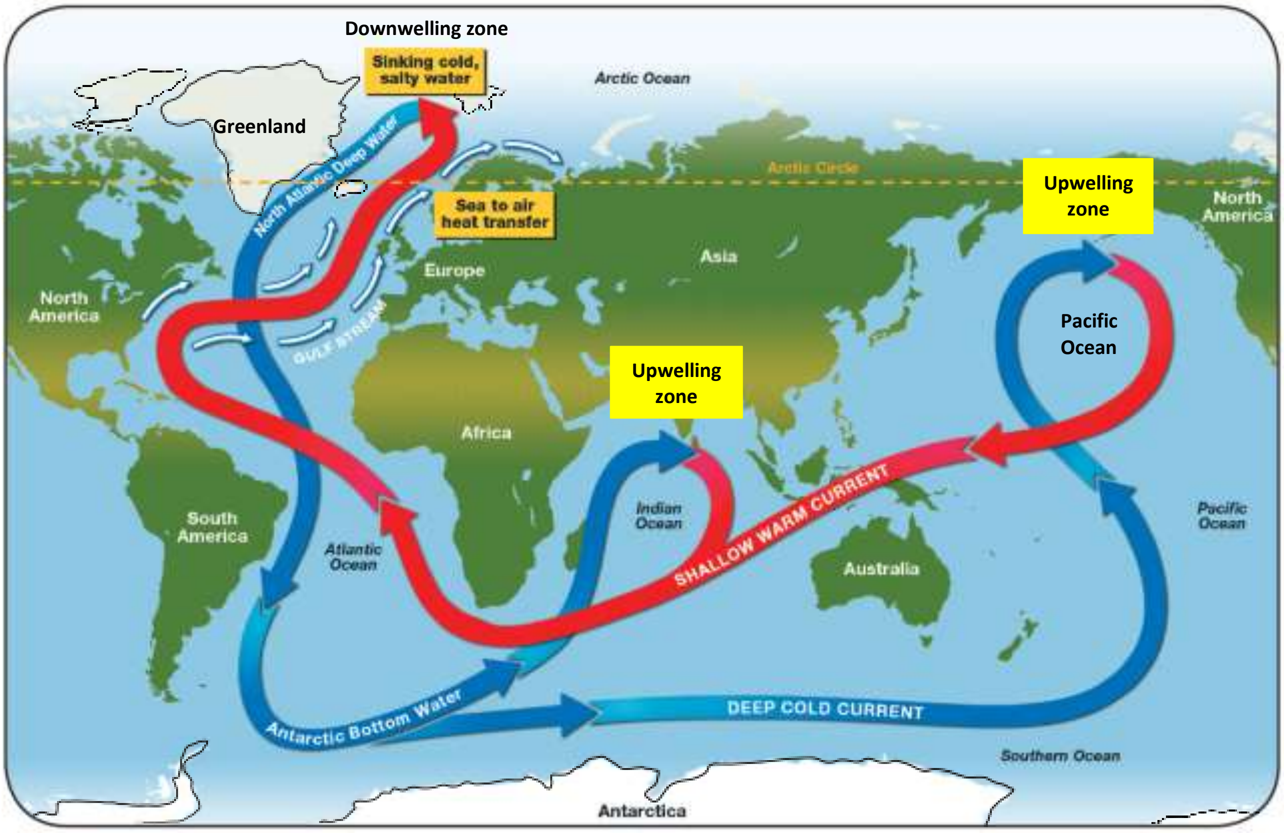


Fig. 2 The Thermohaline Circulation

- How is the ocean circulation relevant to explaining temperature variability?
  - This huge, conveyor belt-like circulation system is estimated to take 2,000 years to complete one revolution. **Any change in this thermohaline circulation will affect the temperature and thus will cause climate change.**
  - There is now convincing evidence to suggest that the thermohaline circulation in the Atlantic Ocean is **not steady**. Rates and locations of sinking water changed abruptly, which in turn affected other aspects of the pattern.
  - Numerous reorganisations of the ocean circulation have been found in marine records running from about 60,000 years ago until about 10,000 years ago. In this way, we have learnt that changes in ocean circulation are implicated in abrupt climate jumps, at least during the last glacial period (see **Box 2**).

Box 2: The Younger Dryas – A Warning from the Past

- About 12,000 years ago, as the Earth was beginning to warm near the end of the Wisconsin glacial, a tremendous cold spell gripped the high latitude regions of the Northern Hemisphere.
- For roughly 1,300 years at least some northern regions returned to peak ice age (glacial) conditions. The onset of this return to glacial conditions was relatively sudden; the transition apparently occurred within a century or less.
- This sudden return to extremely cold (glacial) conditions is known as the **Younger Dryas**, otherwise known as the last stage of the Pleistocene epoch (see **Fig. 3**). Scientists believe **a partial or total shutdown of the thermohaline circulation** may have been involved in the formation of Younger Dryas. The theory goes like this:
  - As the vast North American ice sheets began to melt towards the end of the Wisconsin glacial, it suddenly dumped **a large supply of fresh water into the North Atlantic Ocean in the high latitudes**.
  - The influx of fresh water in the high latitudes reduces the temperature and/or salinity of the North Atlantic Ocean. This stops the downwelling of ocean water and thus shut down the normal cycle of the thermohaline circulation, effectively turning off that current system in a very short time.
  - The thermohaline circulation brings warm, tropical waters northward towards the Arctic and sends cold, polar waters southward. As warm water from the low latitudes stopped coming to the high latitudes, the temperature dropped in the high latitudes and this cooling caused glaciers to expand.
  - A disruption of this flow dramatically altered regional, and possibly even global, patterns of heat transfer. The theory claims that this shutdown temporarily plunged at least some parts of the Northern Hemisphere back into peak "ice age" conditions.
- Some scientists believe a repeat performance of this event, more or less, could happen in the future. Continued rapid melting of Arctic Sea ice, combined with extensive melting of the Greenland ice sheet, would inject a lot of fresh water into the North Atlantic. Could such an infusion be large enough and rapid enough to halt circulation? Nobody knows for sure. Most scientists believe this is a "low probability, but high consequence" scenario. Some think that the Younger Dryas event should serve as a cautionary tale; that not all climate change is gradual, and that a series of unlikely events can sometimes be strung together to produce catastrophic changes.

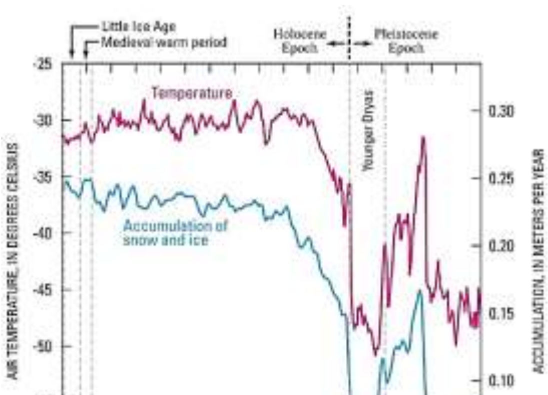


Fig. 3 Temperature changes taken from the central region of Greenland's ice sheet during the Late Pleistocene and beginning of the Holocene

9.2.3 Changes in Ice Sheets: Milankovitch Cycles

- **Orbital forcing** refers to the influence of changes in Earth's orbit and rotation on the planet's climate, specifically variations in the Earth's tilt, shape of its orbit, and 'wobble', which affect the amount of solar radiation received by the Earth over time. The Milankovitch cycles, named after the Serbian engineer and scientist Milutin Milankovitch, describe the three main orbital variations that influence Earth's climate. These orbital variations cause **changes in the amount and distribution of solar radiation reaching Earth**, leading to **shifts in climate patterns**, including **glacial and interglacial periods**. He suggested that our world warms and cools on roughly 100,000-year cycles due to its slowly changing position relative to the Sun.

Milankovitch Cycles. *Schematic of the Earth's orbital changes (Milankovitch cycles) that drive the ice age cycles. 'T' denotes changes in the tilt (or obliquity) of the Earth's axis, 'E' denotes changes in the eccentricity of the orbit (due to variations in the minor axis of the ellipse), and 'P' denotes precession, that is, changes in the direction of the axis tilt at a given point of the orbit. Source: Rahmstorf and Schellnhuber (2006).*

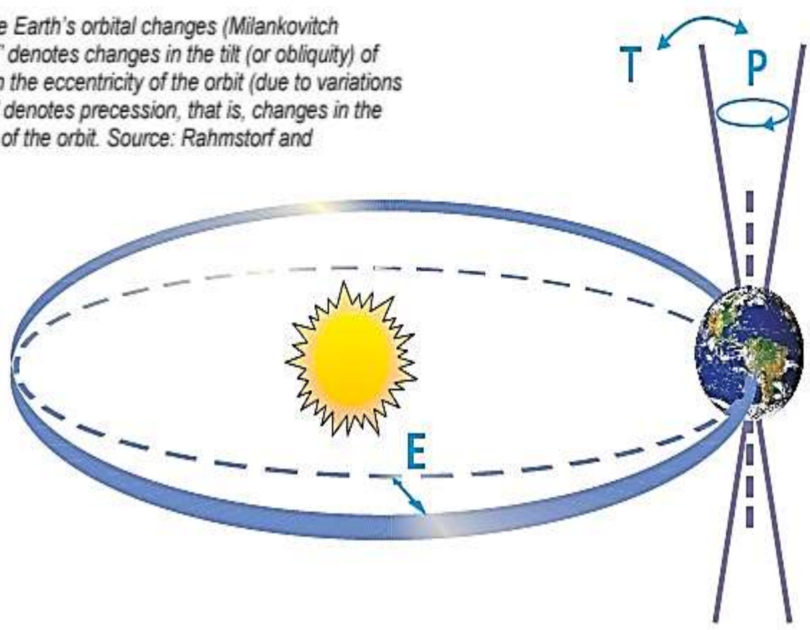


Fig. 4 Note that this is not drawn to scale. The Sun is much bigger than Earth.

(a) Eccentricity (or, the "orbit")

- *Eccentricity* is the variations in the shape of the earth's *orbit* about the sun (see **Fig. 4**). Milankovitch noticed that the Earth's orbit varies from **elliptical** to **circular** on a 100,000-year (or, 100kyr) cycle.
- A circular orbit (see **Fig. 4**, orbit in bold line) favours **glacials** but a more elliptical orbit (see **Fig. 4**, orbit in dashed line) favours **interglacials** as the Earth passes closer to the sun, receiving more solar energy over the year, allowing for more warming.
- Currently, the Earth's eccentricity is near its least elliptic (most circular) and is very slowly decreasing.

(b) Obliquity (or, the "tilt")

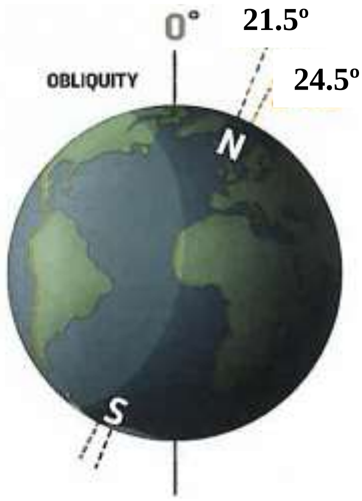


Fig. 5

- *Obliquity* is the tilt of the Earth's axis in relation to its plane of orbit around the Sun. Milankovitch noticed that the tilt of the axis controls seasonal variation in temperature and varies from 21.5° to 24.5° every 41,000 years (or, 41kyr). See **Fig. 5** for the different degrees of the tilt.
- Obliquity **does not** influence the total amount of solar radiation received by the Earth. Instead, the tilt of the Earth affects the **distribution** of insolation in space and time, which can trigger either glaciation or melting of ice sheets.
  - The greater the Earth's axial tilt angle, the more extreme the seasons are.
  - The **smaller the tilt** (less seasonal contrast), the warmer the winters will be. With warmer air, more moisture can be held, producing more snowfall as a result, promoting growth of ice sheets. Summers will also be cooler, resulting in less melting of the winter's accumulation. Such reduced seasonal contrast favours **glacials**. In contrast, **larger tilt angles** (more seasonal contrast) would favour **interglacials**, where there is more melting and retreat of glaciers and ice sheets.
- The Earth's axis is currently tilted at 23.4°, or about halfway between its extremes, and this angle is very slowly decreasing. As obliquity decreases, it will gradually lead to warmer winters and cooler summers.

(c) Precession (or, the 'wobble')

Fig. 6

- Milankovitch suggested that the earth wobbles like a spinning top on a 26,000-year cycle (see **Fig. 6**). Like obliquity, precession affects the **distribution of insolation**, rather than the total amount of solar radiation received by the Earth.

- In **Fig. 7A**, when the northern hemisphere tilted towards the sun (summer in the NH), the Earth is furthest away from it. This tends to make summers cool resulting in less melting of ice, thus more ice sheet grows. However, when the northern hemisphere is tilted away from the sun (winter in the NH) and the Earth is closest to the sun, this tends to make winters mild resulting in more moisture, more snowfall and more ice sheet grows. Both summer and winter has more ice and snow leading to a **glacial** period.

- In **Fig. 7B**, when the northern hemisphere tilted away from the sun (winter in the NH), the Earth is furthest away from it. This tends to make winters cold, resulting in less moisture, less snowfall, less ice sheets.

However, when the northern hemisphere is tilted towards the sun (summer in the NH) and the Earth is closest to the sun, this tends to make summers warmer resulting in more melting, less ice sheet. Both summer and winter have less ice and snow, leading to an **interglacial** period**.**

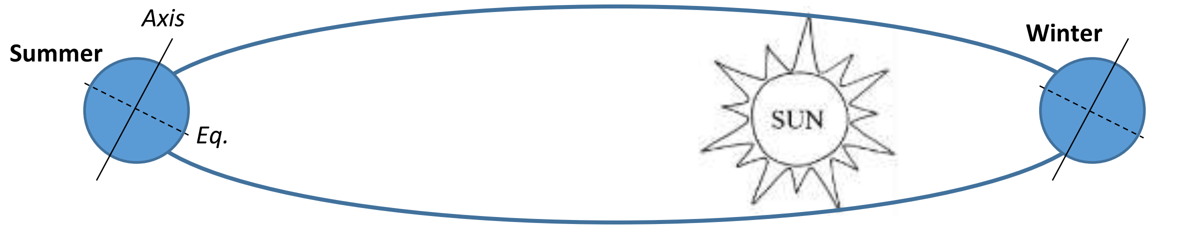


Fig. 7A

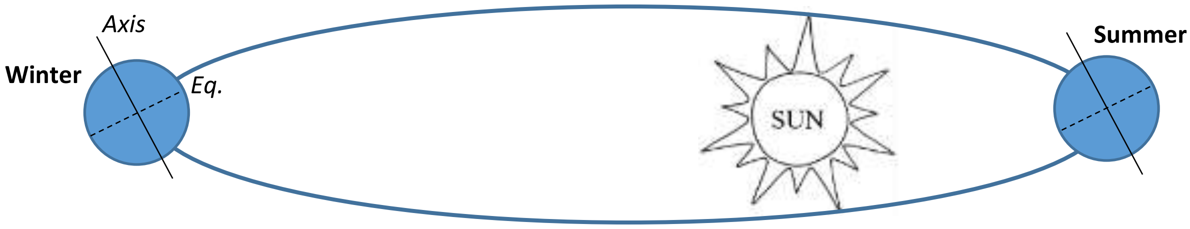


Fig. 7B

Fig. 8 shows the Milankovitch cycles and temperature estimated from the ice core at Vostok Station (a Russian research station in Antarctica) from the Middle Pleistocene till today. In this figure, the timing of the temperature changes was "tuned" to the Milankovitch cycles; that is, to compensate for uncertainties in the depth/age relationship of the ice core, small adjustments were made to the timing of the temperature to agree with the cycles. As can be seen, there is good agreement between the timing of the Milankovitch cycles and the timing of temperature changes. In general, though not always, there is also agreement between the amplitude of radiation from Milankovitch cycles and the temperature changes.

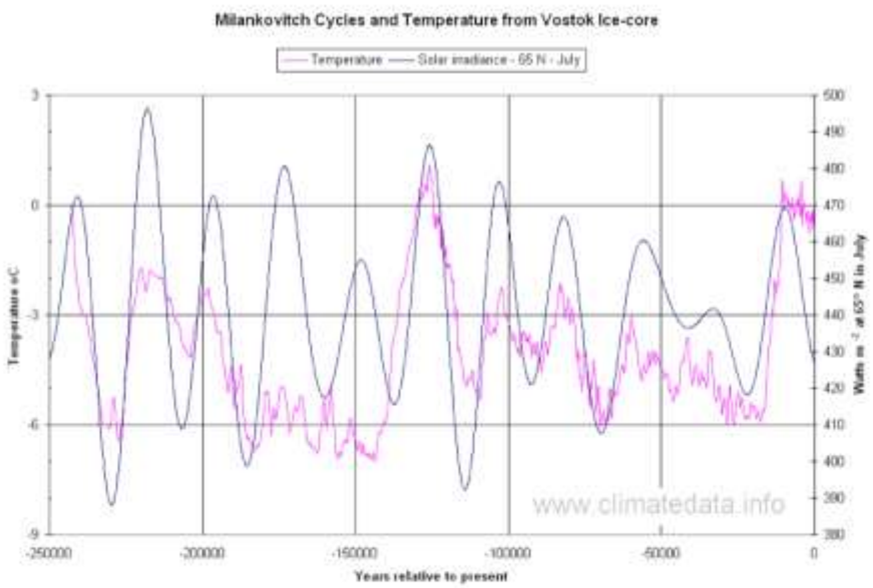


Fig. 8

<u>Box 3</u>: Can the Milankovitch cycles explain contemporary climate change?
No, there is little evidence to suggest so.

Milankovitch cycles operate on long time scales, ranging from tens of thousands to hundreds of thousands of years (see **Fig. 9**). In contrast, the Earth's current warming, or contemporary climate change, has taken place over time scales of decades to centuries. Over the last 150 years, Milankovitch cycles have not significantly changed the amount of solar energy absorbed by the Earth.

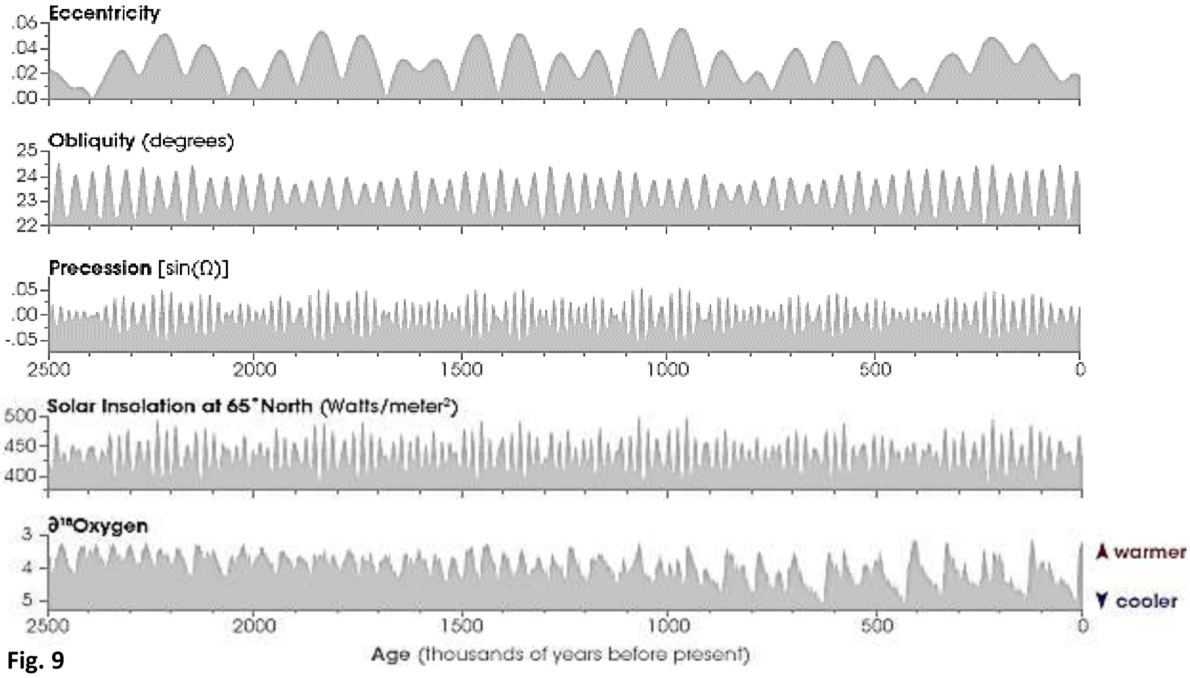


Fig. 9

The graph below (see **Fig. 10**) compares global surface temperature changes (red line) and the Sun's energy received by the Earth (yellow line) in watts (units of energy) per square meter from 1880 to 2019. The lighter/thinner lines show the yearly levels, while the heavier/thicker lines show the 11-year average trends. Eleven-year averages are used to reduce the year-to-year natural noise in the data, making the underlying trends more obvious.

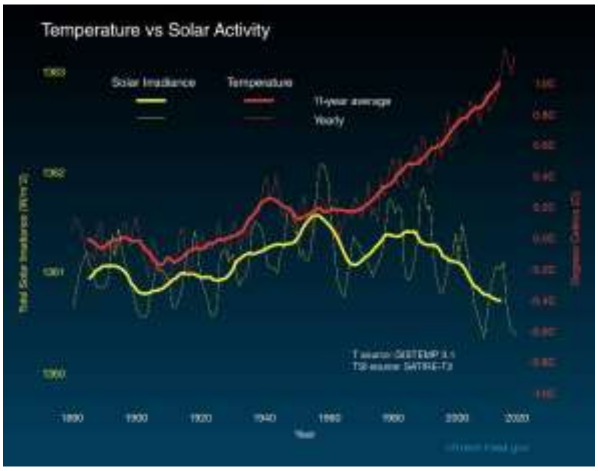


Fig. 10

The amount of solar energy Earth receives has followed the Sun's natural 11-year cycle of small ups and downs, with no net increase since the 1950s. Over the same period, global temperature has risen markedly. These observations support the assertion that the Milankovitch cycles have not significantly changed the amount of solar energy absorbed by the Earth over the last 150 years and hence is not responsible for contemporary climate change.

If there were no human influences on climate, scientists say that the Earth's current orbital positions within the Milankovitch cycles (circular orbit and decrease in axial tilt angle) predict our planet should be cooling, not warming, continuing the long-term cooling trend that began 6,000 years ago.

9.3 Feedback Mechanisms

- Most natural systems, including climate, can be described to be existing at **a state of equilibrium** or not. When the average condition of the system is relatively constant over time, an equilibrium exists which reflects the system's ability to cope with forces either external or internal seeking to disturb it.
- The ability to self-regulate is a characteristic of systems and is frequently controlled by internal adjustments known as **feedback mechanisms**. When the system is not able to cope, the effects can be observed through **feedback loops.**
- In temperature variability, a **feedback loop** is the equivalent of a natural process that **accelerates** or **decelerates** a change. **A <u>positive feedback loop</u> accelerates a temperature change, whereas a <u>negative feedback loop</u> decelerates it.**
- Feedback mechanisms prove that the climate is not solely controlled by solar radiation received by Earth. They are an equally powerful process that determines the climate.

9.3.1 Positive Feedback Loops

- Sea ice and continental ice have high albedos, reflecting much of the shortwave radiation that strikes them. **During interglacials, ice melts and ice cover reduced**. This in turn **reduces albedo** (% of radiation reflected) and **increases absorption** by the surface, which in turn lead to **higher terrestrial radiation,** giving higher temperatures and reducing ice cover – a positive feedback loop (see **Fig. 11**).

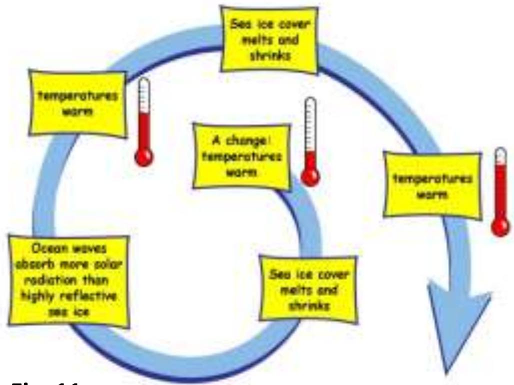


Fig. 11

- Deposits of frozen methane and carbon dioxide lie beneath permafrost in Arctic regions. As temperatures increase and the **permafrost thaws**, these deposits can be released into the atmosphere and further contribute to warming – another positive feedback loop (see **Fig. 12**).

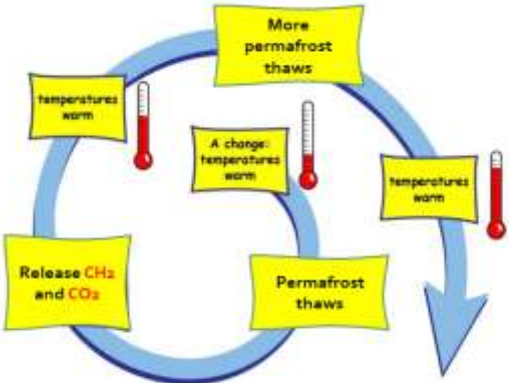


Fig. 12

<u>Linking positive</u> feedback mechanism with <u>changes in ice sheets (caused by Milankovitch's Cycles)</u>

The Earth's shift from glacial to interglacial state at the end of the last Ice Age is suggested to have happened in this manner:

- Variations in Earth's eccentricity and obliquity **increased the amount of sunlight** hitting the high southern latitudes during spring in the Southern Hemisphere.
- That increase **warmed** the Southern Ocean. As a result**, sea ice shrank** back towards Antarctica, uncovering and warming ocean waters.
- As the Southern Ocean warmed, it was less able to hold carbon dioxide, and **great quantities of carbon dioxide** escaped into the atmosphere.
- Carbon dioxide being the greenhouse gas started **trapping more heat** and caused **global temperature to rise**.

Linking <u>positive</u> feedback mechanism with <u>changes in thermohaline circulation</u>

The Younger Dryas is theorised to have happened in this manner:

- A period of warming melted glaciers and ice sheets, reducing salinity in the ocean water, reduced 'downswelling' and weakened the thermohaline circulation. This drastically **reduced temperatures** in the North Atlantic.
- The continued cooling results in **ice sheet expansion**. The ice sheets eventually break up as they spread out over the ocean shelves, helping to release more icebergs into the North Atlantic.
- Upon melting over the North Atlantic, these icebergs **release further fresh water** into the surrounding ocean helping to sustain the prevention of 'downwelling', and shutdown the flow of warm Gulf stream into the North Atlantic. A period of glacial commenced.

9.3.2 Negative Feedback Loops

- Unlike positive feedback loops which amplify the effect of disturbance, negative feedback loops **minimises the effect of any disturbances and seeks to return the system to the pre-existing status quo**.

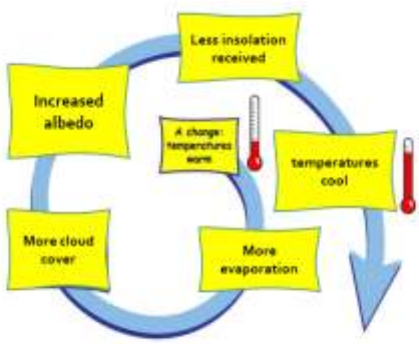


Fig. 13

Linking <u>negative</u> feedback mechanism with <u>changes in solar output</u>

- Greater solar output raises temperatures that will lead to more evaporation and cloud formation.
- More cloud cover helps with reflecting away insolation, as well as preventing more from being absorbed. The increased cloud cover thus promotes a tendency for cooling. See **Fig. 13**.

Linking <u>negative</u> feedback mechanism with <u>thermohaline circulation</u>

We return to the example of the Younger Dryas, in its later stages.

- The cooling caused by thermohaline circulation shutdown can reduce the melting rate and increases the amount of sea ice. Over time, this can result in **more salty and denser water to be on the surface layer of the ocean**, as growing icesheets extract more and more fresh water from the oceans.
- The increase in salty water which is denser resulted in starting 'downwelling' and re-established the North Atlantic Deep Water. Warm waters are pulled from the Caribbean to start the thermohaline circulation again. Eventually, the glacial period ended.

9.4 Conclusion

The natural factors influencing past climate variability are diverse and complex, encompassing changes in solar output, changes in thermohaline circulation and changes in ice sheets. These factors have historically played a significant role in shaping the earth's climate over geological timescales. However, contemporary climate change is predominantly driven by human activities. Natural processes largely amplify the impact of human activities through feedback processes. Understanding the interplay between natural and anthropogenic forces is essential for accurate climate modeling and effective policy-making. Future research should continue to refine our comprehension of these natural drivers, ensuring a holistic approach to addressing climate variability and change.