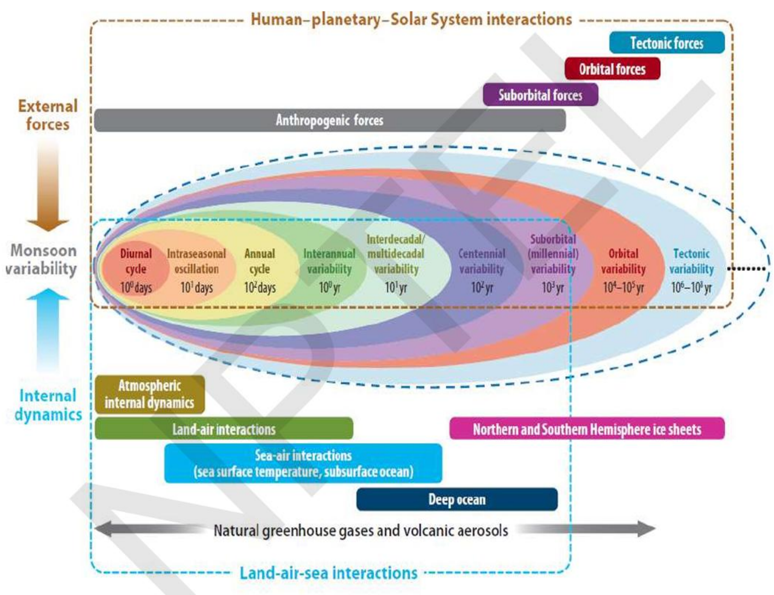
Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 31
Theory of Ice Ages

In the previous lecture, the discussion centered around the transition of Earth's climate from the last glacial period, approximately 20,000 years ago, to the present interglacial period. During this deglaciation, several abrupt climate events were noted, including the Heinrich event (a period of cooling in the North Atlantic), the subsequent Bølling–Allerød warming, and the Younger Dryas (a return to near-glacial conditions). These events were shown to be closely linked to changes in the Atlantic Meridional Overturning Circulation (AMOC), and climate models were able to simulate and explain their timing and drivers.



The current lecture transitions to the study of ice ages, placing them in the broader context of the multiple timescales relevant to climate science. Climate phenomena occur across a wide range of temporal scales. Weather operates on daily timescales, while intra-seasonal and interannual variations span weeks to years, important for events such as the Indian monsoon. Decadal variability is also recognized, particularly in regional systems like the monsoon. When referring to climate change, the focus is typically on century-scale changes, such as those driven by increasing greenhouse gas concentrations.

In contrast, ice ages fall within the domain of millennial to orbital timescales, ranging from 10,000 to 100,000 years. These long-term variations are primarily influenced by changes in Earth's orbit around the Sun. These variations are known as Milankovitch cycles, which affect the amount and distribution of solar radiation at high latitudes. Going further back in time into million-year scales, climate is influenced by continental drift and plate tectonics, which alter ocean currents and atmospheric circulation. This domain includes phenomena such as the hypothesized Snowball Earth episodes.

Understanding ice ages, though seemingly distant from present-day climate concerns, remains important. This is because climate models, developed and refined over the past 50–60 years, need to be tested across all types of climatic conditions to validate their robustness. While weather and seasonal forecasting models can be verified regularly with observations, paleoclimate modeling offers a different kind of validation. It helps to check if the models can replicate the large-scale patterns and transitions known from proxy records.

As shown in earlier discussions, models were able to simulate the abrupt events of deglaciation effectively, reinforcing confidence in their physical foundations. Now, the challenge is extended to determine whether the periodic occurrence of ice ages, as inferred from ice core data spanning the last million years, can also be captured by climate models. This provides a stringent test of the models' ability to represent Earth's climate system over orbital timescales, and helps deepen our understanding of the fundamental drivers of long-term climate variability.

The primary evidence for the occurrence of ice ages in the past comes from proxy records, especially geological evidence. One of the earliest and most compelling indicators is the discovery of rocks found in locations where they do not match the local geology. When a rock appears in a region but is geologically distinct from the surrounding area, it is termed a glacial erratic. Such rocks were understood over 150 years ago to have been transported from distant locations, as they could not have originated locally.

The movement of these rocks raised the question of what force could have carried them. Since rocks cannot move on their own, natural agents like water or ice were considered. While floodwaters can move rocks, their transport capacity is limited in distance typically up to a kilometer. In contrast, glaciers are capable of transporting large rocks over much longer distances. Thus, the presence of glacial erratics strongly suggests past glaciation in those areas.

A specific example comes from Yellowstone National Park, which was extensively glaciated during the last ice age, around 20,000 years ago. As the glaciers retreated, they left behind erratics, providing direct evidence of their former extent. These rocks serve as climatic markers, allowing scientists to map out past ice coverage and retreat patterns. Consequently, much of what is known about past ice ages is derived from geological and geomorphological features that record the movement and presence of ancient glaciers.

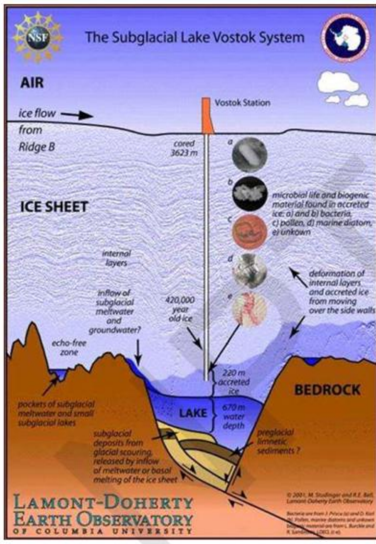
Glaciers can pick up chunks of rocks and transport them over long distances. When they drop these rocks, they are often far from their origin—the outcrop or bedrock from which they were plucked. These rocks are known as glacial Erratics. Erratics record the story of a glacier's travels (From Yellowstone National Park)

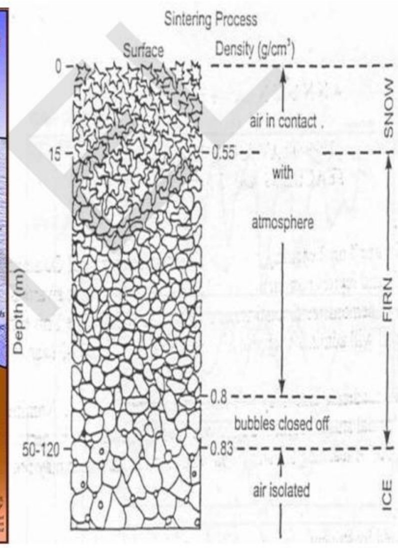
In discussions of ice ages and their transitions, several specific terms are used to describe cold and warm periods of varying durations. It is important to understand these distinctions. A stadial refers to a short cold period, typically less than 1,000 years. Stadials occurred during phenomena such as the Heinrich events, when specific regions experienced brief episodes of cooling. In contrast, an interstadial denotes a short warm period, also generally less than 10,000 years in duration.

When a warm period is longer than 10,000 years, such as the present warm phase following the last ice age, it is termed an interglacial. The current interglacial began around 12,000 years ago, following the last glacial period that peaked about 20,000 years ago.

A glacial period, or simply a "glacial," represents a prolonged cold phase, typically lasting around 100,000 years. These glacial-interglacial cycles are characteristic of the Earth's climate system over the past million years, and understanding their periodicity is essential for studying long-term climate variability.

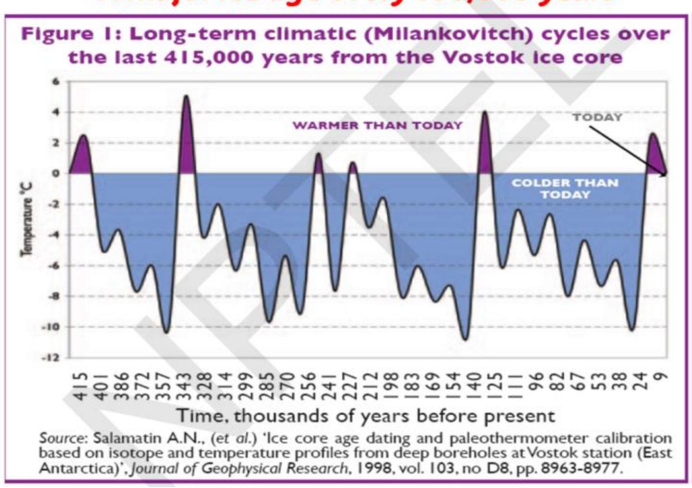
Our understanding of Earth's climate over the past several hundred thousand years has significantly advanced through the study of ice cores, particularly those extracted from Antarctica. One of the most important sources is from Lake Vostok, which lies beneath the deepest ice sheet in the world. Scientists undertook the extraordinary task of drilling through this vast ice sheet, reaching nearly to the lake at the bottom. The existence of a lake in such a cold region is due to the immense pressure exerted by the overlying ice, which causes the ice at the base to melt and form liquid water despite the low temperatures.





The ice core from Lake Vostok provides a continuous and detailed climate record spanning the last 420,000 years. As snow accumulates on the surface and is buried over time, it gets compressed into solid ice. At depths beyond approximately 50 meters, the snow is fully compacted, and the ice contains tiny air bubbles trapped during its formation. These air bubbles preserve samples of the ancient atmosphere, allowing scientists to measure past concentrations of carbon dioxide and methane, thereby reconstructing the composition of the atmosphere over geological timescales. This represents a remarkable scientific achievement and a testament to human ingenuity and dedication. Many such ice cores have since been collected, and they form a critical component of paleoclimate research.

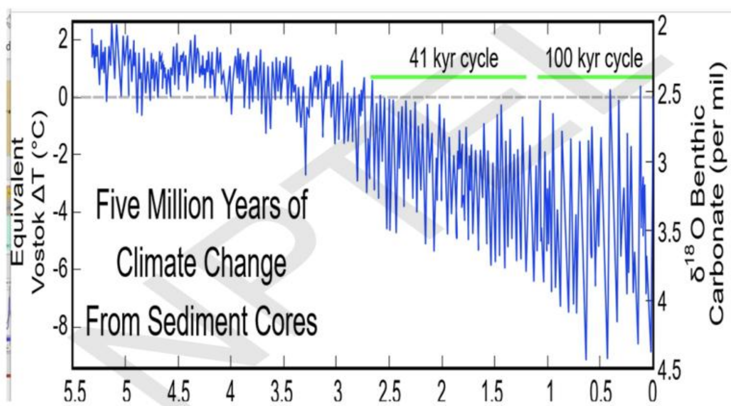
A major ice age every 100,000 years



The ice core data from Vostok revealed a striking pattern in Earth's climate history over the past 400,000 years. Analysis of the local annual mean temperatures showed that temperatures fell as low as –10°C on four separate occasions, indicating the presence of extensive ice sheets and thus the occurrence of four major ice ages during this period. These glacial maxima were separated by four major interglacial warm periods, including the present one. The previous interglacials occurred around 125,000, 340,000, and 415,000 years ago. This pattern demonstrates that ice ages have repeated roughly every 100,000 years, a discovery of fundamental significance in paleoclimatology.

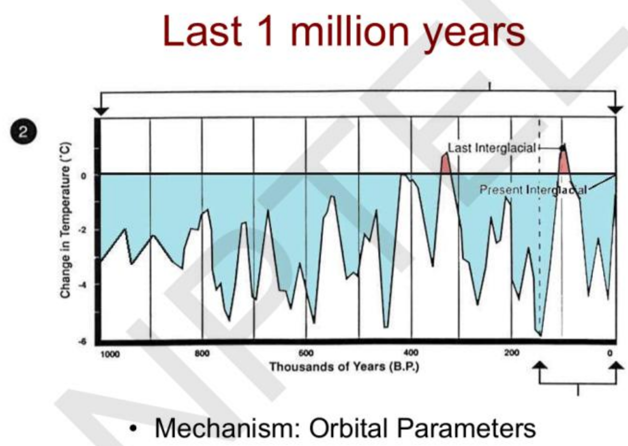
These large-scale climate changes preceded the influence of human activity, strongly indicating they were driven by natural causes. This led scientists to investigate what natural mechanisms could account for the observed 100,000-year periodicity. The most convincing explanation comes from changes in Earth's orbit and orientation relative to the Sun, collectively known as Milankovitch cycles. These include (1) the eccentricity of Earth's orbit (its deviation from a perfect circle), (2) the obliquity or tilt of Earth's rotational axis, and (3) precession, which is the gradual change in the direction of Earth's rotational axis (currently pointing toward the North Star). These variations are driven by gravitational interactions with other planets in the solar system.

Although this theory was developed by Serbian astronomer Milutin Milankovitch nearly a century ago, long before modern ice core data became available, it gained scientific credibility only after the drilling of ice cores confirmed the kind of periodic climate changes he had predicted. His work, initially speculative, is now considered a cornerstone of our understanding of natural climate variability.

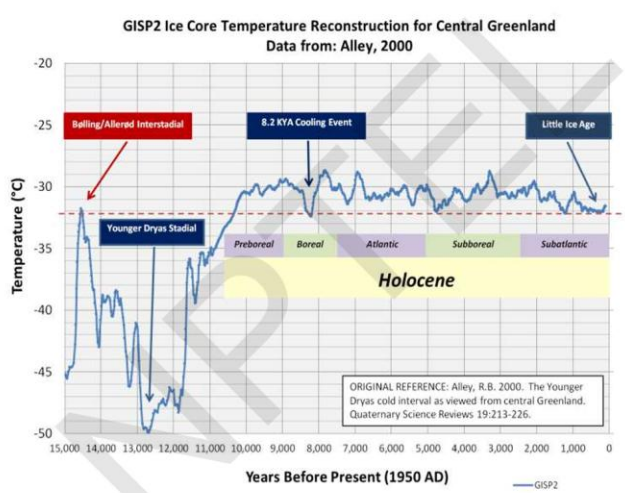


While ice core data, such as from Vostok, provides a detailed record of Earth's climate for the past 400,000 years, deeper insights into the long-term climate history can be obtained from ocean sediment cores, which extend much farther back in time. One such sediment core provides a climate record of the past 5.5 million years. By analyzing the calcium carbonate content in these sediments, scientists can infer the temperature of ocean waters at various points in the past, much like the temperature reconstructions from ice cores.

This long-term record shows that Earth's temperature has fluctuated significantly over millions of years. A key observation is that the frequency of these fluctuations changed over time. Around 4 million years ago, ice ages occurred roughly every 41,000 years, consistent with changes in Earth's axial tilt (obliquity). However, in the last 1 million years, the dominant periodicity shifted to approximately 100,000 years, aligning more with changes in Earth's orbital eccentricity. This transition in the periodicity of ice ages represents a major unresolved puzzle in paleoclimatology: why did the ice age cycle shift from a 41,000-year rhythm to a 100,000-year rhythm in the more recent geological past?



Focusing on just the last million years, data shows that there were about ten significant glaciations, each separated by interglacial periods. Most of this time, Earth was in a colder state, with only brief warm intervals. Understanding what caused these 100,000-year ice age cycles has become a central question in the study of long-term climate dynamics.



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To recall the more recent climate history, the Greenland ice core data shows the transition from the last glacial maximum through a period of abrupt warming, known as the Bølling-Allerød interstadial, followed by a temporary cooling event the Younger Dryas before finally entering the current interglacial period, which has lasted for the past 12,000 years. A previous interglacial occurred around 125,000 years ago, and while natural cycles suggest that another glacial period could occur in the future, model projections and orbital calculations indicate that such a transition may not occur for at least another 25,000 years.

Before delving further into the details of ice ages, it is useful to revisit a simple radiative model of Earth’s global mean temperature introduced earlier in the course. This model (Liou’s model) is based on the planetary energy balance, taking into account the incoming solar radiation, the albedo (reflectivity of the Earth), the absorptivity of solar radiation, and the emissivity of Earth's infrared radiation, which is influenced by the presence of greenhouse gases. Using typical present-day values for albedo of 0.3, solar absorptivity of 0.2, and emissivity of 0.95, this model yields a global mean temperature of 288 K (15°C), which is close to observed values.

By making modest adjustments to the parameters, specifically, increasing the albedo by 0.02 to account for expanded ice sheets during the last glacial period, and reducing the emissivity to 0.90 due to decreased concentrations of greenhouse gases like CO_2 and CH_4, the model predicts a global mean temperature of approximately 282 K. This is 6°C lower than the present climate. This aligns well with estimates of global temperature during the Last Glacial Maximum.

This simple analysis powerfully demonstrates the climate sensitivity of Earth. Even small changes in albedo (less than 10%) and emissivity (about 5%) can result in significant global temperature shifts. It highlights how delicate the Earth’s climate system is, and how relatively minor alterations in ice cover or atmospheric greenhouse gas concentrations can trigger major climate transitions, such as entering or exiting an ice age.

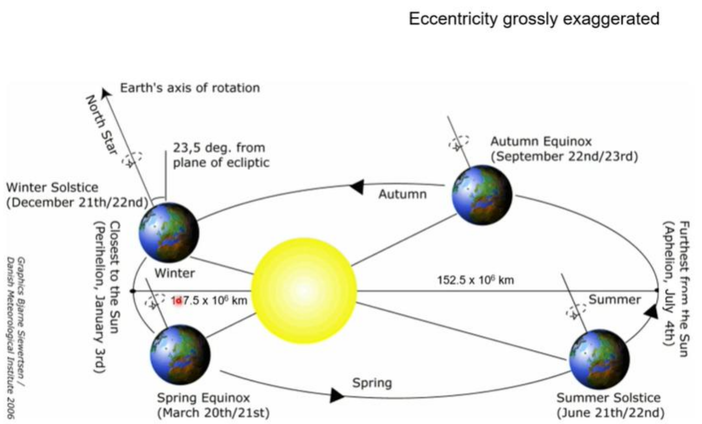
To understand the causes of ice ages, both internal (Earth-based) and external (astronomical) factors must be considered. Among internal factors, a key mechanism is the carbonate-silicate cycle, where CO_2 reacts with silicate rocks to form calcium carbonate, which is eventually transported to and stored in the deep ocean. This long-term removal of CO_2 from the atmosphere can contribute to global cooling. Another significant factor is volcanic eruptions. Large eruptions that inject ash and aerosols into the stratosphere (20–30 km altitude) can reflect solar radiation, causing a temporary but sometimes prolonged cooling of Earth’s climate.

Mountain building is another internal driver. For instance, the collision of the Indian and Eurasian plates led to the formation of the Himalayas and the uplift of the Tibetan Plateau, exposing fresh rock to weathering processes. This enhanced weathering is believed to have played a role in the long-term decline of atmospheric CO_2 over the past 50 million years, contributing to the Earth's gradual cooling trend. Additionally, the geographical configuration of continents and oceans is critical to climate behaviour and will be explored in more detail when discussing phenomena like Snowball Earth.

Turning to external factors, the variability in incoming solar radiation plays a significant role. Early in the Sun’s history, roughly 5 billion years ago, its energy output was much lower than it is today, suggesting a naturally colder climate in Earth's early history. However, the primary focus is on orbital variations of Earth that occur over tens to hundreds of thousands of years. These include:

- Eccentricity: changes in the shape of Earth’s orbit around the Sun (more circular or more elliptical),
- Obliquity: variations in the tilt of Earth's axis, and
- Precession: the gradual wobble or shift in the direction of Earth's axial tilt.

These three astronomical cycles, known collectively as Milankovitch cycles, have been precisely calculated by astronomers and offer a reliable basis for understanding Earth's orbital forcing over the past million years.



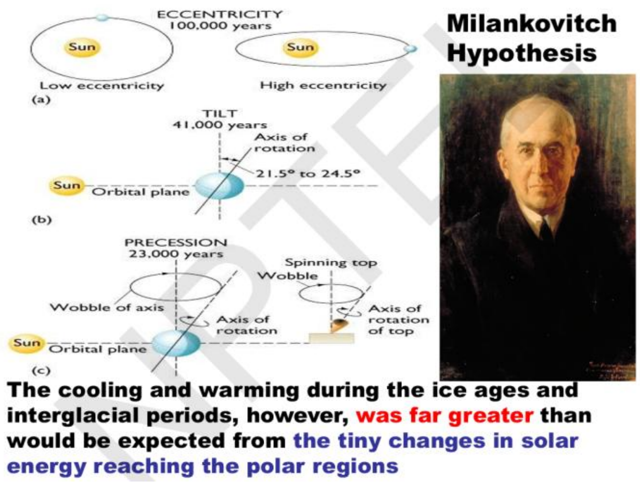
The Earth’s orbit around the Sun is not perfectly circular but slightly eccentric, and its axis is tilted at an angle of approximately 23.5°. Currently, Earth is closest to the Sun (perihelion) around January 3rd–4th, which corresponds to winter in the Northern Hemisphere, and farthest (aphelion) during Northern Hemisphere summer. However, this configuration was different 10,000 years ago. Changes in the timing of perihelion and aphelion due to axial precession affect the distribution of solar radiation across seasons, particularly at high latitudes. One of the key hypotheses proposed by Milutin Milankovitch is that such orbital changes caused increased solar radiation at polar regions, contributing to the melting of ice sheets and the termination of the last glacial period. This alignment of orbital parameters is believed to have played a crucial role in triggering the transition to the current interglacial climate.

Although changes in Earth’s orbit do affect climate, the total amount of solar radiation received by the entire Earth does not vary significantly due to changes in eccentricity. The variation in radiation follows the relationship:

$$S \propto \frac{1}{\sqrt{1 - E^2}}$$

where (E) is the eccentricity of Earth's orbit. Since the maximum eccentricity reaches only about 0.04, and is currently close to zero, the resulting variation in total radiation is minor. Therefore, eccentricity alone cannot account for the onset of ice ages.

However, Milutin Milankovitch proposed that even minor irregularities in Earth's orbital geometry and axial tilt could cause significant changes in the seasonal distribution of solar radiation at specific latitudes, especially the polar regions. In 1941, he argued that if summer insolation in the Northern Hemisphere is reduced, less ice would melt, allowing snow and ice to persist year-round and accumulate over time, thus initiating glaciation. His hypothesis suggested that changes in Earth-Sun geometry, particularly the amount of solar radiation received during high-latitude summers, are critical in driving long-term climate shifts.



Milankovitch meticulously calculated radiation changes by hand without the aid of modern computers or calculators, demonstrating extraordinary perseverance and precision. He considered the three orbital parameters:

1. Eccentricity – changes with a ~100,000-year cycle.
2. Obliquity (axial tilt) – varies between 21.5° and 24.5° over a ~41,000-year cycle.
3. Precession – the direction Earth's axis points, with a ~23,000-year cycle.

These three orbital variations, known collectively as Milankovitch cycles, are now widely accepted as major contributors to the timing and intensity of ice ages. The next lecture will explore how these cycles interact to influence Earth's climate over geologic timescales.