Climate Change Science

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Lecture 23
Paleoclimate (continued)

The previous lecture introduced the importance of studying past climate – paleoclimate - to better understand and predict future climate change. In the distant past, human activity had no influence on the Earth's climate, which was instead shaped entirely by natural factors. These natural causes can be broadly divided into external and internal influences. External factors include plate tectonics, the movement of continents, orbital variations of the Earth around the Sun, and changes in solar radiation. Internal causes involve variations in atmospheric composition (e.g., natural fluctuations in carbon dioxide), changes in ice cover, vegetation, ocean circulation, and land surface properties. These components also affect the energy exchange between different parts of the climate system namely, the atmosphere, ocean, and land, and contribute to what is known as natural internal variability.

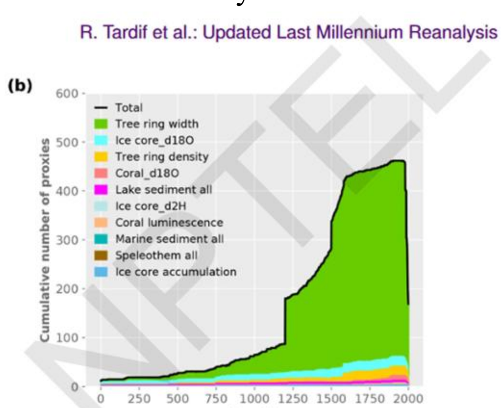
The goal is to utilize proxy data collected over the past 50 years, especially data that reveals how climate changed during the last 20,000 years, to test whether climate models, grounded in the laws of physics, can accurately reproduce past climate behaviour. If models can explain historical climate changes, that builds confidence in their ability to predict future climate scenarios.

An illustrative example is the historical connection between South America and Africa, which were once part of a single landmass. Their eventual separation, caused by continental drift, had a significant effect on ocean circulation and thus on global climate. This underscores how continental configurations, which change over geological timescales, have profound climatic implications.

Another key component of the Earth’s climate is the cryosphere, which includes glaciers, snow cover, sea ice, and permafrost. These icy components strongly influence Earth's albedo (the reflectivity of the planet), as they reflect incoming solar radiation. Alongside the cryosphere, the hydrological cycle comprising water vapor, liquid water, stored water, evaporation, rainfall, and river flow plays a vital role in shaping climate patterns. The global energy balance is determined by how incoming solar energy interacts with the Earth system, which includes the atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere. These components interact continuously to control the global mean temperature, ice cover, and vegetation distribution.

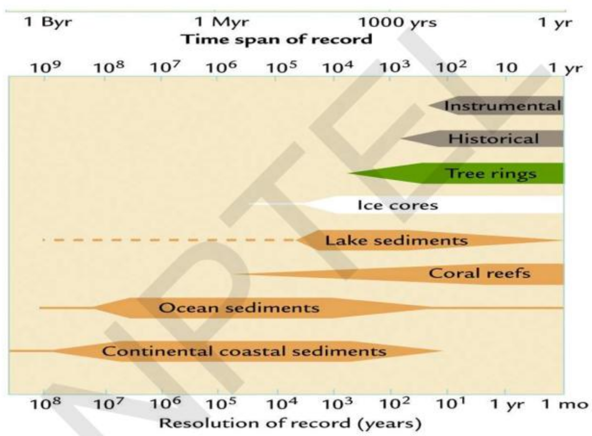
Since thermometers did not exist before the 1700s, scientists must rely on indirect methods to reconstruct past climate conditions. This process is akin to detective work, where proxy records serve as evidence to infer temperature, precipitation, and atmospheric composition from different periods in Earth's history. Marine sediments, particularly from the ocean floor, and fossil shells provide information about oceanic conditions from millions of years ago. Ice cores are especially valuable; they not only contain isotopic data related to temperature but also trap ancient air, preserving a record of past atmospheric composition, including greenhouse gases like CO_2 and methane. Other key proxies include speleothems (mineral deposits in caves) that offer clues about past rainfall and temperature, and corals, which archive ocean temperatures through their growth patterns and chemical composition.

Because these are indirect methods, they involve assumptions and approximations, and the resulting climate reconstructions inherently carry uncertainties or error bars. However, the reliability of such reconstructions increases significantly when multiple proxies are used together. Depending on a single proxy can lead to misinterpretation due to local effects or calibration errors, but if two or more independent proxies all indicate the same climatic condition such as a significant cooling around 20,000 years ago, then the evidence becomes far more robust and trustworthy. The advancement of this multi-proxy approach is a major strength of modern paleoclimatology, enhancing confidence in our understanding of Earth's climatic history.



Over the last 2,000 years, a variety of climate proxies have been used to reconstruct past temperature trends, with tree rings being the most dominant among them. Tree rings are especially informative in mid-latitude and polar regions, where the width of each annual ring is directly related to temperature. Warmer years generally promote more growth, resulting in wider rings. This makes tree-ring analysis a reliable tool for inferring historical temperatures in regions such as Europe, Russia, and North America. However, in tropical regions, where temperature is already high and relatively stable, tree growth is influenced more by rainfall than by temperature. As a result, tree-ring records from the tropics are more indicative of precipitation patterns rather than temperature.

Other proxies used for reconstructing climate over the last millennium include ice cores, lake sediments, and corals, though their spatial and temporal coverage is less extensive compared to tree rings. Despite their smaller individual contributions, these additional proxies are valuable because they serve to cross-check the tree-ring-based inferences. For example, if tree rings suggest a warm period but other proxies like ice cores or corals indicate a cold phase, the interpretation must be re-evaluated. However, when multiple independent proxies agree, pointing to the same climatic condition at a particular time, diffithere is strong confidence in that reconstruction. This consistency across proxies is crucial for building reliable historical temperature records.



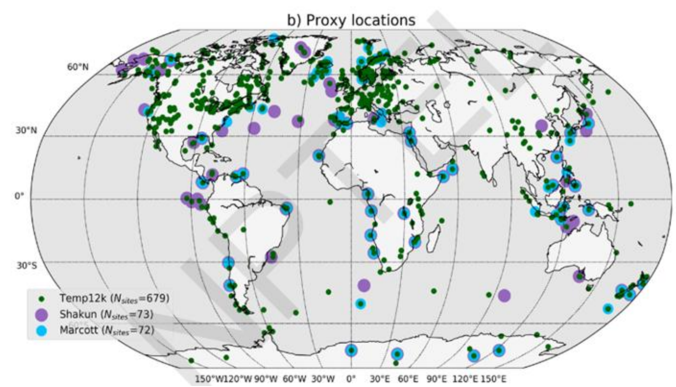
PROXY EVIDENCE FOR CLIMATE CHANGE

To reconstruct Earth's climate over the last 100 million years, scientists have relied on a diverse array of proxy data, each suited to different time scales. For the most recent century, instrumental records, such as thermometer-based measurements, provide highly accurate temperature data. Additionally, historical documents with detailed written accounts of weather and climate events serve as a useful source of climate information from earlier centuries. Tree rings remain a dominant proxy over the last few millennia, especially in mid-latitude and polar regions where temperature strongly influences annual growth patterns.

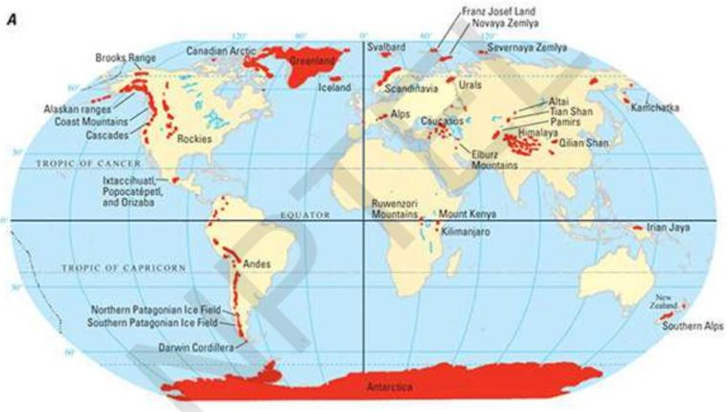
For older time periods, ice cores have been invaluable. In the polar regions, thick layers of ice, sometimes kilometers deep, contain trapped air bubbles and isotopic information that reflect past atmospheric composition and temperature. Lake sediments also serve as important proxies; by extracting cores from the lakebed, scientists can analyze biological and chemical changes in the sediments to infer past temperature and precipitation patterns. Similarly, corals provide insights into past ocean temperatures, as different coral species thrive under specific thermal conditions.

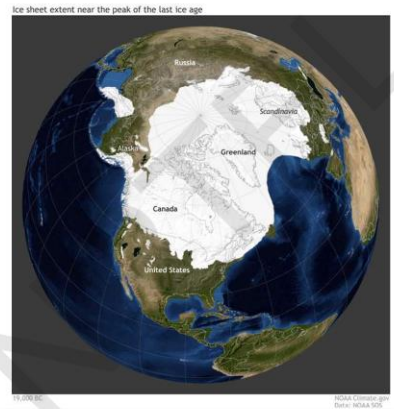
Among all these, deep ocean sediments represent the most critical long-term climate proxies, offering records that stretch back tens to hundreds of millions of years. These sediments contain the remains of marine organisms whose composition and abundance respond to changes in climate. While continental sediments also provide valuable information, oceanic records are generally more continuous and well-preserved.

Importantly, these proxy records overlap in time, particularly over the last 10,000 years, where up to six different proxies may be available for cross-validation. However, as we extend further back in time beyond a few million years, the number and quality of proxies decline, primarily relying on sedimentary records. Thus, while our understanding of recent climate history is quite robust, reconstructions of much older climates carry more uncertainty due to limited proxy availability and increasing geological complexity.

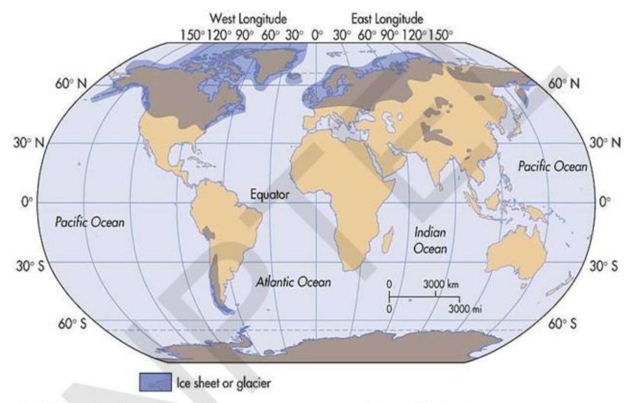


Over the past 50 years, proxy data has been collected from more than 100 locations around the world, including sites in Antarctica, the Arctic, and various land regions. This wide spatial distribution of data points is encouraging, as it allows scientists to compute a reasonably accurate estimate of global mean temperature by averaging across these diverse locations. However, there are still significant data gaps, particularly over large parts of the equatorial oceans, notably the Indian Ocean, Atlantic Ocean, and Pacific Ocean. These gaps raise concerns about whether current reconstructions truly represent the global mean. Despite this limitation, researchers have conducted careful analyses and have demonstrated that, even without full global coverage, such proxy datasets can still provide reliable estimates of global temperature trends. This lends confidence to our understanding of long-term climate change derived from proxy records.



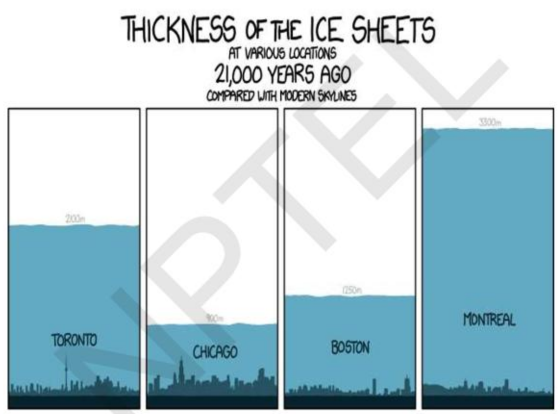


At present, significant ice cover on Earth is largely confined to Antarctica, Greenland, parts of the Arctic, Canada, North America, South America, and the Himalayas, with the rest of the planet having little or no permanent ice. However, around 20,000 years ago, during the last ice age, ice sheets covered vast areas including Canada, Greenland, and much of Europe. This period provides valuable insights into Earth's past climate conditions. Understanding how Earth's climate evolved from the last glacial maximum to the present is critical. Scientists aim to reconstruct this climatic transition using climate models, ranging from simple energy balance models to more complex general circulation models (GCMs) that simulate interactions among the atmosphere, ocean, and land. If these models can successfully reproduce the known changes over the past 20,000 years, they can be considered reliable tools for projecting future climate changes. This is a central objective of paleoclimate research, to validate models using well-documented past climate changes so they can be used with greater confidence for future climate predictions.

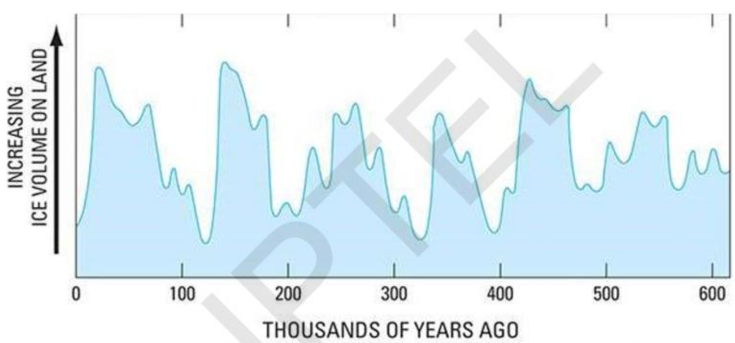


30% of earth covered with ice 20,000 yrs ago. Today only 11%

During the last ice age, approximately 30% of Earth's surface was covered by ice, in contrast to the present-day coverage of only about 11%. This significant decline in ice extent over the past 20,000 years represents a major transformation in Earth's climate system. Understanding the causes and the temporal evolution of this change is essential for climate science. The reduction in ice cover has occurred gradually over millennia, but current trends driven by global warming suggest that the remaining ice may largely disappear within the next few hundred years. By studying and accurately simulating this historical decline using climate models, scientists aim to improve their predictive capability regarding future changes in Earth's ice cover. This objective is central to paleoclimate research and supports efforts to anticipate the consequences of ongoing and future climate change.

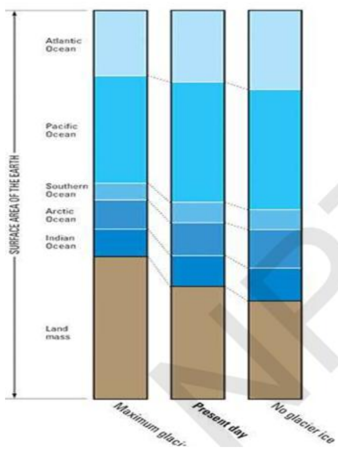


During the last ice age, North America was extensively covered by two major ice sheets: the Cordilleran and the Laurentide Ice Sheets. These ice sheets extended far into the continent, covering vast areas of land with ice thicknesses ranging from 900 meters to over 3 kilometers. For instance, around 21,000 years ago, Montreal was buried under 3.3 km of ice, Toronto under 2.1 km, Boston under 1.25 km, and Chicago under 900 meters. The immense weight of such thick ice sheets caused significant depression of the Earth's crust beneath them. Notably, Greenland was connected to North America during this period due to the expanded ice coverage. As the ice melted and retreated over the past 10,000 years, the land, having been compressed under the enormous weight, has been undergoing post-glacial rebound. However, because bedrock behaves as a viscoelastic material with long-term memory, the rebound is slow and still ongoing in many parts of Canada and northern Europe, even thousands of years after the ice was removed.



Graph showing fluctuation in glacier ice volume on the Earth's land areas during the last 600,000 years [through six glacials (lower sea levels) and interglacials (higher sea levels)]. Maximum volume of glacier ice on land drops sea level approximately -125 m below today's sea level; minimum volume of glacier ice on land, with maximum carbon dioxide concentrations in the Earth's atmosphere of about 280 ppm, raises sea level approximately 6 to 7 m. Modified from figure in Houghton (1997, p. 55).

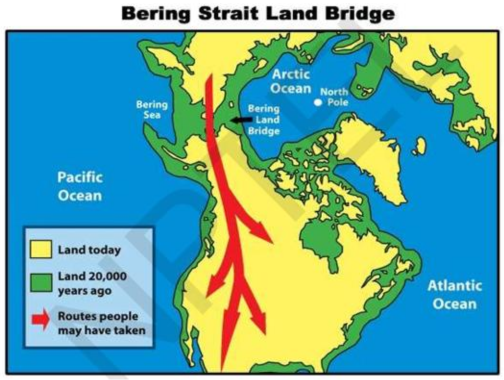
Over the last 600,000 years, Earth has experienced six major ice ages, each marked by a substantial increase in land-based ice cover. These glaciations occurred approximately every 100,000 years, indicating a cyclic pattern in Earth's climate system. The most recent of these glacial periods ended around 20,000 years ago, corresponding to the Last Glacial Maximum. This observed 100,000-year periodicity in ice age occurrences has intrigued scientists for decades, prompting investigations into the underlying mechanisms. While a detailed explanation of this cycle will be covered in a later lecture, it is acknowledged that the phenomenon is not yet fully understood, though significant theoretical progress has been made. The current lecture, however, remains focused on examining climate changes during the last 20,000 years.



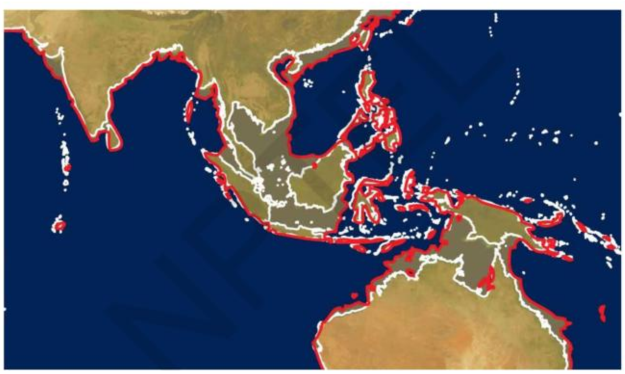
Impact of ice age on the percentage of land area.

During major ice ages, such as the Last Glacial Maximum around 20,000 years ago, significant volumes of ocean water were locked up as ice on land, leading to a drop in global sea level by approximately 120 meters compared to present levels. This substantial decline altered the geography of Earth, exposing large areas of land that are currently submerged. Consequently, the land area during ice ages was much greater than it is today. As the climate warmed and glaciers melted, sea levels rose, submerging previously exposed land and reshaping coastlines. This dynamic relationship between glaciation and sea level has played a critical role in modifying Earth's geographic and ecological landscapes, thereby influencing the evolution and migration of life across different regions.

Currently, approximately 28 to 35 million cubic kilometers of water is stored in glaciers, all originally drawn from the oceans. During the maximum extent of glaciation, this volume was significantly higher, exceeding 70 million cubic kilometers of ice spread across the continents. These massive ice sheets, often 1 to 2 kilometers thick, had a profound influence on the regional climates of glaciated areas. Moreover, the volume of water locked in these glaciers was sufficient to lower global sea levels by as much as 130 meters, demonstrating the critical role of ice sheets in modulating sea level and climate.



One major consequence of lower sea levels during the last ice age was the formation of land bridges, such as the Bering land bridge that connected Asia and North America. This allowed human migration from Asia to North America approximately 20,000 years ago, a fact now confirmed through genetic studies that link Native Americans to Asian ancestors. The land bridge also enabled the migration of animals, such as tigers and other feline species, across continents.

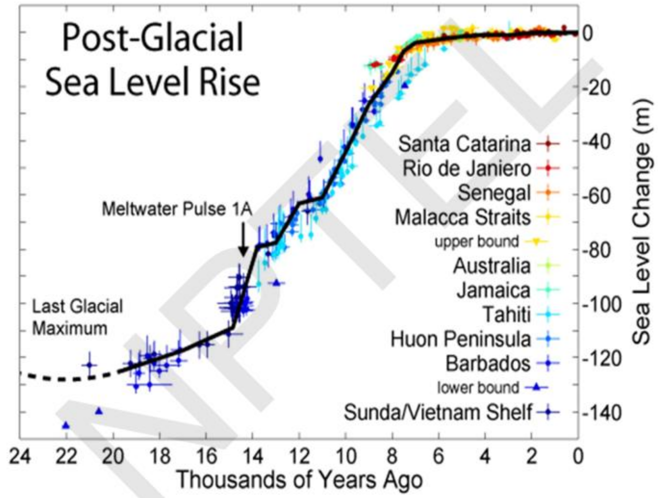


In Asia, the geography was notably different during the ice age. India's western coastal areas, such as Gujarat, extended further into what is now ocean. India and Sri Lanka were joined by land, and large regions of Indonesia were not submerged. This facilitated human movement from India to Southeast Asia and Australia, with genetic links suggesting that Australian Aborigines are related to South Indians, particularly from Tamil Nadu.

These historical shifts demonstrate how glacial cycles dramatically reshaped the world's geography, enabling both human and animal dispersal across vast regions. A notable cultural reference is the mythological city of Dwaraka, believed to have submerged as sea levels rose; underwater explorations off the Gujarat coast have revealed ruins consistent with this account.

Understanding such past events is crucial for interpreting future risks. With global warming accelerating, projections estimate a 1-to-2-meter rise in sea level within the next

100 to 200 years, which could submerge low-lying regions like Bangladesh and threaten small island nations. The dynamic nature of coastlines highlighted through India's changing shape over the past 25,000 years emphasizes that the Earth's map is not static. Therefore, insights from the past climate are essential for preparing for future environmental changes.



Data on sea level rise over the last 20,000 years shows that around 20,000 years ago, global sea levels were approximately 130 meters lower than present levels. While local variations existed, this estimate reflects the global mean. For a period, the sea level remained relatively flat, but then began to rise rapidly in distinct phases, reaching near modern levels by around 6500 years ago. Since then, sea level has continued to rise slowly, in line with the slower rate of global warming during that time.

This information is derived from studies of coastlines around the world, where paleoclimatologists analyze geological and biological markers to determine historical sea levels. However, it's important to note that coastline changes were sometimes sudden and dramatic. This is due to the nature of glacial melting, particularly from massive ice sheets in North America and Europe, which did not melt gradually. Instead, these glaciers often underwent catastrophic collapses, leading to rapid and irregular sea level rises.

Unlike the slow melting of small ice cubes, the behaviour of large ice sheets is unpredictable and non-linear, with the potential for abrupt changes. This historical record serves as an important warning: future sea level rise may also occur in sudden leaps, particularly if major ice sheets collapse under continued global warming. Understanding these past events helps anticipate future risks more accurately.

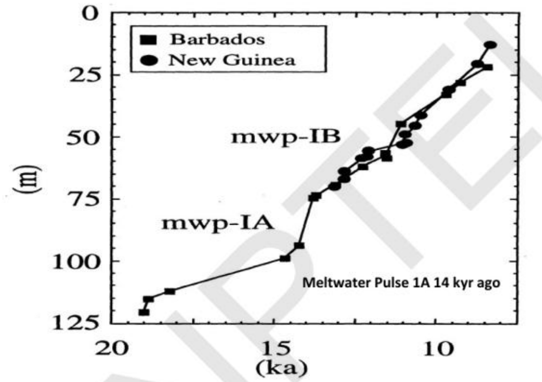


Figure 1. Coral records of sea level dated by U/Th from Barbados [*Bard et al.*, 1990a, 1993] and New Guinea [*Edwards et al.*, 1993]. Two periods of rapid rise of sea level are identified as mwp-IA and mwp-IB.

An important example of sea level rise following the last glacial maximum involves two periods of rapid increase, known as Meltwater Pulse 1A and 1B. These were identified from geological records in New Guinea, and they represent phases when sea level rose significantly over just a few thousand years. Initially, the rise in sea level was gradual, but during these pulses, it occurred at a much faster rate. Understanding the causes behind such abrupt sea level changes is critical for anticipating future changes in Earth's climate.

These rapid rises are believed to result from sudden collapses of large ice shelves, particularly from continental ice sheets. The last 20,000 years have seen periods of both gradual and sudden climate change, and recognizing this variability is crucial. Although the current rate of sea level rise is relatively slow, it is incorrect to assume it will remain that way. If significant portions of the remaining ice shelves in Greenland or Antarctica collapse suddenly, the sea level could rise much faster, as it did during past meltwater pulses.

Therefore, studying the climate transitions of the past 20,000 years is essential to understand the potential for future rapid climate change. The goal of this and the following lecture is to integrate proxy-based reconstructions with climate model simulations to understand these past transitions. Successfully replicating past climate changes using models strengthens confidence in their predictive capabilities, making them more reliable tools for projecting future climate scenarios.