Climate Change Science
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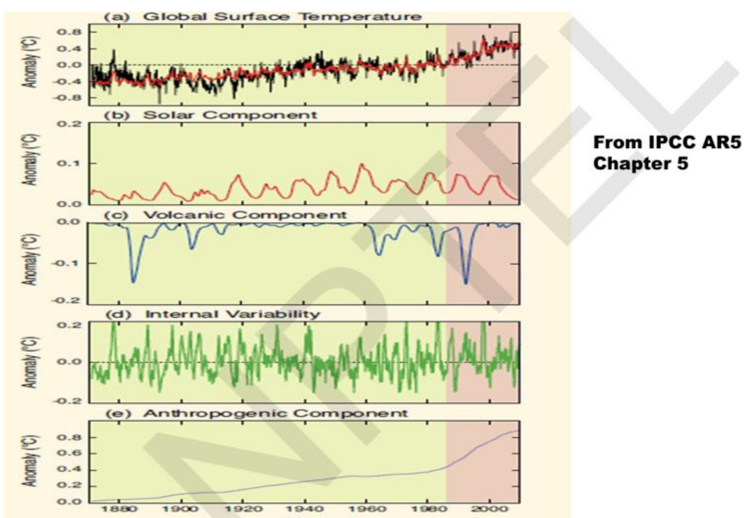
Lecture 22
Paleoclimate

The discussion now shifts to the study of paleoclimate, focusing on Earth's climatic history beyond the instrumental record. Up to this point, attention has been directed primarily toward the present-day climate, particularly the changes observed during the 20th century. A key observation has been the rise in global mean temperature by about 1.5°C over the past 150 years, a trend widely attributed to the increase in atmospheric carbon dioxide levels. However, public skepticism persists, with some attributing recent warming to natural variability, including changes in solar radiation, volcanic activity, or other unknown factors.

To address these doubts and validate the robustness of climate models and theories, it is essential to examine Earth's climate over much longer timescales extending back thousands to millions of years. This broader temporal perspective allows scientists to investigate how the climate system responded to various natural forcings in the past and provides critical evidence to distinguish between natural and anthropogenic influences on recent climate change.



To understand and validate the drivers of recent climate change, it is important to analyze the observed temperature changes over the last 150 years. A comparison of observations with climate model simulations shows that natural factors alone cannot explain the observed global warming. When the model allows only the solar radiation to vary, accounting for the 11-year solar cycle, the resulting temperature variation is only about ±0.05°C, which is far too small to explain the observed 1.5°C warming.

Similarly, incorporating volcanic eruptions into the model, including major events like Mount Pinatubo in 1991, shows temporary cooling effects of around 0.1–0.2°C, but these are short-lived and followed by recovery, indicating they are not responsible for the long-term warming trend. The Earth's internal variability, driven by natural heat exchanges among the ocean, atmosphere, and land, can also lead to temperature fluctuations of about ±0.1 to ±0.2°C. This variability arises without any external forcing and is a normal part of the climate system.

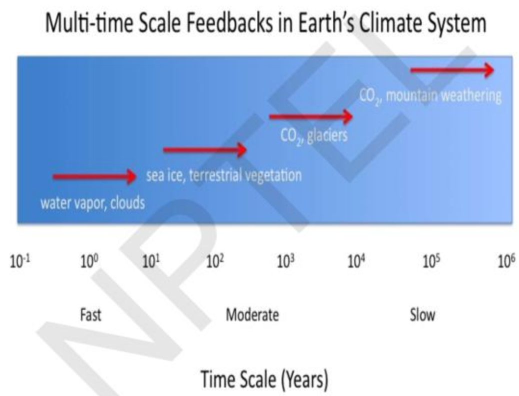
A significant example of internal variability is the El Niño–Southern Oscillation (ENSO). Every 4–5 years, the El Niño phase causes warming in the equatorial eastern Pacific Ocean, near the coast of Peru, transferring stored ocean heat into the atmosphere and raising global temperatures by about 0.1–0.2°C. This is followed by cooler periods. These oscillations can also be linked to broader decadal-scale variability involving the Pacific, Atlantic, and Indian Oceans. However, these changes are not driven by external agents and are instead considered internal climate noise.

When a model includes anthropogenic CO_2 increase, while holding solar radiation and volcanic activity constant, it shows a steady rise in global mean temperature. This rise becomes more evident when internal variability is filtered out, producing a smooth curve that mirrors the observed warming trend. This simulation demonstrates that anthropogenic forcing, primarily CO_2 increase, accounts for about 0.8°C of the total warming, which is significantly larger than the contributions from solar, volcanic, or internal variability.

Therefore, the consistent and growing warming over the industrial era cannot be explained by natural causes alone. Despite this, skepticism persists, and to further validate our models and theories, scientists turn to the climate before 1850 the pre-instrumental era using paleoclimate data to assess how well current models can replicate past climate variations.

In the absence of direct temperature measurements before the invention of the thermometer in the 18th century, scientists rely on proxy methods to reconstruct past climates. These methods provide indirect evidence of Earth's temperature through physical, biological, or chemical indicators preserved in natural records. One widely used proxy is the tree ring method. In cold climates, tree growth varies significantly with temperature. Wider rings typically form during warmer years and narrower rings during colder years. By analyzing tree rings from thousands of trees across Russia, Europe, and America, scientists have reconstructed historical land surface temperatures.

However, trees only grow on land, so this method cannot capture temperature changes over the oceans. For oceanic temperature reconstructions, scientists rely on deep-sea sediment cores. These sediments accumulate slowly over time and contain chemical and biological signatures that reflect the temperature of the seawater when they were deposited. Analyzing these ocean sediments is more complex, but it allows for temperature estimation in marine regions, complementing the land-based data from tree rings.



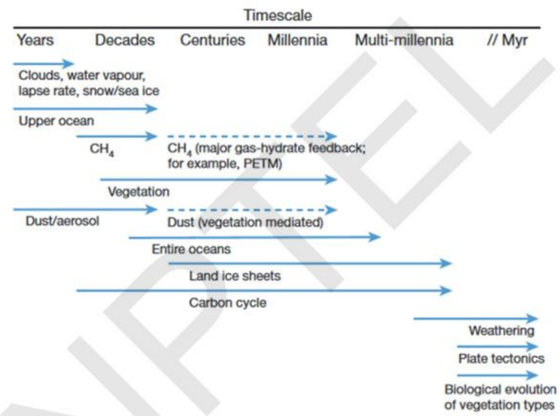


Figure 1 | Typical timescales of different feedbacks relevant to equilibrium climate sensitivity, as discussed in this work. Modified and extended from previous work[98]. Ocean timescales were extended to multi-millennial timescales[99].

To fully understand Earth's climate, it is essential to recognize the variety of time scales over which climate processes operate. So far, discussions have focused on the last 150 years, which aligns with the human timescale and is directly relevant to recent changes such as variations in water vapor, clouds, sea ice, and vegetation. However, Earth's climate history spans over 4.5 billion years, and processes influencing the climate become more complex and slower as one looks further back in time.

For instance, over thousands to tens of thousands of years, changes in carbon dioxide concentrations and glacier extents become important. Over millions of years, geological processes take precedence. These include the formation and erosion of mountains, chemical weathering of rocks—particularly the transformation of calcium silicate rocks into calcium carbonate—and plate tectonics, which drive the movement of continents, volcanic activity, and long-term changes in CO_2 levels. Vegetation changes on these timescales also influence the carbon cycle.

Thus, the mechanisms that dominate climate over millions of years are very different from those relevant over the past century or the coming century. Nevertheless, understanding these long-term processes is critical for validating climate models, ensuring they can accurately simulate both the past and future states of Earth's climate system.

Climate models are built upon fundamental physical laws namely the conservation of momentum, energy, and mass, to predict Earth's temperature and broader climate behaviour. If these laws are universally valid, then the models should also be able to accurately simulate climates that existed thousands, tens of thousands, or even millions of years ago, despite the fact that the climatic mechanisms operating during those periods were quite different from today.

For example, in past epochs when large ice sheets covered substantial parts of the land, Earth's climate was significantly colder. These glaciated conditions led to low water vapor, absence of forests, and widespread dust, since much of the land lacked vegetation. Dust, in turn, played a major role in influencing climate. Moreover, the carbon cycle itself was strongly affected by the presence of ice sheets, volcanic activity, and rock weathering. All these factors created a climate system markedly different from the current one.

Despite these differences, studying such ancient climates is highly valuable for testing and validating climate models. If models built using known physical laws can accurately reproduce past climates, which had vastly different boundary conditions and climate drivers, it boosts confidence in their predictive capability. This is a critical part of the scientific method, where models are intentionally challenged under extreme or unfamiliar scenarios. If they continue to perform well, it strengthens the case that they are robust and reliable.

Looking ahead, if CO_2 emissions continue unchecked, the Earth may become ice-free within the next 100–200 years, resulting in a climate regime vastly different from anything experienced in the last 150 years. The ability of models to simulate such future scenarios depends on how well they handle past ones. Thus, understanding and testing models using paleoclimatic data is essential for anticipating what lies ahead.

To understand Earth's climate system, it is essential to examine its behavior over different geological time scales, a field known as paleoclimate. One of the most notable episodes in Earth's climatic history occurred around 600 million years ago, referred to as the Snowball Earth. During this period, the entire planet was likely covered in ice, indicating an extreme departure from present conditions. If climate models can accurately reproduce such a dramatically different state, it would greatly increase our confidence in the underlying physics and assumptions of these models.

Another critical time frame is the last 3 million years, which featured repeated glacial–interglacial cycles. These cycles were driven by changes in Earth's orbital parameters, known as Milankovitch cycles. These include the shape of Earth's orbit (eccentricity), the tilt of its rotational axis (obliquity), and the direction of the axis (precession). Each of these parameters varies over tens to hundreds of thousands of years, modulating the amount and distribution of solar energy Earth receives, thereby triggering large-scale climate shifts. These mechanisms have been well documented by geologists and climatologists using various proxy data sources.

Particularly significant is the Last Glacial Maximum (LGM), which occurred about 20,000 years ago. This period is valuable for model validation because it is rich in high-resolution data, especially from ice cores in Antarctica and the Arctic, offering a detailed record of temperature and atmospheric composition. By simulating this period accurately, climate models can be further validated against empirical data.

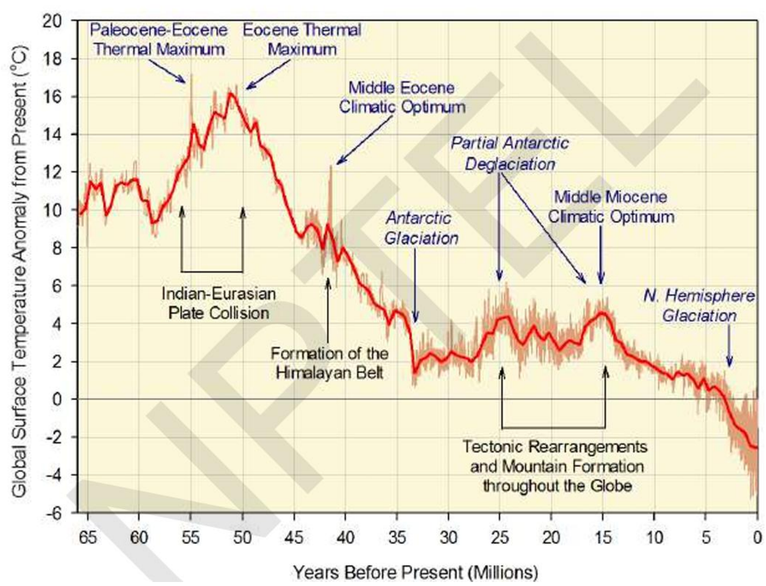
Of equal importance is the climate of the Holocene epoch, especially the last 10,000 years leading up to the industrial era. During this time, Earth's temperature remained remarkably stable, which is unusual given the longer-term variability seen throughout Earth's history. This stable climate enabled the development of agriculture, which, in turn, led to a dramatic increase in human population. Prior to agriculture, humans lived as hunter-gatherers in small numbers due to food limitations. However, with a stable climate, humans began cultivating crops, leading to a population explosion from less than a million to over 8 billion today.

This population growth has brought with it an ironic twist. Human activity is now disrupting the very climate stability that made agricultural civilization possible. The global mean temperature has already risen by 1.5°C in the last 150 years and is projected to rise further. Since agriculture requires stable climate conditions, such rapid warming poses a serious threat to food security. Therefore, it is crucial to understand how Earth maintained a stable climate over the past 10,000 years and how human actions are now destabilizing it. This knowledge is not just academic, it has profound implications for sustainability and human survival.

While the last 10,000 years provided a period of overall climatic stability that supported the rise and expansion of human civilizations, it is important to recognize that this era was not entirely free of disruptions. Despite global population growth and agricultural development, numerous major civilizations collapsed due to episodes of abrupt climate change, particularly prolonged droughts. Historians and archaeologists have documented the fall of several advanced societies such as the Anasazi, Tiwanaku, Akkadian, and Mayan civilizations in North and South America, as well as the Roman Empire in Europe and other cultures across Asia tracing their decline to sustained periods of rainfall failure.

These collapses underscore the vulnerability of human societies to climate extremes, even in eras of general climatic stability. While humans have demonstrated remarkable adaptability and resilience, their dependence on consistent freshwater availability, especially for agriculture, remains a critical vulnerability. When rainfall fails for extended durations, typically 5 to 10 years, civilizations can experience severe stress leading to social, economic, and political collapse, often forcing large-scale migration in search of more hospitable conditions.

Understanding the mechanisms behind such historical droughts is now more urgent than ever, especially in the context of ongoing global warming. As anthropogenic climate change progresses, there is a real risk that the frequency and severity of these multi-year droughts could increase, posing a significant threat to modern civilization. Therefore, studying past climate variability over the Holocene is essential not only to comprehend the Earth's natural climate dynamics but also to anticipate and prepare for potential future disruptions to human society.



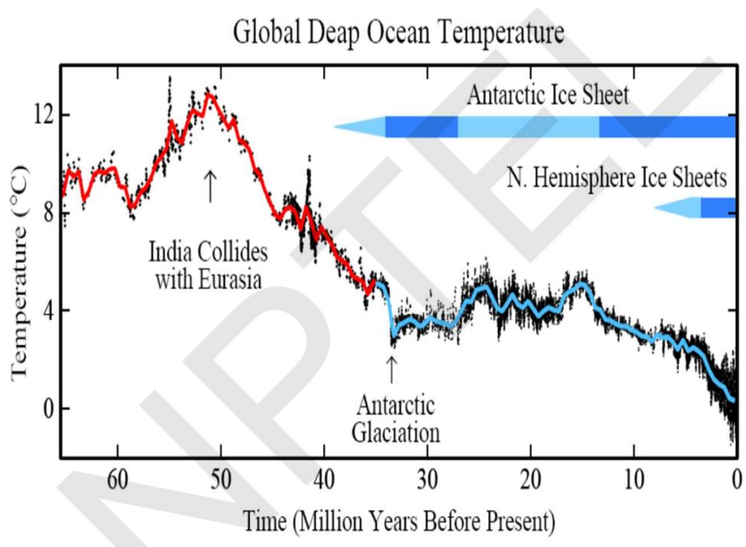
To begin understanding the broader context of Earth's paleoclimate, it is essential to look at long-term temperature trends derived from proxy data—though the specifics of data extraction are complex and will be discussed later. Approximately 50 million years ago, during the Paleocene-Eocene Thermal Maximum (PETM), Earth's global mean temperature was about 16°C higher than today, with the global average reaching nearly 31°C. At that time, Earth was extremely warm and largely ice-free. However, starting around that period, the Earth's climate began a gradual cooling trend. By 30 million years ago, temperatures had fallen to around 2°C above present levels.

One leading theory attributes this long-term cooling to tectonic activity, particularly the collision of the Indian plate with the Eurasian plate, which led to the uplift of the Himalayas and the Tibetan Plateau. The exposure of vast quantities of silicate rocks in these regions likely accelerated chemical weathering, a process that removes CO_2 from the atmosphere, thereby contributing to global cooling. Despite this significant drop of 14°C over 14 million years, the change was extremely slow, averaging 1°C per million years.

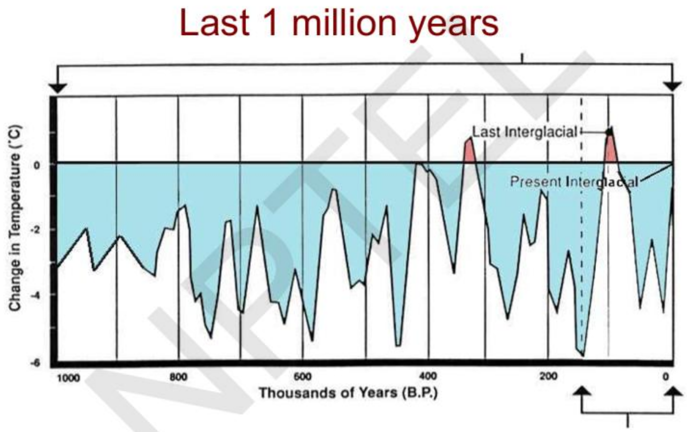
In stark contrast, current global warming is occurring at a rate of approximately 2°C per 100 years, a pace 10,000 times faster than the ancient cooling trend. This rapid rate of change is unprecedented in Earth's history and poses serious challenges for species and ecosystems, which cannot adapt as quickly as they can during slow climatic transitions.

The slow cooling in the past allowed evolutionary processes to operate over millions of years, enabling species to adapt and thrive under progressively cooler conditions. Life continued and evolved through this period, despite the dramatic decline in temperature, precisely because of the gradual nature of the change. Around 30 million years ago, the first Antarctic glaciers began to form, and as temperatures continued to decline, Northern Hemisphere glaciation followed.

Although the available temperature data from this period is impressive, there is limited information on rainfall and atmospheric CO_2 concentrations, so many details remain uncertain. Nonetheless, this paleoclimate record underscores a crucial lesson: life on Earth can withstand significant climatic shifts, but only when those shifts occur slowly. Rapid climate change, such as what is happening today, represents a far more serious and immediate threat to biodiversity and human civilization.

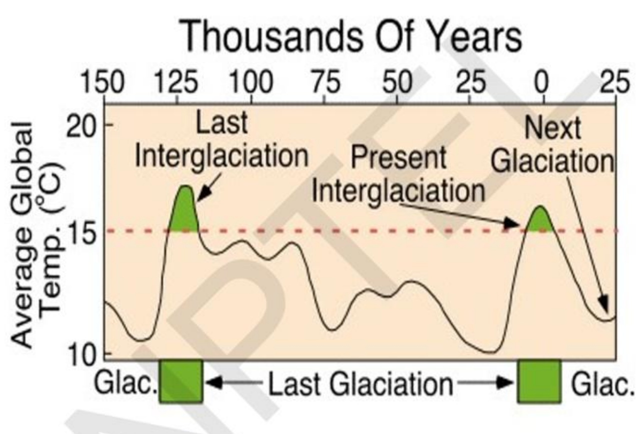


The above is another picture of the same phenomenon showing when the Antarctic ice sheet and the Arctic ice sheet formed. Antarctic formed about 35 million years ago, Arctic around 10 million years ago. So, these happened after the Earth's climate dropped substantially.



Focusing on the last one million years, Earth's climate was characterized predominantly by cold, glacial conditions. For most of this period, the global mean temperature remained around 4 to 5°C lower than present-day levels, resulting in extensive ice cover, especially over the polar regions. During this time, glacial periods dominated, with ice sheets expanding over large portions of the Northern Hemisphere.

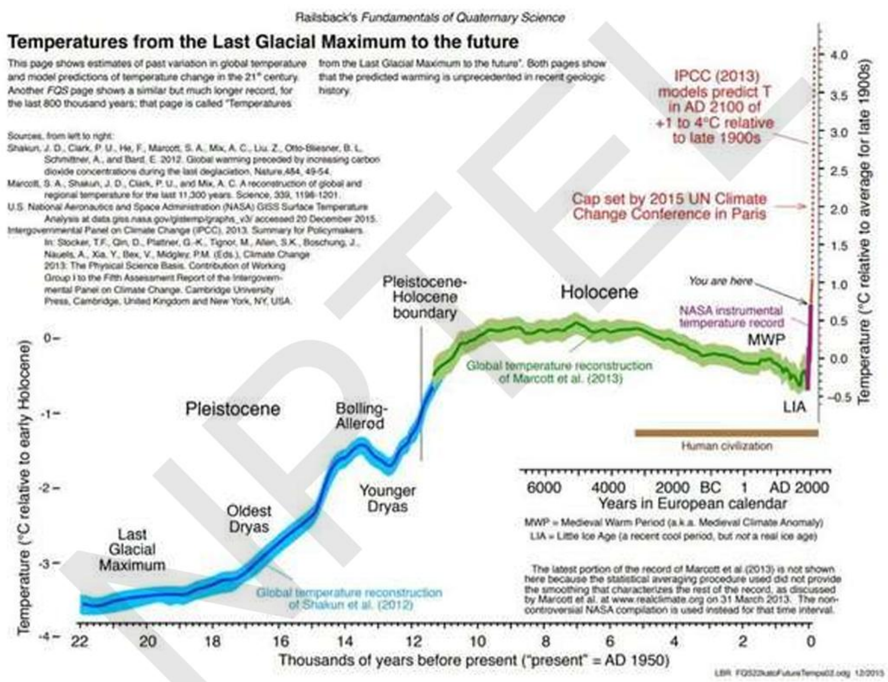
However, this long glacial epoch was interrupted by two brief interglacial periods when the Earth's climate warmed significantly. One such warm interval occurred around 120,000 years ago, known as the last interglacial, and another occurred approximately 320,000 years ago. These interglacials were exceptions in an otherwise persistently cold climate. For the rest of the last million years, Earth remained in a state of intense glaciation, underlining the dominance of ice ages over this extended timescale.



Examining the last 150,000 years, we move closer to the timeframe relevant to human history. During this period, the Earth experienced the last interglacial period around 125,000 years ago, a time of relative warmth during which human beings could have potentially thrived. Following this interglacial, the planet entered a prolonged glacial phase, characterized by extensive cooling and ice coverage. Eventually, Earth transitioned out of this cold phase into the current interglacial period, known as the

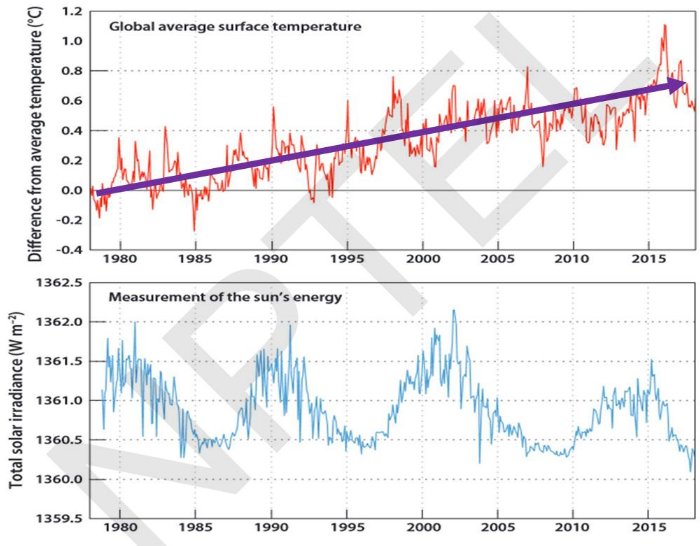
Holocene, which began around 11,700 years ago. This is the interglacial in which we currently live.

Under natural conditions, driven by variations in Earth's orbital parameters, the planet would have likely begun transitioning into the next glacial period in the coming centuries. In fact, based on orbital patterns, such a transition could have begun within the next 10 to 30 thousand years. However, this natural cycle may now be disrupted due to human-induced global warming. With a temperature rise of about 1.5°C above pre-industrial levels already underway, the onset of the next glacial age is now uncertain. Continued warming may delay or even prevent the return of glacial conditions unless significant efforts are made to reduce greenhouse gas emissions.



The temperature evolution over the last 22,000 years is effectively illustrated using a figure adapted from *Railsback's Fundamentals of Quaternary Science*. This period begins with the Last Glacial Maximum, a time when large portions of the Earth were covered in ice. Following this, the planet began to warm gradually, passing through several notable climatic phases, ultimately entering the Holocene epoch, a period of relative climatic stability. It was during this stable phase that agriculture developed and flourished, enabling the growth of human civilization.

The pre-industrial era marked the tail end of this natural climatic stability. However, with the onset of industrialization, atmospheric CO_2 levels began to rise sharply, leading to a rapid increase in global temperatures. Presently, global mean temperature is already 1.5°C above pre-industrial levels and continues to rise. This contrast in rates of change is critical: the Earth naturally warmed by about 5°C over 15,000 years, whereas current projections suggest a similar magnitude of warming could occur within just a few hundred years. Such a rapid rate of climate change is unprecedented in Earth's history, presenting a significant warning to scientists and policymakers. It underlines the urgency of understanding and mitigating human-induced climate change.



Over the last 35 years, global temperatures have risen by approximately 0.8°C. During this time, the incoming solar radiation has followed the natural 11-year solar cycle, exhibiting periodic fluctuations. However, there is no significant correlation between these solar variations and the long-term warming trend observed. While minor temperature responses of about 0.1 to 0.2°C may occur in association with changes in solar output, the sustained rise in global temperature cannot be attributed to solar variations. This conclusion is reinforced by highly accurate satellite data, which clearly shows that the increased warming is not driven by changes in solar radiation. This distinction is important, as some astronomers have previously suggested that solar variability could be responsible for recent climate change. However, current observational evidence firmly refutes that hypothesis, emphasizing that human-induced factors, rather than solar influences, are responsible for the recent warming trend.

In the following lecture, the focus will shift further to examining how various Earth system components such as ice cover, vegetation, land surface changes, and ocean dynamics, have historically interacted to influence the Earth's temperature and overall climate. Understanding these interactions in the context of past climate changes is essential for building a reliable understanding of future climate behavior. This reflects the central goal of the climate change science course: to leverage insights from the past in order to improve predictions for the future. While there is a reasonably good grasp of the present-day climate, a deeper exploration of past climate dynamics is necessary to refine projections and ensure the robustness of climate models.