Climate Change Science

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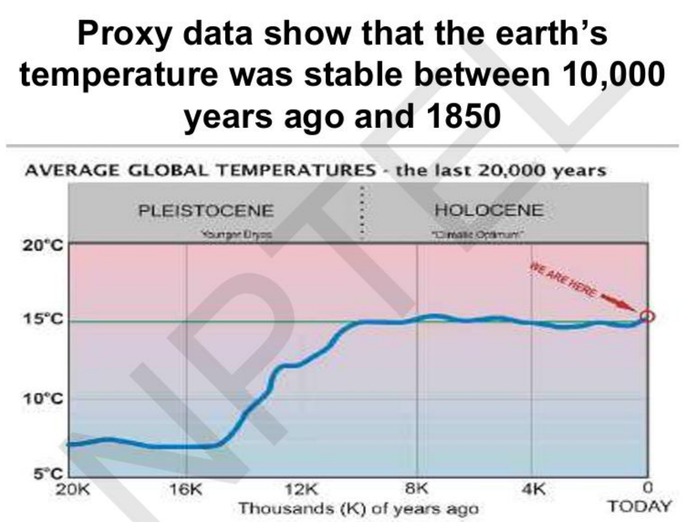
Lecture 02
Global Mean Temperature

There is often confusion between local and global climate change, and it is essential to understand the distinction. Global climate change is influenced by large-scale processes such as variations in ice cover, cloud dynamics, greenhouse gas concentrations, changes in incoming solar radiation, and volcanic activity. These factors alter the overall energy balance of the Earth and drive long-term climate trends. In contrast, local climate change can be affected not only by global changes but also by specific local factors, such as shifts in wind direction, land use modifications (e.g., transforming forests into urban areas), and levels of air pollution. These localized influences can lead to significant climate variations in a particular region. While both are interconnected, this course emphasizes global climate change, as it is more straightforward to analyze and forms the foundation for understanding more complex local changes.

Local climate change is inherently more complex than it may initially appear, as it involves a wide range of region-specific variables and interactions. Due to this complexity, the course will not delve deeply into local climate dynamics. Instead, the focus will remain on global climate change, which, while still multifaceted, is conceptually simpler and more consistent across the planet. A solid understanding of global climate processes is essential before one can effectively analyze and interpret local climate variations.



To understand how the Earth's climate has changed over the last 20,000 years, scientists rely on **proxy data**, since thermometers have only existed for about 300 years. Proxy data involves indirect measurements that provide clues about past temperatures. Through these methods, researchers have determined that the Earth was significantly colder 20,000 years ago, during the peak of the last Ice Age. This evidence forms the foundation of our understanding of historical climate change.

The global mean temperature was around 8^0C about 20,000 years ago. At present, it is 15^0C. So, we emerged from the last ice age 20,000 years ago and rapidly warmed to the present climate around 10,000 years ago. We remained at an almost constant temperature from 10,000 years ago until 1850. From 1850 to present the global mean temperature has increased by 1.5^0C.

Now the question is, how did the Earth maintain almost a constant temperature for 10,000 years and then suddenly start warming up? The reason is that between 10,000 years ago and 1850, human beings had no impact on the climate. We did not use coal, oil or gas. We were burning only firewood and a few local fuels. So, we did not have an impact on the global climate. Natural factors kept the temperature constant for almost 10,000 years. This is called a climatic optimum. Because the climate was very steady for 10,000 years, agriculture thrived. Agriculture does well only under constant climate. As the climate was constant, agriculture thrived, and the human population increased rapidly during this period.

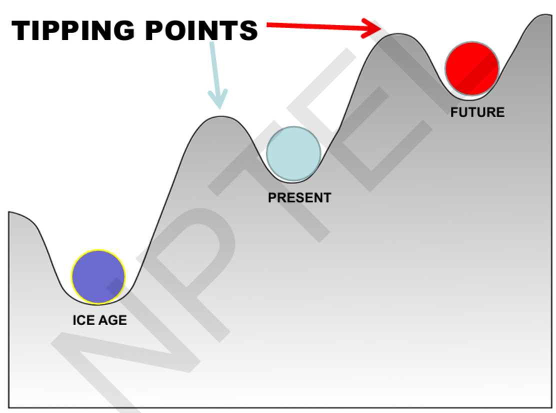
Remember that 20,000 years ago, farming was not possible. Earth was too cold, and only hunter-gatherers lived in caves, where they hunted various animals. Once the Earth became warm, agriculture became possible, and the human population started to increase because of the availability of food. Now, in the last 150 years, since we started burning oil, coal, and gas, we have been increasing the temperature more rapidly. We need to be concerned about that because if we continue to do so, the temperature will increase even more rapidly.

This course primarily focuses on the rapid temperature changes observed over the past 150 years, exploring their underlying causes and potential solutions to mitigate further warming. Since direct temperature measurements using thermometers are limited to recent centuries, scientists study past climates using proxy data. These proxies include biological, physical, or chemical indicators found in natural archives such as sediments, fossils, shells, ice cores, air bubbles trapped in ice, cave formations (speleothems), and deep-sea corals. These indirect records allow us to infer historical temperature and rainfall patterns over millennia.

So, these are surrogates for the climate. That is, we cannot measure temperature with a thermometer, which was not available in the past. So, from various other sources, we infer temperature or rainfall by indirect means. This is not very accurate, but by using various techniques, we can get a rough idea of what the climate was like, for example, 20,000 years ago. So, this is the only method we have for inferring past climate.

Now, from this proxy data, we know that the Earth was once completely ice-free millions of years ago. It was also completely ice-covered, called the Snowball Earth. So, the fact that Earth has oscillated between an ice-free Earth and an ice-covered Earth should bother us, as it means Earth's climate is not stable. It can change. The fact that it did not change between 10,000 years ago and 1850 should not make us complacent.

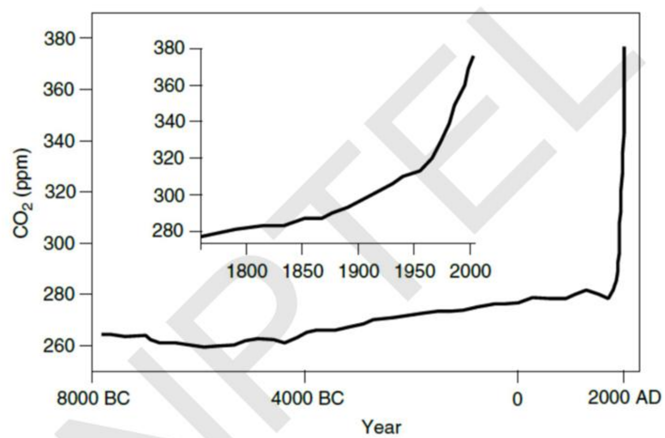
It is important to understand that the Earth's climate is not inherently stable. Over the past 100 million years, the planet has experienced significant shifts, oscillating between ice-covered and ice-free states—changes that are evident through proxy data. A key objective of this course is to explore the drivers behind these historical climate transitions and to assess whether similar large-scale changes could occur again, particularly as a result of human activities. By studying both the past climate and the possible future trajectories, we can better grasp the dynamics and risks of ongoing climate change.



Understanding past climate transitions is crucial because the Earth emerged from the last Ice Age around 20,000 years ago through a relatively rapid warming of about 8°C to 9°C. This swift shift from a cold to a warmer climate is referred to as a tipping point—a critical threshold beyond which the climate system undergoes abrupt and potentially irreversible change. While some climate changes occur gradually, others can happen in just a few thousand years. This raises a significant concern: could human-induced climate change push the Earth past another tipping point, leading to a much warmer and potentially unstable climate state?

This course focuses on whether human actions are driving climate change to the point where the Earth may become much warmer. While it's uncertain whether such a drastic shift is inevitable, the Paris Agreement, signed around 10 years ago, highlighted the concern that the 1.5°C warming already caused by human activities could lead to even greater warming. The agreement emphasized the need to limit the global temperature rise to 1.5°C to avoid surpassing a critical tipping point.

The exact location of the tipping point in the Earth's climate remains unknown, but we must exercise caution, as tipping points have occurred in the past. For example, the transition from the ice age to the current climate allowed the development of agricultural societies. However, today, human-induced changes are happening at a much faster pace. This raises the possibility that we may be heading toward a much warmer climate. A key focus of this course will be to understand the potential tipping points in the Earth's climate.



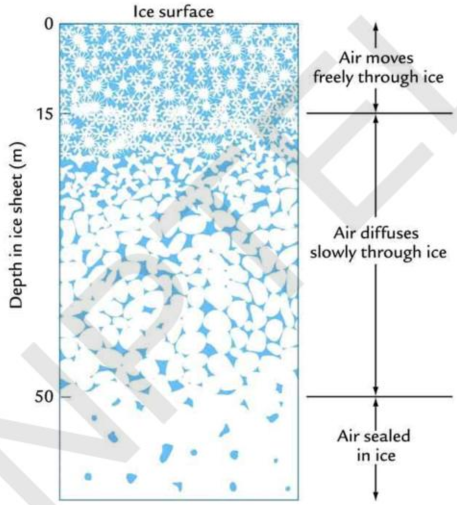
From
The Science and Politics of Climate Change by Dessler and Parson, 2010

Carbon dioxide (CO_2) plays a significant role in influencing Earth's climate. Looking at CO_2 levels over the past 200 years, where data is reliable, we observe a sharp increase from about 280 ppm (parts per million) in 1750 to approximately 380 ppm in 2000. This rapid rise is largely attributed to the burning of coal, oil, and gas. In contrast, examining the past 10,000 years shows a much slower change. From 8000 B.C. to around 850 A.D., CO_2 levels only increased by about 10 to 20 ppm. However, after 1850, the rise in CO_2 levels accelerated dramatically, with an increase of around 100 ppm between 1850 and 2000. This stark contrast between the gradual change before 1850 and the rapid change after requires further investigation into the underlying causes of these shifts.

The rapid changes we are seeing today are of major concern because they are happening much faster than those in the past. Many people question why small changes in ppm or temperature matter, but the key issue is the speed at which these changes are occurring.

To understand past climate changes, scientists have relied on drilling ice cores from glaciers in Antarctica. These ice sheets are up to 4 kilometers wide and very thick. By drilling into the ice, researchers can obtain samples that contain a detailed record of

Earth's climate history. When snow falls in polar regions, it compresses over time, and air from past periods becomes trapped in the ice as it accumulates. By drilling down to about 50 meters, scientists can extract air bubbles from this ancient snow, which provide valuable information about past climates.

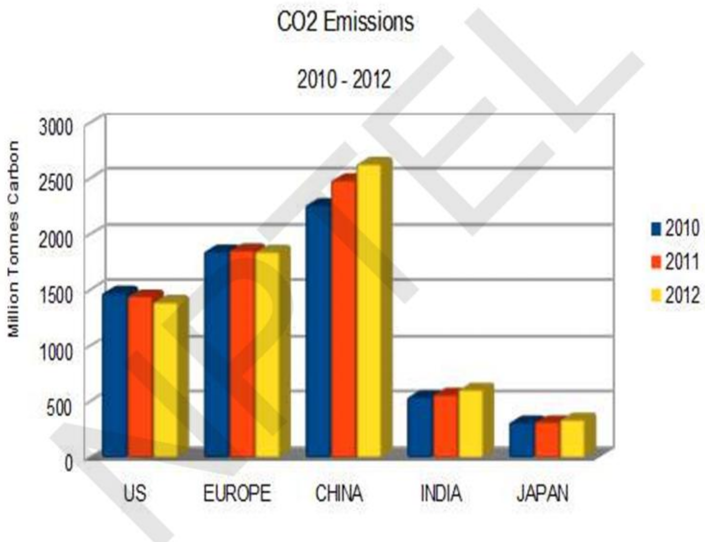


Scientists have used ice cores to study the changes in air trapped in the ice, providing valuable insights into past climates. These ice cores, which contain air bubbles, reveal how carbon dioxide levels have fluctuated over time due to the long-term carbon cycle. This cycle operates on a timescale of 100,000 to 1 million years and is a slow process that helps maintain balance in Earth's atmosphere.

Carbon dioxide is introduced through volcanic eruptions, which release CO_2 into the atmosphere. Additionally, mid-ocean ridges also contribute to CO_2 release, but rainwater dissolves the gas, which eventually forms limestone (calcium carbonate) through a series of chemical processes. The shifting of tectonic plates further influences this cycle by causing sediments to heat up and release CO_2, which then returns to the atmosphere through volcanic activity. Thus, large-scale variations in Earth's climate are driven by these slow, natural changes in the carbon dioxide cycle. However, this cycle has been accelerated by human actions. The burning of coal, oil, and natural gas not only increases local CO_2 concentrations but also spreads the gas globally, raising carbon dioxide levels across the planet.

The global rise in carbon dioxide is a major concern because CO_2, once released, circulates around the entire planet. Whether carbon dioxide is emitted in places like Bengaluru, New York, Beijing, or London, the winds carry it to every part of the Earth, ensuring that CO_2 spreads globally. While human activities contribute to CO_2 emissions in specific locations, the gas is ultimately dispersed worldwide.

A portion of the CO_2 released by human actions is absorbed by the oceans, and another part is utilized by plants during photosynthesis. However, about 50 percent of the released CO_2 remains in the atmosphere. This accumulation has caused carbon dioxide levels to increase from 280 ppm in 1750 to 426 ppm by 2024. Over the last 170 years, human activities have raised the global mean CO_2 concentration by more than 140 ppm, marking a significant and impactful change to Earth's atmosphere.

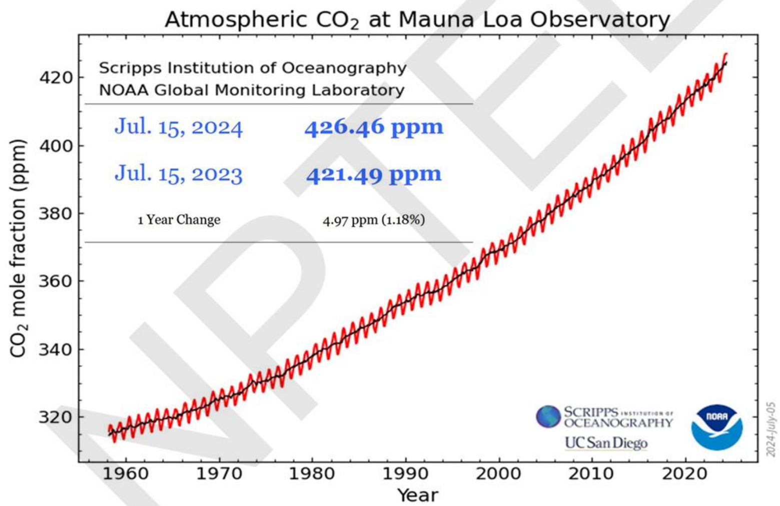


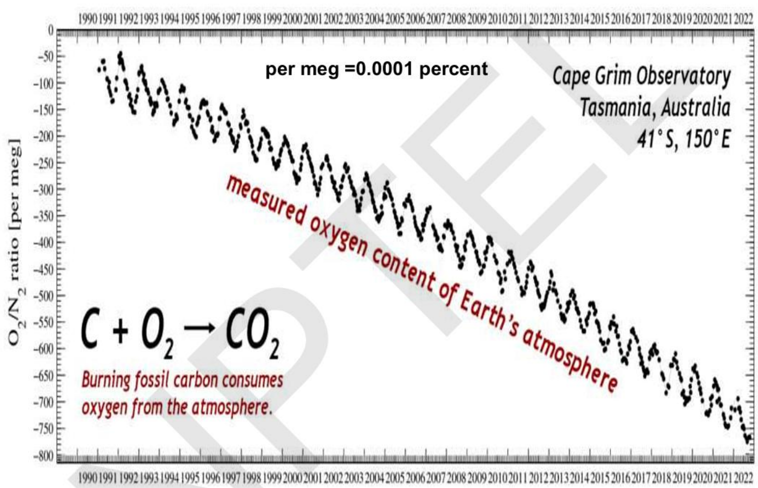
Carbon dioxide emissions vary significantly between countries. Currently, China is the largest emitter, followed by Europe, the USA, and then India. However, the key point is that it doesn't matter which country is releasing carbon dioxide because, once emitted, it spreads globally. CO_2 released in any part of the world ultimately impacts every region, leading to a global effect.

This is why the focus is on global temperature change, as it is not about which country emits more or less CO_2—it's about the collective impact. The increase in CO_2 levels will lead to rapid global warming, affecting everyone, regardless of where the emissions originate. This underscores the importance of global negotiations to control CO_2 emissions, as they are a primary driver of climate change.

There is clear evidence supporting the fact that the increase in carbon dioxide is primarily due to human activities. One of the key sources of this data comes from Mauna Loa in Hawaii, where accurate measurements of carbon dioxide levels have been conducted since 1958. These measurements show a steady increase in CO_2, with small seasonal fluctuations. The seasonal cycles are linked to photosynthesis, particularly in the Northern Hemisphere, where vegetation absorbs CO_2 during the summer. This causes a temporary drop in CO_2 levels by a few ppm. However, due to the continuous release of CO_2 from burning fossil fuels, the overall trend remains upward.

How do we know that the increase in CO_2 during the last 60 years is on account of burning fossil fuels?



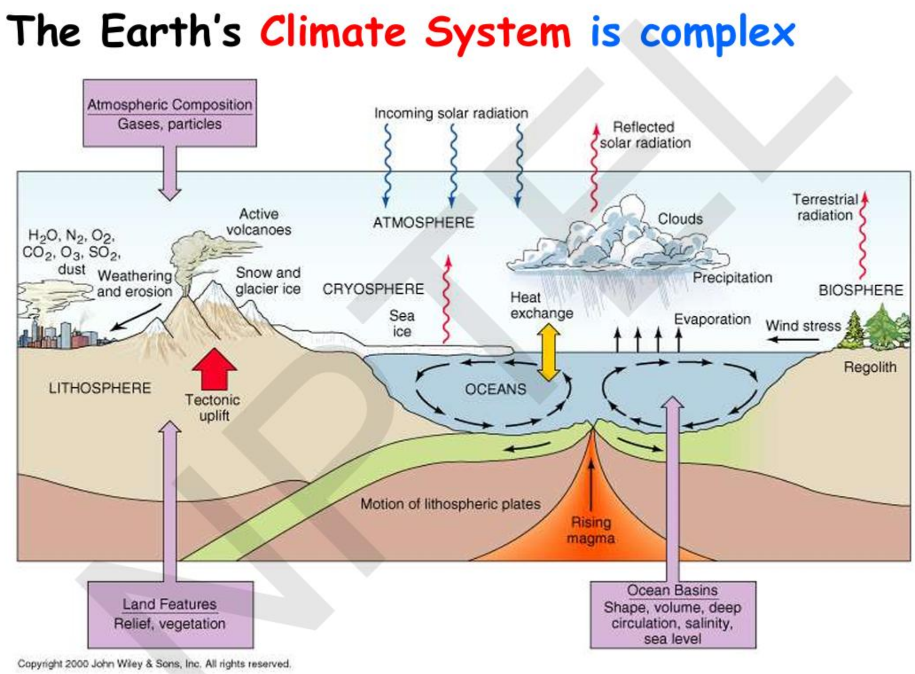


This data provides strong evidence that the rise in CO_2 is not due to natural causes, but rather the burning of fossil fuels. Furthermore, scientists have been able to measure the corresponding decline in atmospheric oxygen, which is directly related to the amount of carbon being burned. While the oxygen reduction is very small—only about 0.0001 percent—it perfectly matches the amount of CO_2 being emitted. This precise measurement allows scientists to create a "carbon budget" that correlates the burning of fossil fuels with the increase in CO_2.

This evidence has been crucial in dispelling the idea that the rising CO_2 levels might be due to natural factors like volcanic eruptions. The accurate data on both carbon dioxide and oxygen confirms beyond doubt that the increase in CO_2 is mainly the result of human activities, particularly the burning of fossil fuels. This proof was essential in convincing skeptics that the rise in CO_2 is not part of a natural cycle but a direct consequence of our actions.

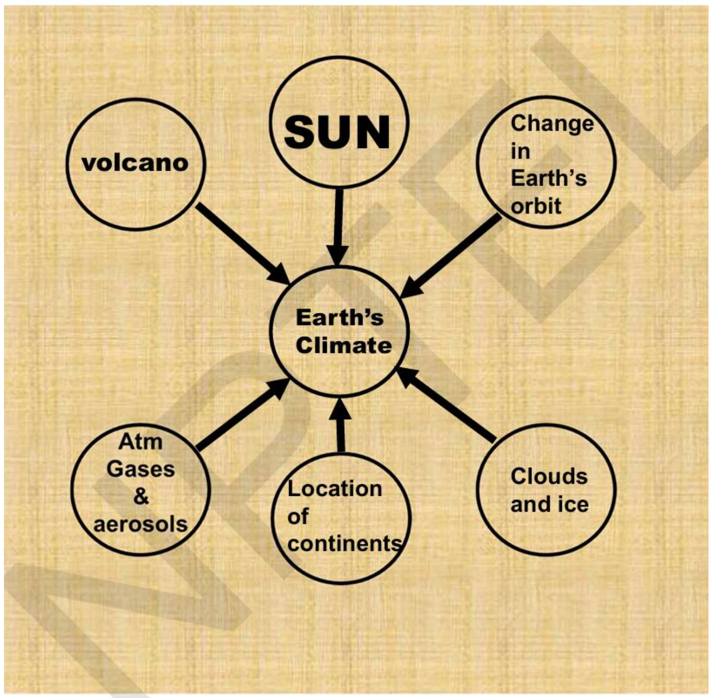
In the past 100 years, the global temperature has risen at a rate ten times faster than it did over the previous 20,000 years. Historically, carbon dioxide levels increased by about 20 ppm in 100 years due to an abrupt climate change (15,000 years ago). Today, however, CO_2 levels are rising by 20 ppm every 10 years. This rapid acceleration of both carbon dioxide concentrations and temperature increase is what is alarming experts worldwide.

This sharp increase underscores the unsustainable nature of our actions, particularly the burning of fossil fuels. The current rate of change is expected to lead to major environmental disasters and significant climate shifts, causing considerable harm to humanity. Recognizing the urgency of the situation, the Paris Agreement was established to address this issue. It became clear that the rapid rise in CO_2 and global temperatures cannot continue unchecked, and global action is required to mitigate the impacts and control this dangerous trend.



The Earth's climate system is highly complex, influenced by a range of factors beyond just carbon dioxide. These include radiation from the sun, oceanic circulation, clouds, ice sheets in the cryosphere, and the biosphere. All of these elements play a role in regulating the Earth's temperature. However, in this course, we will focus on a few key factors that are particularly important, as it is not feasible to cover every aspect of the climate system in an introductory course.

While the Earth system as a whole is complicated, simplifying certain components will allow us to better understand how human activities influence the climate. Once we grasp the global factors that drive climate change, we will be in a better position to explore local climate changes, which are even more intricate than global changes.



The Earth's climate is influenced by six major factors. First, the sun, which provides the energy that drives Earth's climate, plays a crucial role in determining temperature. Volcanic eruptions also have an impact, as they can release particles and gases that temporarily affect the climate. Changes in Earth's orbit around the Sun, which we will explore in more detail later, can also influence long-term climate patterns. The composition of atmospheric gases, including greenhouse gases, and aerosols (small particles suspended in the atmosphere) are key factors in shaping the climate. Additionally, the way continents are positioned on Earth's surface affects climate by influencing ocean currents and atmospheric circulation. Finally, clouds and ice contribute to climate regulation by reflecting sunlight and affecting heat retention.

To understand how each of these factors influences the climate, we must simplify the Earth's complex climate system, focusing on the key elements that drive climate change.

To understand global climate change, it's essential to grasp the balance between the radiation Earth absorbs from the sun and the radiation it emits back into space. This balance is what primarily controls the Earth's temperature. In this course, the major focus will be on how this balance is disrupted by factors such as gases in the atmosphere, clouds, and ice cover. Understanding how these elements affect the Earth's energy balance will help us comprehend how the global mean temperature is altered, which is at the heart of climate change.

The global mean temperature is primarily controlled by carbon dioxide, with water vapor playing a crucial role as an amplifier. While water vapor is important, it is not the main driver of temperature changes; instead, it amplifies the effect of CO_2. The reason for this is that the amount of water vapor in the atmosphere is governed by temperature, which is in turn influenced by carbon dioxide levels.

This relationship is described by the Clausius-Clapeyron equation from thermodynamics, which shows that as the temperature of the Earth changes, the amount of water vapor in the atmosphere also changes. Therefore, water vapor does not remain constant when the temperature fluctuates, and its amount is directly tied to the temperature changes driven by carbon dioxide.

For a long time, this important interaction was not fully understood, and the role of carbon dioxide as a major climate driver was not fully recognized. Water vapor essentially acts as a "slave" to the temperature control exerted by carbon dioxide. This is a key concept in climate science, and understanding the role of CO_2 is essential. In the next class, we will delve into radiation heat transfer and discuss the textbooks that will help us understand how radiation impacts Earth's atmosphere.