

4.3 CLIMATE SENSITIVITY AND FEEDBACKS

Climate sensitivity refers to the amount of global warming that occurs in response to a doubling of atmospheric carbon dioxide (CO₂) concentrations compared to pre-industrial levels. It's a crucial parameter in climate science because it helps us understand how Earth's temperature responds to changes in greenhouse gas concentrations and provides insights into future climate projections.

Climate feedbacks are processes in the Earth's climate system that can either amplify or dampen the initial warming caused by changes in greenhouse gas concentrations. Feedbacks can occur through various mechanisms, including changes in cloud cover, ice-albedo feedback (where changes in ice and snow cover affect the amount of sunlight reflected back into space), water vapor feedback, and changes in vegetation.

Here's how they work together:

1. Positive Feedbacks:

These feedbacks amplify the initial warming caused by greenhouse gas emissions. For example, as temperatures rise, ice and snow melt, reducing the Earth's albedo (reflectivity), which leads to more absorption of sunlight and further warming. Another example is the water vapor feedback: as the atmosphere warms, it can hold more water vapor, which is itself a greenhouse gas, leading to additional warming.

2. Negative Feedbacks:

Conversely, negative feedbacks tend to mitigate the initial warming. For instance, as temperatures rise, clouds may form more frequently or become thicker, reflecting more sunlight back into space and cooling the Earth. Additionally, increased CO₂ levels can stimulate plant growth, which can absorb carbon from the atmosphere, acting as a negative feedback.

The combined effect of these feedbacks determines the overall climate sensitivity. If positive feedbacks dominate, the climate system becomes more sensitive to changes in greenhouse gas concentrations, leading to greater warming. Conversely, if negative feedbacks dominate, the system is less sensitive, resulting in less overall warming.

Understanding climate sensitivity and feedbacks is critical for improving climate models and making more accurate projections of future climate change. It helps scientists and

policymakers assess the potential impacts of different emission scenarios and develop strategies to mitigate and adapt to climate change.

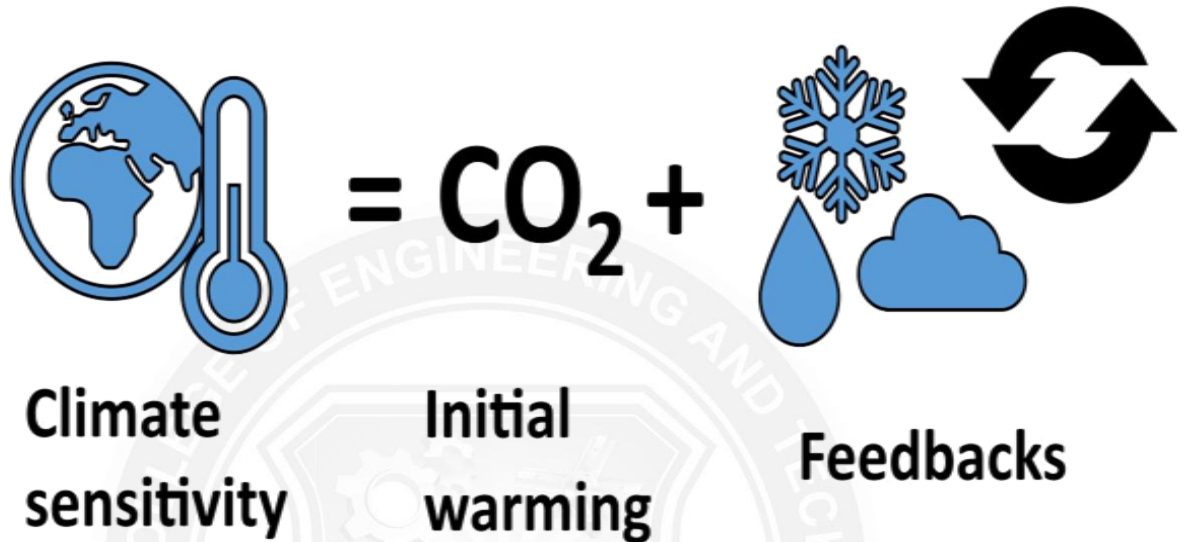


FIG. 4.3.1 CLIMATE SENSITIVITY AND FEEDBACKS

Understanding the balance between these feedbacks and the overall sensitivity of the climate system is crucial for making accurate predictions about future climate change. If positive feedbacks dominate, the climate system could be more sensitive to greenhouse gas emissions, leading to potentially more severe warming. Conversely, if negative feedbacks are stronger, they could dampen the warming effect, resulting in a more moderate climate response.

Climate sensitivity and feedbacks are areas of active research in climate science. Improving our understanding of these processes helps refine climate models and improve the accuracy of future climate projections. It also informs policymakers and stakeholders about the potential risks and impacts of climate change and the importance of mitigation and adaptation strategies.

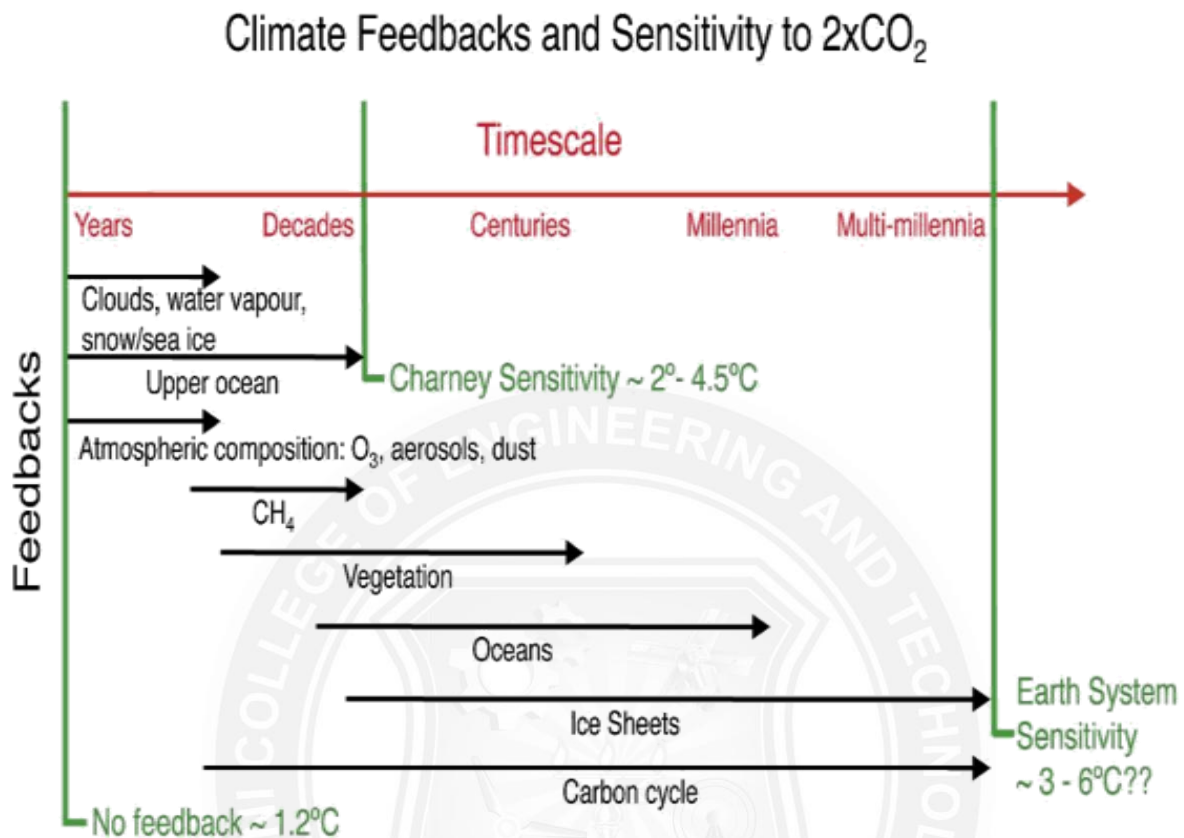


FIG. 4.3.2 CLIMATE SENSITIVITY AND FEEDBACKS

Water vapour feedback

Unlike concentrations of other greenhouse gases, the concentration of water vapour in the atmosphere cannot freely vary. Instead, it is determined by the temperature of the lower atmosphere and surface through a physical relationship known as the Clausius-Clapeyron equation, named for 19th-century German physicist Rudolf Clausius and 19th-century French engineer Émile Clapeyron. Under the assumption that there is a liquid water surface in equilibrium with the atmosphere, this relationship indicates that an increase in the capacity of air to hold water vapour is a function of increasing temperature of that volume of air. This assumption is relatively good over the oceans, where water is plentiful, but not over the continents. For this reason the relative humidity (the percent of water vapour the air contains relative to its capacity) is approximately 100 percent over ocean regions and much lower over continental regions (approaching 0 percent in arid regions). Not surprisingly, the average relative humidity of Earth's lower atmosphere is similar to the fraction of Earth's surface covered by the oceans (that is, roughly 70 percent). This quantity is expected to remain

approximately constant as Earth warms or cools. Slight changes to global relative humidity may result from human land-use modification, such as tropical deforestation and irrigation, which can affect the relative humidity over land areas up to regional scales.

The amount of water vapour in the atmosphere will rise as the temperature of the atmosphere rises. Since water vapour is a very potent greenhouse gas, even more potent than CO₂, the net greenhouse effect actually becomes stronger as the surface warms, which leads to even greater warming. This positive feedback is known as the “water vapour feedback.” It is the primary reason that climate sensitivity is substantially greater than the previously stated theoretical value of 0.25 °C (0.45 °F) for each increase of 1 watt per square metre of radiative forcing.

Cloud feedbacks

Different types of clouds form at different heights.

It is generally believed that as Earth’s surface warms and the atmosphere’s water vapour content increases, global cloud cover increases. However, the effects on near-surface air temperatures are complicated. In the case of low clouds, such as marine stratus clouds, the dominant radiative feature of the cloud is its albedo. Here any increase in low cloud cover acts in much the same way as an increase in surface ice cover: more incoming solar radiation is reflected and Earth’s surface cools. On the other hand, high clouds, such as the towering cumulus clouds that extend up to the boundary between the troposphere and stratosphere, have a quite different impact on the surface radiation balance. The tops of cumulus clouds are considerably higher in the atmosphere and colder than their undersides. Cumulus cloud tops emit less longwave radiation out to space than the warmer cloud bottoms emit downward toward the surface. The end result of the formation of high cumulus clouds is greater warming at the surface.

The net feedback of clouds on rising surface temperatures is therefore somewhat uncertain. It represents a competition between the impacts of high and low clouds, and the balance is difficult to determine. Nonetheless, most estimates indicate that clouds on the whole represent a positive feedback and thus additional warming.

Ice albedo feedback

Another important positive climate feedback is the so-called ice albedo feedback. This feedback arises from the simple fact that ice is more reflective (that is, has a higher albedo)

than land or water surfaces. Therefore, as global ice cover decreases, the reflectivity of Earth's surface decreases, more incoming solar radiation is absorbed by the surface, and the surface warms. This feedback is considerably more important when there is relatively extensive global ice cover, such as during the height of the last ice age, roughly 25,000 years ago. On a global scale the importance of ice albedo feedback decreases as Earth's surface warms and there is relatively less ice available to be melted.

Carbon cycle feedbacks

Another important set of climate feedbacks involves the global carbon cycle. In particular, the two main reservoirs of carbon in the climate system are the oceans and the terrestrial biosphere. These reservoirs have historically taken up large amounts of anthropogenic CO₂ emissions. Roughly 50–70 percent is removed by the oceans, whereas the remainder is taken up by the terrestrial biosphere. Global warming, however, could decrease the capacity of these reservoirs to sequester atmospheric CO₂. Reductions in the rate of carbon uptake by these reservoirs would increase the pace of CO₂ buildup in the atmosphere and represent yet another possible positive feedback to increased greenhouse gas concentrations.

In the world's oceans, this feedback effect might take several paths. First, as surface waters warm, they would hold less dissolved CO₂. Second, if more CO₂ were added to the atmosphere and taken up by the oceans, bicarbonate ions (HCO₃⁻) would multiply and ocean acidity would increase. Since calcium carbonate (CaCO₃) is broken down by acidic solutions, rising acidity would threaten ocean-dwelling fauna that incorporate CaCO₃ into their skeletons or shells. As it becomes increasingly difficult for these organisms to absorb oceanic carbon, there would be a corresponding decrease in the efficiency of the biological pump that helps to maintain the oceans as a carbon sink (as described in the section Carbon dioxide). Third, rising surface temperatures might lead to a slowdown in the so-called thermohaline circulation (see Ocean circulation changes), a global pattern of oceanic flow that partly drives the sinking of surface waters near the poles and is responsible for much of the burial of carbon in the deep ocean. A slowdown in this flow due to an influx of melting fresh water into what are normally saltwater conditions might also cause the solubility pump, which transfers CO₂ from shallow to deeper waters, to become less efficient. Indeed, it is predicted that if global warming continued to a certain point, the oceans would cease to be a net sink of CO₂ and would become a net source.

As large sections of tropical forest are lost because of the warming and drying of regions such as Amazonia, the overall capacity of plants to sequester atmospheric CO₂ would be reduced. As a result, the terrestrial biosphere, though currently a carbon sink, would become a carbon source. Ambient temperature is a significant factor affecting the pace of photosynthesis in plants, and many plant species that are well adapted to their local climatic conditions have maximized their photosynthetic rates. As temperatures increase and conditions begin to exceed the optimal temperature range for both photosynthesis and soil respiration, the rate of photosynthesis would decline. As dead plants decompose, microbial metabolic activity (a CO₂ source) would increase and would eventually outpace photosynthesis.

Under sufficient global warming conditions, methane sinks in the oceans and terrestrial biosphere also might become methane sources. Annual emissions of methane by wetlands might either increase or decrease, depending on temperatures and input of nutrients, and it is possible that wetlands could switch from source to sink. There is also the potential for increased methane release as a result of the warming of Arctic permafrost (on land) and further methane release at the continental margins of the oceans (a few hundred metres below sea level). The current average atmospheric methane concentration of 1,750 ppb is equivalent to 3.5 gigatons (3.5 billion tons) of carbon. There are at least 400 gigatons of carbon equivalent stored in Arctic permafrost and as much as 10,000 gigatons (10 trillion tons) of carbon equivalent trapped on the continental margins of the oceans in a hydrated crystalline form known as clathrate. It is believed that some fraction of this trapped methane could become unstable with additional warming, although the amount and rate of potential emission remain highly uncertain.