Climate Change Science
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Lecture 12
Cloud Feedbacks (continued)

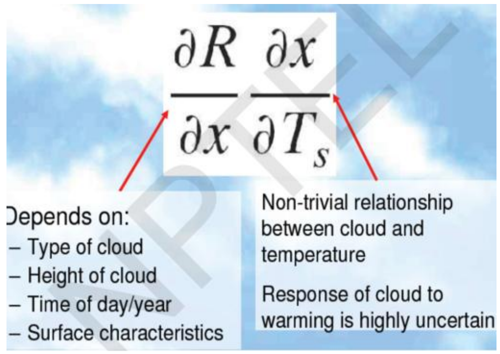
In the previous lecture, the role of clouds in the Earth's climate system was discussed, particularly the uncertainty they introduce in predicting the response of global temperature to increasing atmospheric carbon dioxide. This uncertainty arises because current climate models are not yet able to accurately simulate how clouds will respond to global warming. In this lecture, examples from specific climate models are used to illustrate the extent of this variability.

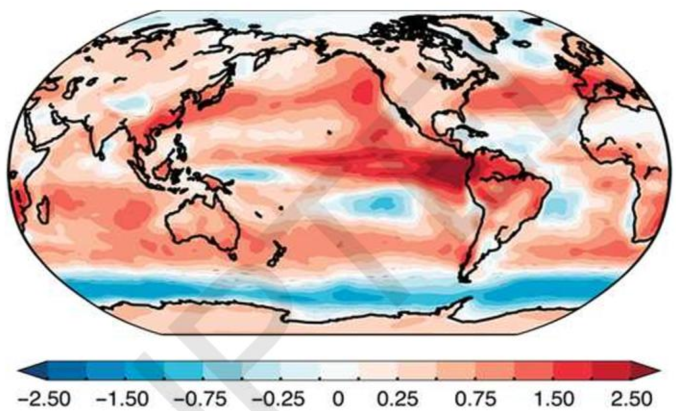
Two climate models are compared: one developed by the Goddard Institute of Space Studies (GISS) led by James Hansen, and the other by the Princeton group, particularly the work of Wetherald and Manabe. These models exhibit significant differences in cloud feedback estimates. For instance, the feedback due to changes in cloud fraction (which affects albedo) differs notably: one model estimates it as 0.33 W/m² per °C, while the other estimates 0.12 W/m² per °C, almost a factor of three difference. Similarly, the cloud height feedback, which impacts the greenhouse effect, is 0.4 W/m² per °C in one model and 0.25 W/m² per °C in the other.

	Cloud amount feedback ($W/m^2/K$)	Cloud height feedback ($W/m^2/K$)	Total cloud feedback ($W/m^2/K$)
Hansen et al (1984)	0.33	0.40	0.73
Wetherald and Manabe (1998)	0.12	0.25	0.37

When both the cloud amount and cloud height feedbacks are combined, one model yields a total feedback of 0.73 W/m² per °C, while the other yields 0.37 W/m² per °C, showing a twofold discrepancy. This large divergence in cloud feedback estimates across models is a key contributor to the uncertainty in climate sensitivity - how much the Earth will warm in response to a given increase in CO_2. Despite significant research efforts, this uncertainty remains unresolved.

The major challenge in understanding cloud feedback lies in the complex relationship between net radiation (R) and a cloud-related variable 'x' such as cloud fraction, height, or other characteristics, and how this relationship changes with temperature. This defines the cloud feedback, which remains one of the most uncertain aspects of climate modeling. Different cloud types, heights, and properties affect the radiation budget in different ways, leading to a non-linear and spatially variable feedback pattern.

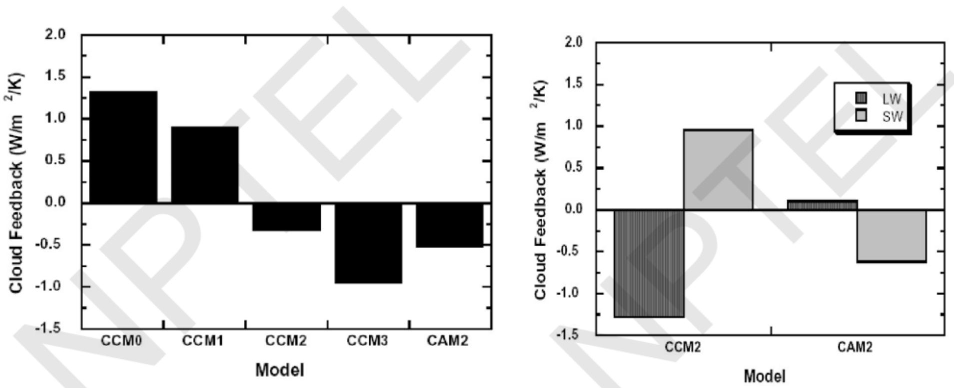




Spatial distribution of cloud feedback (in W m−2 per K surface warming) predicted by a set of global climate models subjected to an abrupt increase in CO2

For example, spatial variation in cloud feedback reveals both positive and negative values across the globe. In some polar oceanic regions, the feedback is negative, whereas over Antarctica, it turns positive. These variations are model-dependent and further complicate the task of accurately predicting climate responses.

To illustrate this complexity, a case study is presented from the Community Climate Model (CCM) developed by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. Over the past 40 years, successive versions of this model have shown dramatic changes in cloud feedback. Early versions of the model exhibited positive cloud feedback values (between 1 to 1.25 W/m²/°C), but as the cloud parameterizations were updated, the net feedback became negative. Remarkably, these shifts occurred even though the base model framework remained the same, only the treatment of clouds was altered, highlighting how highly sensitive cloud feedback is to modeling choices.



Furthermore, within the same model series, differences between longwave and shortwave feedbacks were observed. In the earlier version (CCM2), the longwave feedback was negative and the shortwave feedback was positive, more or less cancelling each other out. In later versions, this pattern reversed—the longwave feedback became positive, the shortwave feedback negative, and the net feedback remained negative, but for entirely different reasons. This reversal underscores the instability in how cloud processes are modeled and the significant uncertainty it introduces in climate projections.

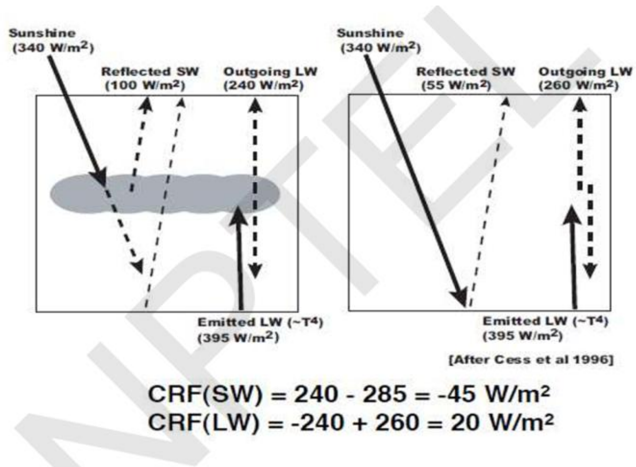
Given the significant role that clouds play in Earth's radiation balance, scientists define a diagnostic quantity known as cloud forcing. This is the difference in radiative fluxes between cloudy and clear-sky conditions, with the clear sky (no cloud) taken as the reference state. Cloud forcing is analyzed in both the longwave (infrared) and shortwave (visible/solar) parts of the spectrum, and the sum of these gives the total cloud radiative effect or total cloud feedback.

Based on satellite observations collected in the 1980s, scientists estimated that the longwave cloud forcing was about +30 W/m², reflecting the greenhouse effect of clouds, which trap outgoing infrared radiation. In contrast, the shortwave cloud forcing was approximately –47 to –48 W/m², due to clouds reflecting incoming solar radiation and thereby cooling the planet. The net annual effect was thus –17 to –18 W/m², indicating that clouds currently cool the Earth on average.

This global average hides important hemispheric and seasonal variations. The Southern Hemisphere, which is dominated by oceans, shows a stronger net cooling effect than the Northern Hemisphere, where land–ocean contrasts and differing cloud dynamics lead to a lesser net cooling. Seasonal changes also modulate the radiative impacts of clouds, further adding to the complexity of cloud feedbacks in climate models.

A graphical representation of the Earth's radiation budget helps to clarify the relative magnitudes of energy flows and cloud effects. On average, about 340 W/m² of solar radiation reaches the Earth. Of this, approximately 100 W/m² is reflected back to space, primarily due to clouds and surface albedo. The Earth's surface emits about 390–395

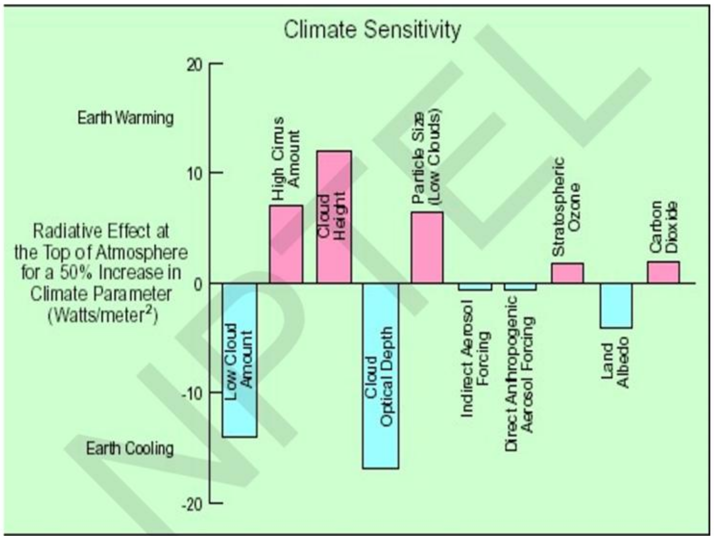
W/m^2 as longwave (thermal) radiation, but only 240 W/m^2 escapes to space after accounting for absorption and re-emission by the atmosphere, particularly by clouds and greenhouse gases.



This energy balance is commonly divided into shortwave (solar) and longwave (infrared) components, and further into clear-sky and cloudy-sky conditions. Comparing these reveals the cloud radiative effects that clouds strongly reduce the shortwave flux reaching the surface due to their reflective properties and trap longwave radiation due to their greenhouse effect.

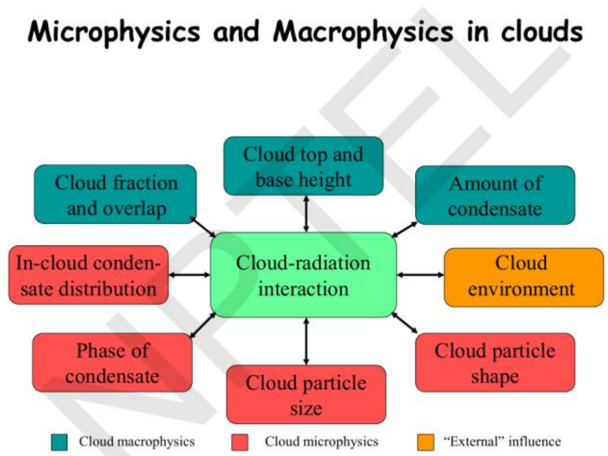
When the radiative impact of CO_2 increase from 1750 to 2005 is considered, it is estimated to contribute a positive forcing of about +1.6 W/m^2. However, this is much smaller than the total radiative impact of clouds, whose combined shortwave cooling and longwave warming effects far exceed that of CO_2 alone. This emphasizes the critical importance of cloud processes in determining Earth's climate sensitivity and highlights why uncertainty in cloud feedback remains a major challenge in climate modeling.

The impact of clouds on climate can be analyzed by examining how different cloud parameters influence the Earth's energy balance. For instance, a 50% increase in low-level clouds leads to a negative radiative forcing, resulting in cooling, due to their high reflectivity of incoming solar radiation. Conversely, a 50% increase in high clouds, such as cirrus, which are efficient at trapping outgoing infrared radiation, produces a positive forcing, resulting in warming. Similarly, increasing cloud top height by 50% enhances the greenhouse effect, also leading to warming. An increase in cloud thickness or optical depth by 50% causes more reflection of solar radiation and leads to cooling. If the particle size in low clouds increases by 50%, it results in less reflection and more solar energy absorption, thus causing warming.



The aerosol effects on clouds, which are complex and include both direct and indirect effects, generally lead to slight cooling. Ozone changes, though not yet discussed in detail, tend to cause warming. Land surface changes, such as deforestation or forest fires, affect surface albedo and typically lead to cooling by increasing reflectivity. The impact of carbon dioxide, while being the primary anthropogenic forcing, results in a relatively small positive radiative effect when compared individually to these cloud-related changes.

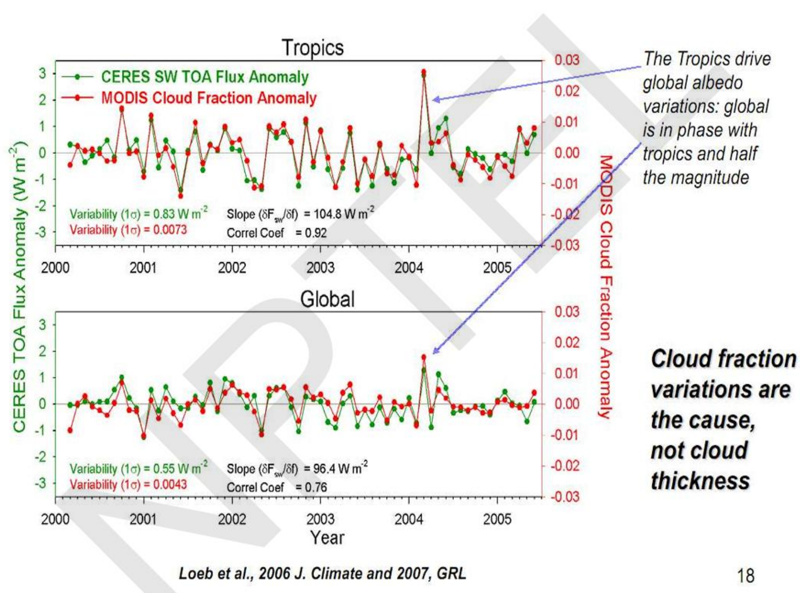
The key takeaway is that many of these cloud-related feedbacks and surface changes can have radiative effects larger than that of CO_2 alone, contributing to the difficulty in predicting how Earth's climate will evolve in response to increasing greenhouse gases. The dominance and complexity of cloud feedbacks underscore their central role in climate uncertainty.



The complexity of clouds and their interaction with radiation can be illustrated through a range of interrelated processes. Cloud-radiation interactions influence cloud properties in several ways. One key aspect is the change in cloud fraction and the vertical overlap of high and low clouds, both of which significantly impact cloud reflectivity and the greenhouse effect. Equally important is the cloud top height, which affects both shortwave albedo and longwave trapping of radiation. Additionally, the amount of cloud condensate - ice or liquid water content within the cloud, plays a major role in determining cloud feedback.

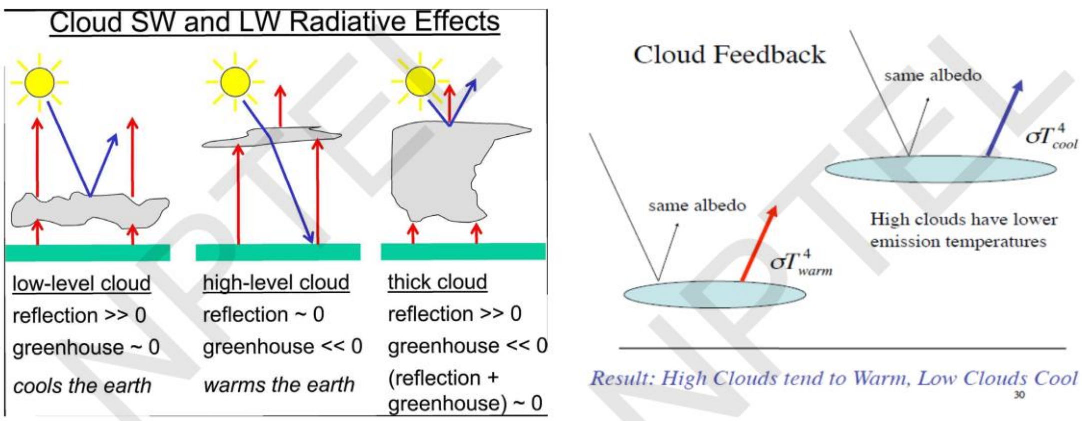
These components fall under the category of cloud macrophysics, which refers to large-scale cloud properties. On the other hand, cloud microphysics deals with finer-scale processes, such as whether the condensate is ice or liquid, and the size of the cloud particles. These characteristics alter the optical properties of clouds and therefore their radiative impact. Particularly for ice particles, the shape becomes a crucial factor. Unlike liquid droplets, which are spherical, ice particles come in diverse shapes, each with different reflective properties.

Furthermore, the spatial distribution of condensate, both horizontally and vertically, affects how clouds interact with radiation. Lastly, environmental context is critical as clouds behave differently depending on whether they are in the tropics, mid-latitudes, or polar regions, as the surrounding atmospheric conditions vary greatly. Thus, cloud feedback is shaped not only by intrinsic cloud properties but also by the environment in which the cloud exists. Both macrophysical and microphysical processes, as well as their interaction with the environment, must be accurately represented to model cloud-radiation feedbacks reliably, making it one of the most complex challenges in climate science.



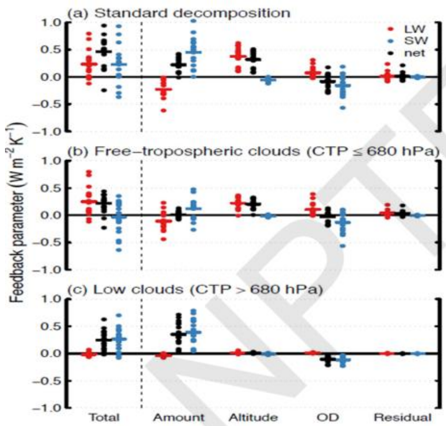
Satellite data have provided highly accurate insights into cloud behaviour, particularly in the tropics where clouds exert a significant influence on the climate system. Observations from the MODIS satellite, which measures cloud fraction, and the CERES satellite, which assesses cloud albedo, show a strong correlation between changes in cloud amount and changes in albedo over the tropics. This strong agreement is an encouraging result, indicating that if a climate model can accurately simulate cloud fraction, it is likely to produce reliable estimates of cloud-induced radiative changes in that region.

This relationship holds true on a global scale as well. Global mean values of cloud fraction from MODIS closely match the albedo changes measured by CERES, with cloud fraction shown in red and albedo in green. The two datasets follow each other closely, reinforcing the conclusion that cloud fraction is the dominant factor controlling cloud albedo. This finding suggests that improving the representation of cloud amount in models can significantly enhance the accuracy of predictions related to cloud radiative effects.



The role of clouds in the Earth's climate system varies significantly depending on their altitude and type. Low-level clouds primarily increase the Earth's albedo by reflecting incoming solar radiation, while their greenhouse effect is minimal because their cloud top temperatures are close to surface temperatures. Thus, low clouds have a cooling effect, and this dominates their influence on climate change. In contrast, high-level clouds, such as cirrus clouds, have a small reflective effect but a strong greenhouse effect, since they are located higher in the colder regions of the troposphere and reduce the amount of longwave radiation emitted to space. As a result, high clouds tend to warm the Earth.

Deep convective clouds, which extend vertically through much of the troposphere, exhibit both strong reflection and strong greenhouse effects. These two impacts tend to cancel each other out, resulting in a net effect that is close to zero. Therefore, from the perspective of climate feedback and radiative forcing, shallow clouds, particularly low clouds, are of greatest concern. They play a crucial role in altering both the reflectivity (albedo) and outgoing longwave radiation (OLR), and hence their behavior must be accurately modeled to improve climate predictions.



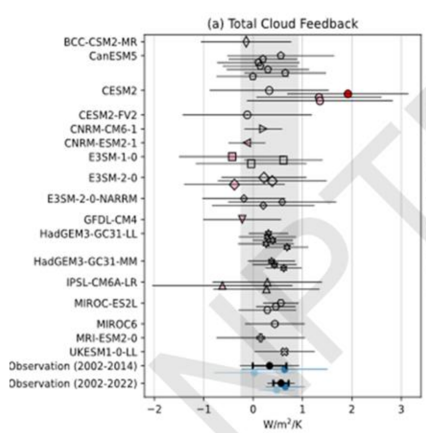
Global mean LW (red), SW (blue), and net (black) cloud feedbacks decomposed into amount, altitude, optical depth (OD) and residual components for (a) all clouds, (b) free-tropospheric clouds only, and (c) lowclouds only, defined by cloud top pressure (CTP). Multi-model mean feedbacks are shown as horizontal lines.
Results are based on an analysis of 11 CMIP3 and 7 CMIP5 models

Zelinka et al., Geophysical Research Letters, 43, 2016

A comprehensive simulation study involving approximately 18 climate models, as presented in a paper by Zelinka, provides valuable insights into how different cloud properties influence radiative feedback. The analysis breaks down the shortwave, longwave, and net radiative effects due to three cloud parameters: cloud amount, cloud altitude, and cloud optical depth.

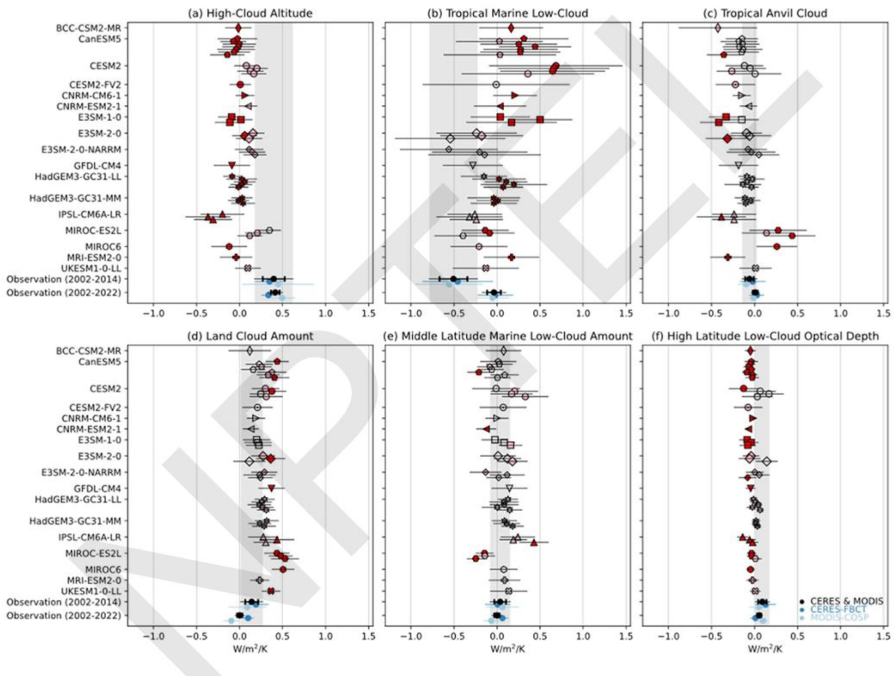
Starting with cloud amount, the models show a notable total effect, with the sum of shortwave and longwave components reaching around 1 W/m², particularly in both the upper and lower troposphere. In contrast, for cloud top altitude, the shortwave effect is minimal, whereas the longwave impact is significantly larger, consistent with the idea that higher clouds exert a stronger greenhouse effect by trapping more outgoing longwave radiation. For optical depth, the results reveal that shortwave and longwave effects oppose each other, and the net effect is slightly negative, indicating a minor cooling tendency.

This comparison highlights that cloud amount is a major contributor to the net cloud feedback, and underscores how shortwave and longwave responses differ depending on the cloud characteristic under consideration. The summed net effect across these factors reveals the complexity and model-dependence of cloud feedbacks in the climate system.

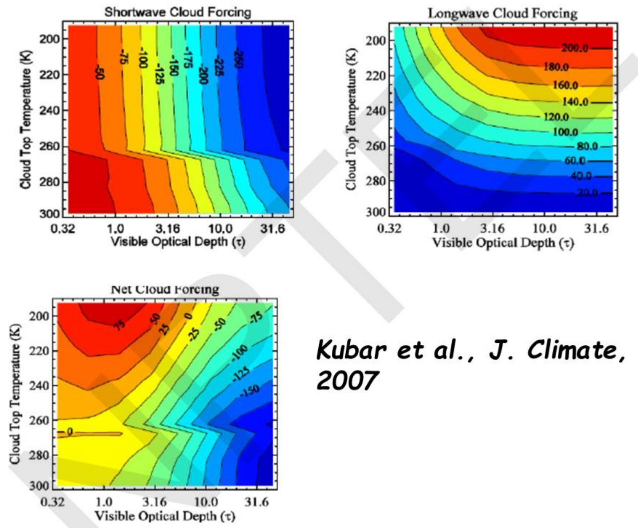


CMIP6 AMIP simulations between 2002 and 2014.
Gray shading represents 90% confidence intervals for observations from 2002 to 2014.
From Chao et al., Journal of Geophysical Research, Jan ,2024 10.1029/2023JD039427

A recent study published a few months ago consolidated results from numerous climate models to evaluate the total cloud feedback, incorporating all components, longwave and shortwave effects, and contributions from both high and low clouds. The key takeaway from this multi-model comparison is that most models converge on a total cloud feedback value ranging between 0 and 1 W/m², which aligns well with observational estimates accumulated over the past 12 years. Only two or three models deviated significantly, one exceeding the range of natural variability and another falling noticeably outside the common range. This overall agreement is encouraging, as it suggests that climate models have substantially improved in capturing cloud feedback processes, with most now producing results consistent with empirical data.



A more detailed comparison among different climate models reveals their performance across various cloud types, including high clouds, mid-level marine clouds, tropical annual clouds, and low, medium, and high liquid water content clouds. The analysis suggests that, for most cloud categories, the models perform reasonably well and align with observational ranges. However, a significant exception lies in the simulation of tropical marine low clouds. These low-level clouds pose the greatest challenge for climate models, and as a result, many model outputs fall outside the observed range, indicated by the gray shaded region. This discrepancy highlights a major issue in simulating marine low cloud amount, which remains a persistent source of uncertainty in climate feedback predictions.



Kubar et al., J. Climate, 2007

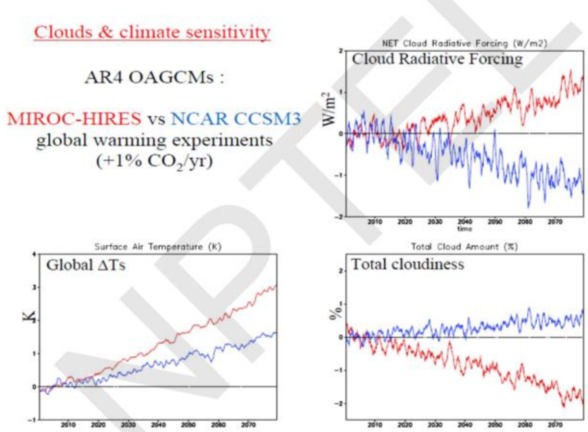
A detailed comparison of longwave and shortwave cloud feedbacks reveals how they are governed by distinct cloud properties namely visible optical depth and cloud top temperature. For shortwave radiation, increasing the visible optical depth which represents the cloud’s ability to reflect and absorb solar radiation leads to a significant rise in shortwave cloud forcing, reaching values up to 300 W/m^2. A sharp transition occurs around 273 K, marking the phase change from liquid water clouds to ice clouds. This transition introduces a discontinuity in shortwave response due to the optical properties of ice.

In contrast, longwave cloud forcing is primarily influenced by cloud top temperature, which correlates with cloud height. The longwave response does not show strong sensitivity to optical depth but varies with cloud altitude. Therefore, the shortwave effect depends mainly on optical depth, while the longwave effect is driven by cloud top height.

When these two effects are combined, the resulting cloud feedback becomes highly complex, with certain regions where shortwave cooling and longwave warming cancel out, resulting in net-zero cloud forcing. This intricate interplay between cloud properties highlights the difficulty of modeling cloud feedback accurately and reinforces the need to separately resolve shortwave and longwave effects to understand the overall climate response.

To emphasize why climate models diverge in their projections, a comparison is made between two models: the high-resolution MIROC model from Japan and the NCAR model from the U.S., both participating in a global coupled ocean-atmosphere modeling project. Each model simulated a 1% per year increase in CO_2 until doubling. Surprisingly, MIROC projected a 3 K warming, while NCAR projected only 1.5 K—a substantial difference in climate sensitivity. Such a disparity has profound implications, as a 1.5 K warming over 70 years is potentially manageable, but 3 K could trigger serious disruptions in the Earth system.

Courtesy:Bony et al., 2008



The core reason for this discrepancy lies in cloud radiative forcing and cloud fraction. In the MIROC model, cloud radiative forcing was positive (~+1.5 W/m²) due to a decrease in cloud cover, leading to reduced reflection of solar radiation and greater warming. In contrast, the NCAR model showed negative radiative forcing (~–1.5 W/m²) because cloud cover increased, enhancing reflectivity and mitigating warming. This stark difference illustrates how changes in cloud fraction directly control whether a model predicts strong or weak warming.

This comparison underscores a fundamental uncertainty: how clouds will respond to CO_2 increases. While some hope that cloud cover will increase and buffer warming, the MIROC model does not support this outcome. The truth likely lies somewhere between the two model projections, but the observational data from satellites over the past 40 years are inconclusive. The observed changes in cloud fraction have been too small to decisively determine a trend. This persistent uncertainty in cloud feedback remains one of the biggest challenges in climate prediction.

In summary, the total climate feedback is the sum of individual feedback components, each contributing differently to the Earth's radiative balance. The largest negative feedback is the Planck feedback, which results from the Earth emitting more longwave radiation as it warms, this effect is well understood and universally agreed upon. Another negative feedback comes from the lapse rate, associated with increased longwave emission to space due to changes in the vertical temperature gradient. In contrast, water vapor feedback is positive, because warmer air holds more moisture, enhancing the greenhouse effect. Likewise, albedo feedback is also positive, as warming leads to decreased surface reflectivity, particularly from melting ice and snow, allowing more solar energy to be absorbed. These four feedbacks - Planck, lapse rate, water vapor, and albedo - differ in magnitude and sign, with some reinforcing warming and others damping it. The key quantity of interest is their net effect, which results from the sum of these opposing contributions. Although each feedback is individually large, the net climate feedback is a delicate balance between positive and negative terms.

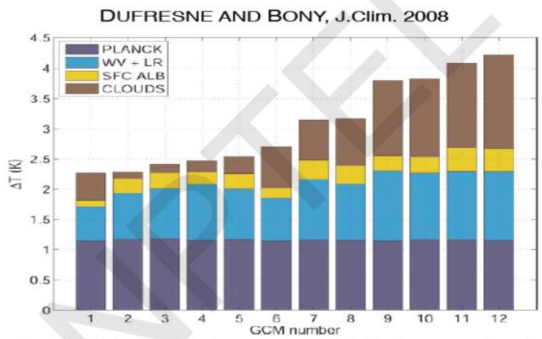
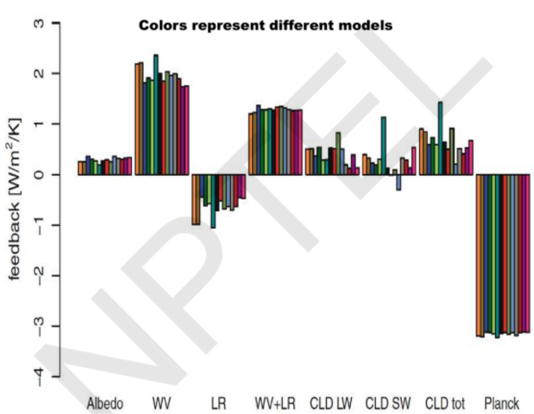
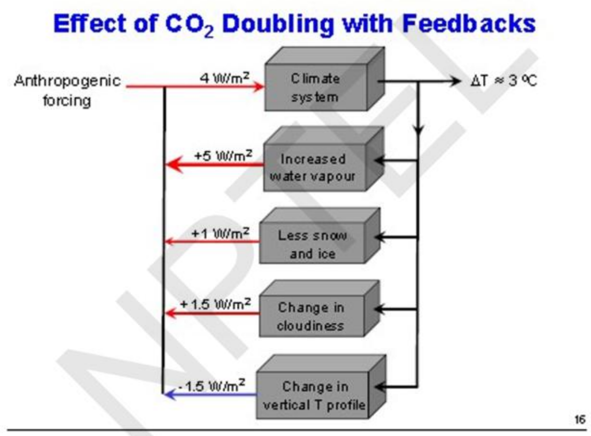


FIG. 2. Equilibrium temperature change associated with the Planck response and the various feedbacks, computed for 12 CMIP3/AR4 AOGCMs for a 2 × CO_2 forcing of reference (3.71 W m^{-2}). The GCMs are sorted according to ΔT_s^*.

When comparing the results from 12 different climate models, it is observed that the Planck feedback which represents the Earth's fundamental radiative response to warming is consistent across models, with a value of approximately 1.1 K per CO_2 doubling. The combined water vapor and lapse rate feedbacks show minor variations between models but are largely similar, reflecting general agreement on the radiative effects of moisture and atmospheric stability. The surface albedo feedback, which accounts for changes due to melting snow and ice, is relatively small and uniform across all models. However, the most significant source of disagreement is the cloud feedback. For instance, Model 2 shows nearly zero cloud feedback, while Model 12 shows a substantially large positive value. This variation underscores that cloud feedback remains the greatest uncertainty in climate projections. Despite over four decades of research, climate models still diverge considerably in their estimates of cloud-related feedbacks, making this a critical focus for ongoing and future climate modeling efforts.



A more dramatic illustration of feedback uncertainties is revealed in the above figure where model outputs are compared in color-coded graphs. In these, the albedo feedback, primarily from ice and snow melt, is consistent across all models. The water vapor feedback is also universally large and positive, approximately +1.75 W/m²/K, while the lapse rate feedback is consistently negative (~–0.5 W/m²/K). When water vapor and lapse rate feedbacks are combined, their net effect shows good agreement among models. Similarly, the Planck feedback shows no disagreement, reinforcing its robustness as a stabilizing negative feedback. However, cloud-related feedbacks, both shortwave and longwave, exhibit substantial discrepancies. These feedbacks are responsible for the widest range in total feedback estimates, making cloud feedback the single largest source of uncertainty in climate sensitivity projections. Despite more than 40 years of satellite observations, the changes in cloud fraction have remained too small and ambiguous to resolve which models best represent the cloud processes. This persistent uncertainty highlights the critical need for further research to constrain cloud responses under global warming.



In the above schematic of climate feedback processes, the initial radiative forcing of approximately 4 W/m² from a doubling of carbon dioxide sets off a cascade of responses in the climate system. These include changes in water vapor content, snow and ice extent, cloud properties, and the vertical temperature profile of the atmosphere. Each of these components contributes either positively or negatively to the total climate feedback. The net outcome of these feedbacks, when combined with the base forcing, leads to a global mean temperature increase of about 3°C. However, this apparent simplicity masks a complex interplay of opposing feedbacks, where some reinforce warming (like water vapor and cloud longwave feedback), while others mitigate it (such as Planck and lapse rate feedbacks). Among all these, the feedback from clouds remains the most uncertain, both in magnitude and sign, and continues to be the largest source of uncertainty in predicting the Earth's climate response to increased CO_2.

To summarize, cloud radiative changes associated with CO_2-induced climate change are inherently complex. Some cloud adjustments happen very rapidly, within a few days of the increase in CO_2 concentration. According to formal definitions, these rapid responses should be classified as part of the radiative forcing. However, more significant are the slower cloud responses, which occur in response to changes in sea surface temperature (SST)—these are true feedbacks. While clouds introduce uncertainty in both forcing and feedback, it is the feedback component that has a larger impact on long-term climate projections. The changes in cloud properties, particularly those linked to global mean temperature increase, play a central role in shaping climate feedbacks and remain a key source of uncertainty in determining the Earth's climate sensitivity.

Experiment B is from the standard UKMO GCM using the cloud scheme as described in Smith (1990).
Experiment A differs from the standard model in that cloud particle size is calculated based on the cloud liquid amount through an empirically observed relationship.
Experiment C differs from B in that the assumed subgrid scale distribution of total water within a GCM grid is changed

Table 2, Climate change simulation and cloud feedbacks in the UKMO GCM

Experiment ID	A	B	C
ΔT_s (°C)	1.9	3.4	5.5
ΔCRF (W/m^2)	−1.04	0.93	3.64
Cloud Feedback (W/m^2/K)	−0.55	0.27	0.66

An illustrative example of the uncertainty in cloud feedbacks comes from the UK Met Office model, which was tested under different cloud microphysical schemes. In one experiment, cloud particle size was derived using a method based on the cloud liquid water amount and an empirical relationship. In another, the calculation incorporated sub-grid scale variations in cloud liquid water. Despite using the same climate model, these experiments produced very different temperature responses. One simulation showed a cooling of about 0.5°C, while another showed a warming of 0.66°C, entirely due to differences in cloud radiative forcing. This stark contrast highlights the sensitivity of climate projections to the way cloud processes are represented in models. It underscores the persistent challenge in cloud feedback research: even small changes in cloud parameterizations can yield large differences in climate outcomes. This concludes the discussion on cloud feedback, emphasizing that while much progress has been made through modeling and observations, cloud feedback remains an unresolved and critical source of uncertainty in climate projections. Policy decisions based on climate model outputs must, therefore, account for this uncertainty.