Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 11
Cloud Feedbacks

In the previous lecture, various feedback mechanisms in the Earth's climate system were discussed, including those related to water vapor, lapse rate, and the melting of ice and snow. Among these, cloud feedback stands out as the most important yet most uncertain due to the complex nature of clouds. Clouds exhibit significant variability in form and behavior, and each type of cloud influences climate differently. Over 45 years ago, the National Research Council, in a report led by Jule Charney, identified cloud modeling as a major weakness in general circulation models (GCMs). Despite decades of scientific advancement, cloud feedback continues to pose significant challenges.

Clouds play a crucial role in the Earth system by reflecting incoming solar radiation, contributing significantly to the planetary albedo, which is approximately 0.3 (30%). This albedo results from both cloudy and clear skies. On average, clouds cover about 60% of the globe, while clear skies account for 40%. Cloudy regions typically have an albedo of 0.4, whereas clear sky regions, primarily ocean and some land, have a lower albedo of 0.15. Using these values, the mean planetary albedo can be calculated as:

$$\alpha_{Planetary} = A_{Clouds}\alpha_{Clouds} + (1 - A_{Clouds})\alpha_{Clear\ Sky}$$

where:

$\alpha_{Planetary}$ – Planetary Albedo
α_{Clouds} – Cloud Albedo (0.4)
$\alpha_{Clear\ Sky}$ – Clear Sky Albedo (0.15)
A_{Clouds} – Cloud Cover Fraction (0.6)

$$\alpha_{Planetary} = 0.6 \times 0.4 + (1 - 0.6) \times 0.15 = 0.3$$

Satellite measurements of Earth's radiative fluxes show that the outgoing longwave radiation (OLR) averages around 234 W/m², and the absorbed solar radiation is about 239 W/m². These values ideally should balance, but a small discrepancy of approximately 5 W/m² remains due to measurement uncertainties.

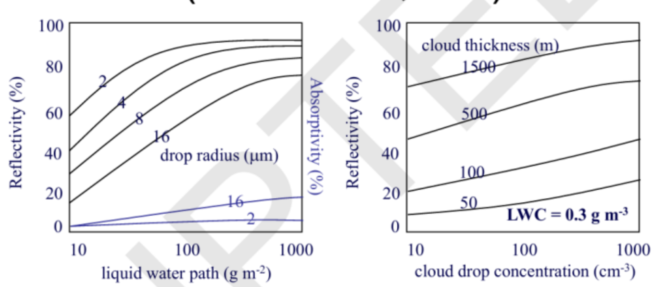
When comparing cloudy and cloud-free regions, satellites observe that cloud-free areas emit more longwave radiation by about 31 to 32 W/m² more because the Earth's surface, which is warmer than cloud tops, is directly visible in these regions. This reduction in OLR due to clouds is known as cloud longwave forcing, indicating a warming effect. In the shortwave spectrum, clouds reflect incoming sunlight, leading to less absorbed solar radiation in cloudy regions by about 48 to 49 W/m² less compared to clear skies. This is referred to as cloud shortwave forcing, indicating a cooling effect.

Net rad = Absorbed Solar radiation - OLR

	Average	Cloud-Free	Cloud Forcing
OLR	234	266	+31
Solar	239	288	-48
Net	+5	+22	-17
Albedo (%)	30	15	-15

When both effects are combined, the net impact of clouds on Earth's radiation budget is cooling, with a net reduction of about 17 W/m². Furthermore, clouds increase Earth's albedo by approximately 15% compared to cloud-free conditions, reinforcing their cooling role. Thus, while clouds warm the planet in the longwave spectrum and cool it in the shortwave, the cooling dominates, making their overall effect crucial in shaping Earth's energy balance.

Cloud Reflectivity in Solar Spectrum (Shortwave, SW)



- Visible light absorption negligible
- Some weak absorption in near-IR part of solar spectrum
- Cloud drop size and number is important in global energy balance

To understand why clouds affect Earth's radiation budget as they do, it is necessary to examine how their reflectivity in the shortwave spectrum varies with cloud microphysical properties. Climate models calculate cloud reflectivity as a function of the total liquid water path, which is the vertically integrated amount of liquid droplets from the surface to the top of the atmosphere. This quantity is typically expressed in grams per square meter. Most cloud droplets have radii around 10 micrometres, though this can vary.

An important relationship is that smaller droplets reflect more sunlight (i.e., have higher albedo), while larger droplets reflect less. As the liquid water path increases, the reflectivity of the cloud also increases. However, beyond a certain value of liquid water path, the reflectivity asymptotically approaches a maximum, often around 70%, depending on the droplet size.

When the data is plotted differently with cloud reflectivity shown as a function of cloud droplet concentration and cloud thickness it highlights the distinct roles of droplet size, droplet number concentration, and cloud thickness. This representation separates the contributions to total liquid water path and shows how higher concentrations of smaller droplets and greater cloud thickness both enhance reflectivity.

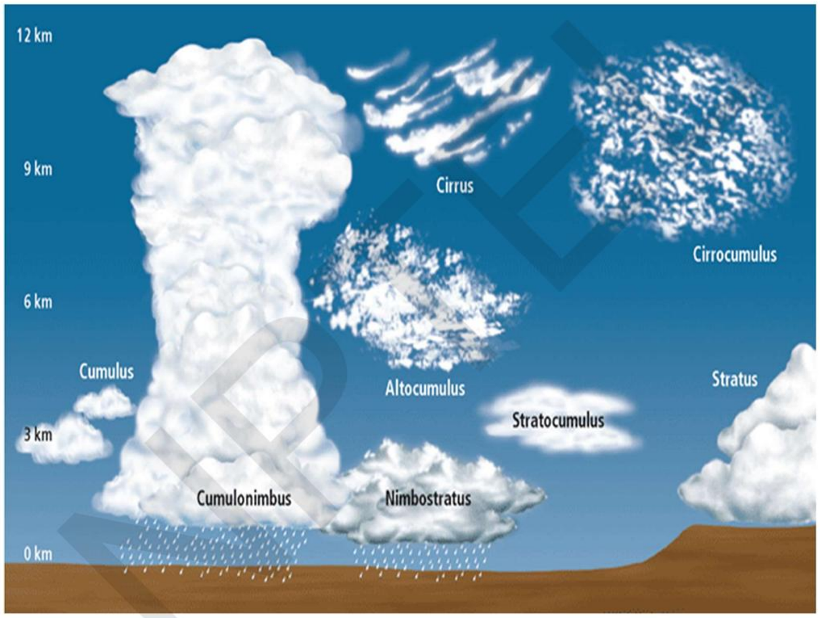
In summary, both the size and concentration of cloud droplets significantly influence cloud albedo, and thus, the cloud's overall radiative impact on the climate system.

Historically, researchers investigated why different climate models yielded different estimates of climate sensitivity, and it was found that the key source of disagreement lies in cloud representation. A comparison of clear-sky and all-sky (i.e., including both clear and cloudy regions) conditions in models showed that clear-sky top-of-atmosphere net radiation was consistent across models. However, when all-sky conditions were considered, the models diverged significantly. This indicated that clouds were the main factor driving inter-model variability in climate sensitivity.

The clear-sky simulations agreed on both the greenhouse effect and albedo changes, but differences emerged when clouds were included, suggesting that clouds were modeled very differently across systems. This was notably highlighted in the influential study by Cess et al. (1989), after which a concerted effort was made to better understand and reduce model discrepancies related to clouds.

A core problem is that cloud processes are not resolved from first principles in climate models. Most clouds are on the order of 1 kilometer in size, whereas typical model grid cells are around 50 by 50 kilometers. This resolution mismatch means that individual clouds cannot be explicitly simulated. Instead, models rely on empirical relationships, often linking relative humidity to cloud fraction, and these relationships vary across modeling centres, depending on the regional observational datasets used to derive them.

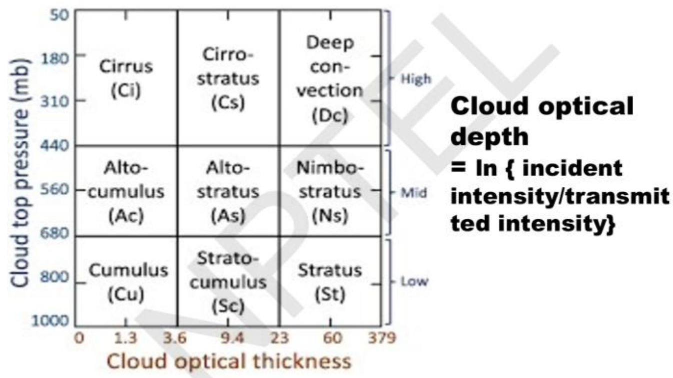
This variability in cloud parameterizations is critical because even small changes in cloud properties can produce radiative effects comparable to those of increased carbon dioxide. For example, a 3% change in cloud reflectivity or a 5% change in outgoing longwave radiation due to cloud variation can offset the 1.6 W/m^2 radiative forcing from CO_2. Therefore, relatively small differences in cloud representation among models can lead to large discrepancies in simulated climate change projections.



Clouds in the atmosphere exist in a wide variety of forms, and while models often simplify them into seven or eight types for practical purposes, the actual diversity is far greater. In the Indian context, one of the most significant cloud types is the cumulonimbus cloud, which extends vertically from approximately 1 kilometer to 12–13 kilometers above the surface. These clouds are crucial during the Indian monsoon, as they bring intense rainfall. In contrast, small cumulus clouds, found at 2–3 kilometers altitude, do not produce significant rainfall but still impact cloud albedo due to their reflectivity.

Cirrus clouds, which occur at high altitudes, are composed of ice crystals. While they are not very reflective, they are effective at trapping outgoing longwave radiation, contributing to the greenhouse effect. On the other hand, low-level clouds such as Nimbostratus are important rain-bearing clouds, whereas Stratocumulus clouds, found slightly higher, contribute to albedo changes but do not produce much precipitation. Cumulus clouds vary in height and have vertical development, influencing both albedo and the greenhouse effect by trapping terrestrial radiation. Stratus clouds, which are widespread low-level clouds, cause significant changes in the Earth's albedo due to their large horizontal extent and high reflectivity.

For a climate model to accurately simulate Earth's energy balance and climate response to rising CO_2 levels, it must correctly represent the distribution, type, and physical characteristics of clouds. Only by simulating the changes in cloud albedo and greenhouse effects can models provide realistic climate projections.



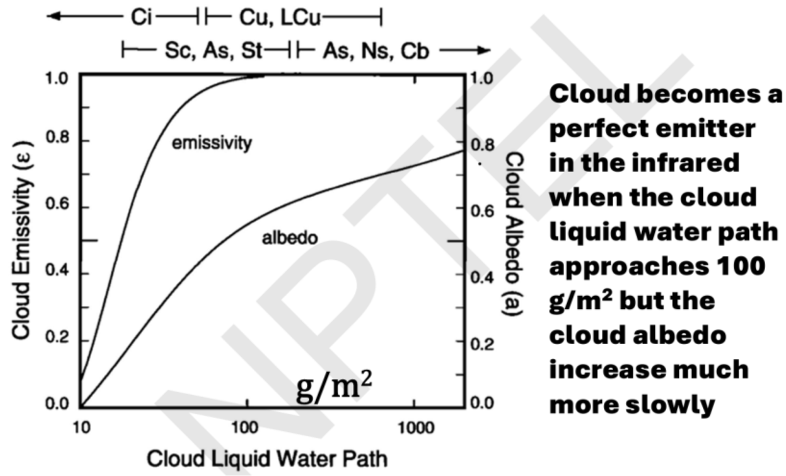
Given the complexity and diversity of cloud types in the atmosphere, a simplified classification scheme was developed using satellite data. This scheme categorizes clouds into nine types based on two key parameters: cloud optical thickness and cloud top height. Cloud optical thickness is a measure of how much a cloud absorbs or scatters incoming solar radiation. It is mathematically defined as the logarithm of the ratio of incoming to transmitted radiation. Since transmitted radiation is always less than incoming radiation, the optical thickness is a positive quantity. A large optical thickness indicates that the cloud significantly absorbs or scatters radiation, whereas a small optical thickness implies minimal interaction with radiation.

The second parameter in cloud classification is cloud top height, which indicates how high a cloud extends into the atmosphere. High-level clouds—such as cirrus, cirrostratus, and cumulonimbus—have cloud tops that can reach up to 180 millibars, or about 6 kilometers altitude. These clouds typically contain ice particles, especially in their upper regions. Cumulonimbus clouds, being deep convective systems, span a wide vertical range and are especially significant for precipitation and radiation dynamics.

Mid-level clouds, including altocumulus, altostratus, and nimbostratus, reside between the low and high cloud levels. Some of these, particularly nimbostratus, are responsible for rainfall, while others influence the radiation budget without precipitation.

At the lowest level of the atmosphere, within the boundary layer (up to ~3 kilometers), are clouds such as cumulus, stratocumulus, and stratus. While these clouds are not major rain producers, they play a crucial role in modifying the Earth's albedo by reflecting incoming solar radiation, thereby influencing the planetary energy balance.

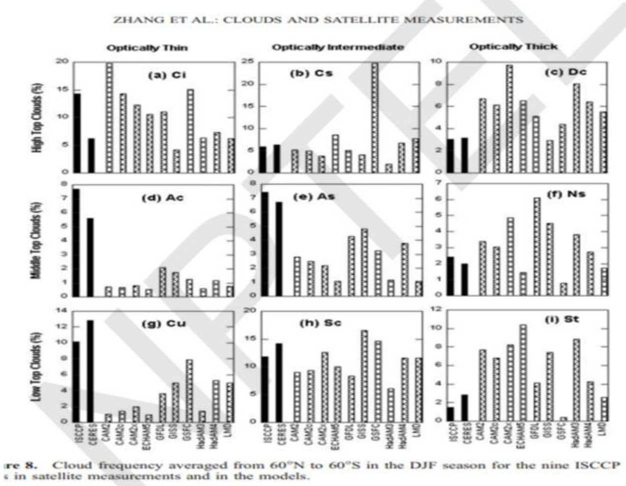
Satellite observations, particularly from the International Satellite Cloud Climatology Project (ISCCP), have provided valuable insights into global cloud distributions and types over the past 40 years. This long-running project integrates data from multiple satellites orbiting the Earth to generate a comprehensive record of cloud variations across different regions of the globe. The ISCCP database enables researchers to examine spatial and temporal patterns of various cloud types, their frequencies, and associated properties such as optical thickness, cloud top height, and radiative effects. This extensive dataset has become an essential tool for validating climate models and understanding the role of clouds in Earth's energy balance and climate system.



Clouds influence both emissivity in the longwave (infrared) and albedo in the shortwave (visible) spectrum, and these two properties vary with the cloud liquid water path (measured in grams per square meter). As the amount of liquid water or ice in a vertical column increases, both the cloud's reflectivity (albedo) and emissivity increase. However, emissivity increases more rapidly than albedo. When the liquid water path reaches approximately 100 g/m², the cloud's emissivity approaches 1, indicating it behaves like a blackbody in the infrared, efficiently absorbing and emitting radiation. In contrast, the albedo at this stage is only about 0.5, meaning the cloud reflects just 50% of incoming solar radiation. This illustrates a fundamental difference in cloud behavior across the electromagnetic spectrum: in the shortwave (solar visible) region, clouds are moderately reflective but not blackbody-like, whereas in the longwave (terrestrial infrared) region, they act nearly as blackbodies. This behavior is analogous to greenhouse gases like CO_2 and water vapor, which are mostly transparent in the shortwave but strongly absorbing in the longwave, highlighting the complex radiative properties of clouds in Earth's climate system.

A comparison of how different climate models simulate clouds reveals substantial discrepancies, particularly when contrasted with satellite observations. The analysis includes a range of cloud types, high clouds such as cirrus, cirrostratus, and deep convective clouds; mid-level clouds like altocumulus, altostratus, and nimbostratus; and low-level clouds including cumulus, stratocumulus, and stratus. Two primary satellite datasets, the International Satellite Cloud Climatology Project (ISCCP) and CERES (Clouds and the Earth's Radiant Energy System) are used for reference, though they themselves show differences due to sampling methods. ISCCP, relying on geostationary satellites, provides better coverage in the tropics, while CERES has fewer such satellites. These differences are most apparent in optically thin clouds, though they largely agree on thicker cloud types.

Comparison between satellite data and observations



When comparing models to satellite observations, significant variation is evident. For instance, cirrus clouds are estimated as low as 5% in some models and as high as 20% in others, while observations average around 10%. Cirrostratus clouds show better agreement, though a few models still overestimate. A major problem arises with deep convective clouds, where satellite observations report about 3%, but model means reach 6%, indicating overestimation. Similar underrepresentation is seen for altocumulus and altostratus clouds, where models show only about 1% versus observational values near 6%. Nimbostratus clouds are relatively well simulated on average. For low-level clouds, there is reasonable agreement for stratocumulus, but cumulus clouds show some deviation, and stratus clouds are overestimated by models.

Despite four decades of intensive research, the simulation of cloud types and distributions in climate models remains unsatisfactory, largely because climate models cannot resolve cloud-scale processes. Most clouds are around 1 km in size, while traditional models have grid resolutions of 50 x 50 km, requiring them to use empirical parameterizations. However, future models with higher resolutions (e.g., 10 x 10 km) promise improvement in cloud representation. Until then, these discrepancies highlight a critical area of uncertainty in climate projections.

An evaluation of the Community Atmospheric Model (CAM2) developed by NCAR (National Center for Atmospheric Research) highlights significant discrepancies in cloud fraction simulations across different latitudes and altitudes when compared with satellite observations from ISCCP and CERES. For high clouds, CAM2 significantly overestimates cloud fraction in the tropics, showing values around 45%, while satellite datasets indicate approximately 25%. This overestimation in the tropical region is a major shortcoming of the model. In contrast, the simulation of mid-level clouds shows better agreement. The model output lies between the two satellite datasets, and if the actual value is assumed to be the average of the two, the model performs reasonably well.

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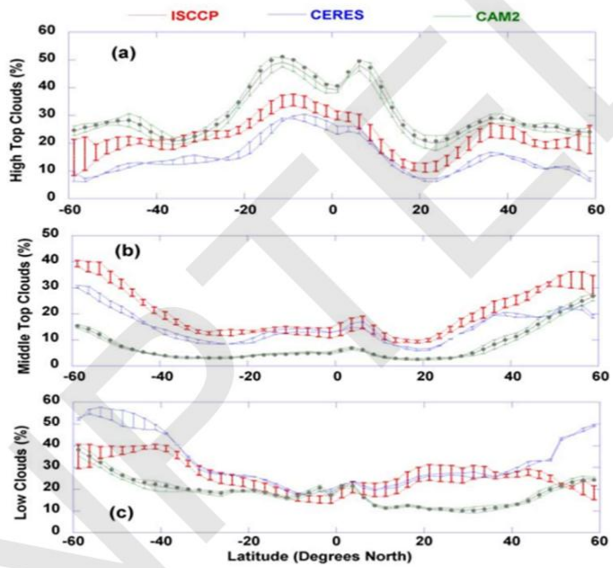
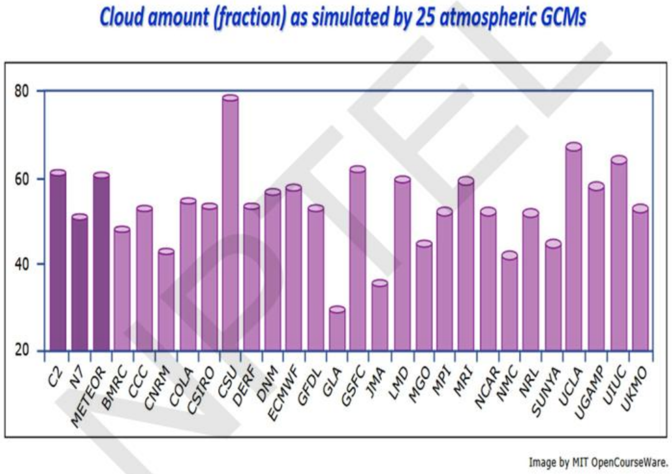


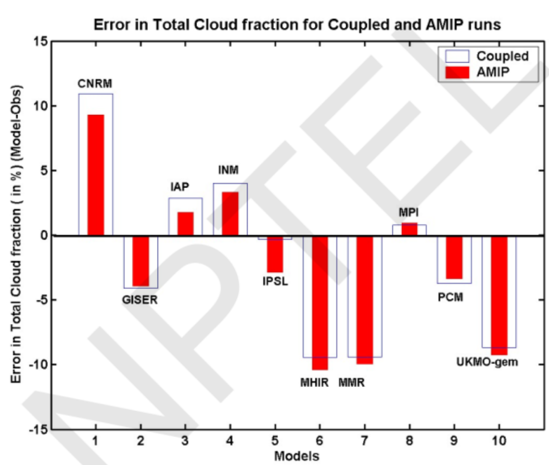
Figure 1. Interannual ranges of clouds DJF seasons from ISCCP (red), CERES (blue), and CAM2 (green) for: (a) high top clouds, (b) middle top clouds, and (c) low clouds. El Nino years have been excluded in the ISCCP data and CAM simulations. The CERES data refer to the two DJF seasons of 2001 and 2002. The difference between the black line and dashed line with solid circle for the CAM2 represent whole day sampling versus daytime sampling of calculating the ISCCP clouds in the simulator.

For low-level clouds, CAM2 aligns well with ISCCP data between 40°S and 40°N, but the discrepancy between ISCCP and CERES observations introduces uncertainty. However, at higher latitudes, CAM2 consistently overpredicts low cloud fractions, a pattern not supported by either satellite dataset. These biases indicate two critical areas for model improvement: the excessive simulation of high clouds in the tropics and the overestimation of low cloud coverage at high latitudes. Addressing these issues is essential for improving the model’s accuracy in simulating the Earth's radiation budget and cloud-climate interactions.

A comparison involving 25 climate models and three satellite datasets reveals that the global mean cloud fraction is reasonably well simulated. Satellite observations indicate a mean cloud fraction of approximately 55%, and most models successfully replicate this value, falling within the range of observational uncertainties. Thus, in terms of the global average, climate models demonstrate satisfactory performance. However, when the data is disaggregated by region, particularly for the tropics and polar areas, model performance deteriorates. Both low-level and high-level cloud fractions are not well captured individually in these specific regions. Nevertheless, when the cloud fractions are averaged across all levels and latitudes, the agreement between models and observations improves significantly, masking the underlying regional and vertical biases. This highlights the importance of going beyond global means to evaluate model performance in cloud simulations more accurately.



A comparison was made between simulations from an Atmospheric Model Intercomparison Project (AMIP) and coupled atmosphere-ocean models. In the AMIP setup, sea surface temperatures (SSTs) are prescribed, and the atmospheric model is run over 20–30 years, whereas in the coupled model, the SSTs are calculated dynamically by the ocean model. The analysis showed that differences in global mean cloud fraction between these two setups are relatively small, indicating that cloud fraction errors are not significantly influenced by the choice of coupled versus uncoupled configuration. In the dataset presented, four models slightly overestimate cloud fraction, while six models underestimate it. Although this may appear to be a modest variation, it is emphasized that even a 10% error in cloud fraction is critical, as it can lead to errors comparable to or exceeding the radiative forcing due to CO_2. Thus, inaccurate cloud simulation severely limits model confidence in predicting future climate change.



This persistent challenge highlights a fundamental uncertainty in climate modeling: the imperfect simulation of clouds introduces significant errors in climate projections. Importantly, this should not be interpreted as a reason to distrust climate models entirely. Rather, this uncertainty suggests that the true impacts of CO_2-induced warming might be underestimated, not overestimated. Therefore, this calls for greater caution and urgency in efforts to mitigate CO_2 emissions, rather than complacency due to model limitations.

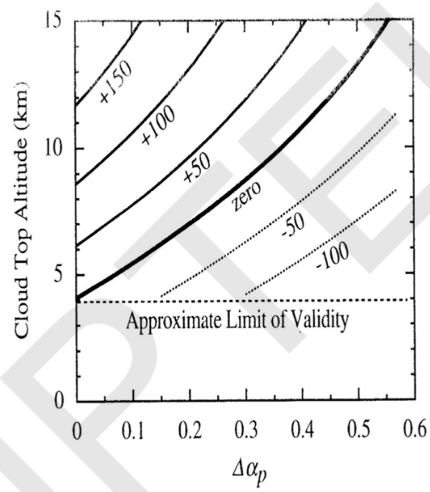


Fig. 3.20 Contours of change in net radiation at the top of the atmosphere caused by the insertion of a cloud into a clear atmosphere, plotted against cloud top altitude and the planetary albedo contrast between cloudy and clear conditions. The net radiation changes are calculated with the approximate model

The above chart illustrates how clouds impact both the visible (shortwave) and infrared (longwave) parts of the Earth's radiation budget, but in opposite directions. In the visible spectrum, clouds increase planetary albedo, reflecting more solar radiation and thereby cooling the Earth. In contrast, in the infrared, clouds trap outgoing longwave radiation, exerting a strong greenhouse effect that warms the Earth. The net climate effect of clouds depends on the relative magnitude of these two competing influences, albedo enhancement versus greenhouse trapping, and also on cloud top altitude. There exists a theoretical line along which the shortwave cooling and longwave warming effects cancel each other. However, in practice, different models fall on either side of this line, leading to variation in predicted global warming.

Critically, it remains uncertain whether such a perfect cancellation occurs in the real climate system. This lack of observational clarity poses a challenge for climate modeling. Since clouds can both amplify and dampen warming depending on their characteristics, and models differ in how they simulate this balance, future climate predictions are inherently uncertain. This underscores the need for caution in interpreting model projections, especially those involving cloud feedbacks.

Due to the decrease in temperature with altitude in the troposphere, clouds that form at higher altitudes are colder and consequently emit less thermal (infrared) radiation to space. This leads to a stronger greenhouse effect, as less energy escapes the Earth system. Therefore, increased cloud top height contributes to warming by reducing outgoing longwave radiation. This phenomenon is supported by theoretical understanding, cloud-resolving model experiments, and observations of both short-term variability and long-term trends in cloud properties. As global warming progresses, isotherms shift upward, and cloud tops are expected to maintain a relatively fixed temperature, resulting in a positive cloud feedback. This is considered a realistic assumption for Earth's warming climate.

Satellite measurements comparing clear-sky and all-sky radiation conditions quantify the net radiative effect of clouds. The cloud albedo effect cools the planet by approximately -45 W/m^2, while the greenhouse effect of clouds reduces outgoing longwave radiation by 27 W/m^2. The net impact is a cooling of about -18 W/m^2 under present-day conditions. However, how this balance will change in the future remains uncertain. As atmospheric CO_2 concentrations rise, changes in cloud fraction, height, or albedo may alter this cooling effect—potentially enhancing or reducing global warming. Because current climate models still struggle to simulate these changes accurately, this introduces significant uncertainty in future climate projections. Therefore, caution is warranted when interpreting model predictions related to cloud feedbacks and climate sensitivity.