Recent Advances in Simulating Cloud Albedo with GCMs.

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ABSTRACT

This review explores the recent advances and issues with simulating cloud albedo in global climate models (GCM). GCMs represent the most comprehensive description of all interactions between atmospheric processes, or feedback mechanisms. Because of the currently abbreviated understanding of feedback mechanisms, the precision of these climate models is limited. Recent advances in GCMs and cloud parameterization show that more is understood today about climate processes than ever before. This continued acquisition of knowledge will eventually lead to an accurate simulation of most microprocesses in the Earth's climate.

Fig.1 Earth's view from satellite. Shows cloud cover and complex nature of clouds (NASA)

1. Introduction

Albedo is described as the ratio of reflected to incident radiation. It can be defined by Equation 1

$$A = (1 - c)A_{clr} + cA_{oc} \tag{1}$$

and can be further expressed as a function of seven variables,

$$A = A(c, \alpha_{clr}, \alpha_{oc}, \mu_{clr}, \mu_{cld}, \gamma_{clr}, \gamma_{cld}) \tag{2}$$

(Taylor *et al*. 2006). Where α is surface albedo, γ is fluxes and μ represents coefficients for absorption. The subscripts signify clear (clr), overcast (oc), and clouds (cld).
Cloud albedo can then be defined by Equation 3.

$$\Delta A_{cld} = (\Delta A_{\mu_{cld}} + \Delta A_{\gamma_{cld}}) + \Delta A_c \qquad (3)$$

Where the subscripts signify clear (clr), overcast (oc), and clouds (cld).

Of the 0.31 total fraction of incoming radiation reflected by the Earth (Earth's albedo), 0.2 of that is from cloud albedo. Higher values of cloud albedo mean that the cloud reflects more solar radiation.

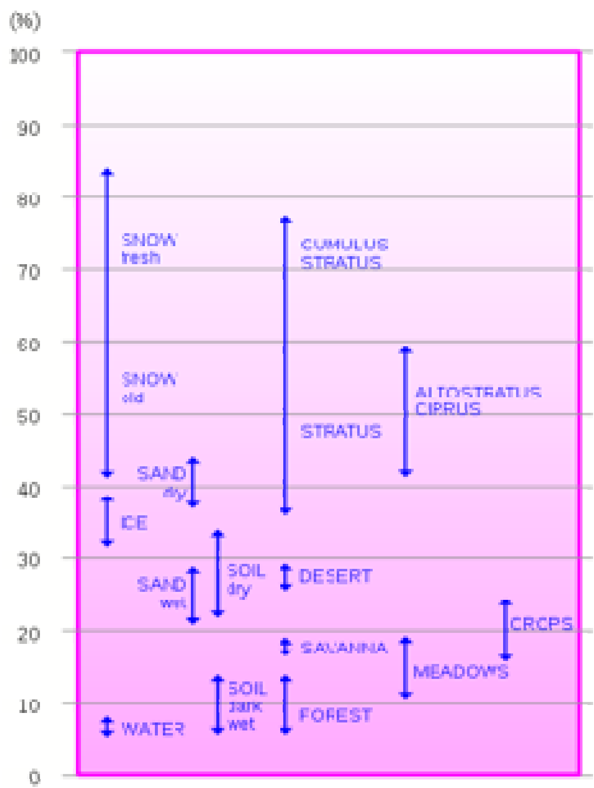

FIG. 2. Percentage of reflected sun light in relation to the various surface conditions of the earth. This shows the wide variation of albedo from different sources. Groebe (2006)

Cloud albedo varies depending on drop sizes, liquid water or ice content, thickness of the cloud, and the sun's zenith angle. Generally stratocumulus clouds, which are low and thick clouds, reflect most of the incoming solar radiation, while high thin clouds, also known as cirrus clouds, reflect less. Figure 2 outlines the variations of albedo from different sources.

Judith Curry and Peter Webster's textbook, *Thermodynamics of Atmospheres and Oceans*, explains that in order to understand and simulate climate accurately, "it is necessary to interpret the role of various physical processes in determining the magnitude of the climate response to a specific forcing." (Curry 1998) These processes are changing the sensitivity of climate response and are categorized as feedback mechanisms. An example of a negative feedback mechanism would represent an increase in surface air temperature, which increases evaporation and the extent of cloud cover. Increased cloud cover reduces the solar radiation reaching the Earth's surface, thereby lowering the surface temperature. On the other hand a positive feedback mechanism example could be represented by an increase in surface air temperature, which would increase the water vapor present in the atmosphere. The concentration of water vapor in the atmosphere increases exponentially with temperature. Therefore, increases in temperature will yield increases in atmospheric water vapor. The increased water vapor will act as a greenhouse gas, leading to further warming. Understanding cloud albedo can lead to a more comprehensive understanding of these climate feedback mechanisms.

Unlike water vapor, clouds impart an almost equal effect on the deposition of solar radiation primarily through the albedo effect. The thermal effects at the top of the atmosphere, are largely offset by the albedo effect. During the 1960s and 70s, the interrelation between albedo and emission from clouds was not well understood (Stephens et al. 2005). A lot of predictions from GCMs at the time did not match scientific observations. It was Twomey in 1977 that described the effects of aerosols concentrations and how they can lead to increases in cloud albedo using the assumption of a fixed water content. With higher aerosols concentrations, a larger number of smaller droplets will be formed, which reflect more sunlight than large drops and do not rain out easily.

To better understand cloud albedo and resulting feedback, recent studies were selected as examples. These papers studied different GCMs, the Community Atmospheric Model, Version 3 (CAM3), Geophysical Fluid Dynamics Laboratory Atmospheric Model 2 (AM2), ECHAM5-HAM. They explained how cloud feedback, aerosols, and radiative forcing affect cloud albedo. All of these studies looked at how these factors are considered in trying to create a more precise GCM for the future. Figure 3 shows the evolution of GCMs from the 1970's into the present. As can be inferred from this diagram, the main difference between the models is the addition of more parameters with each subsequent model. The First Annual Report (FAR), Second annual report (SAR), Third annual report (TAR), and fourth annual report (AR4) were used as examples in the figure. As GCMs become more complex and accurate, to help improve climate predictions, it will impact government planning and policy for the future.

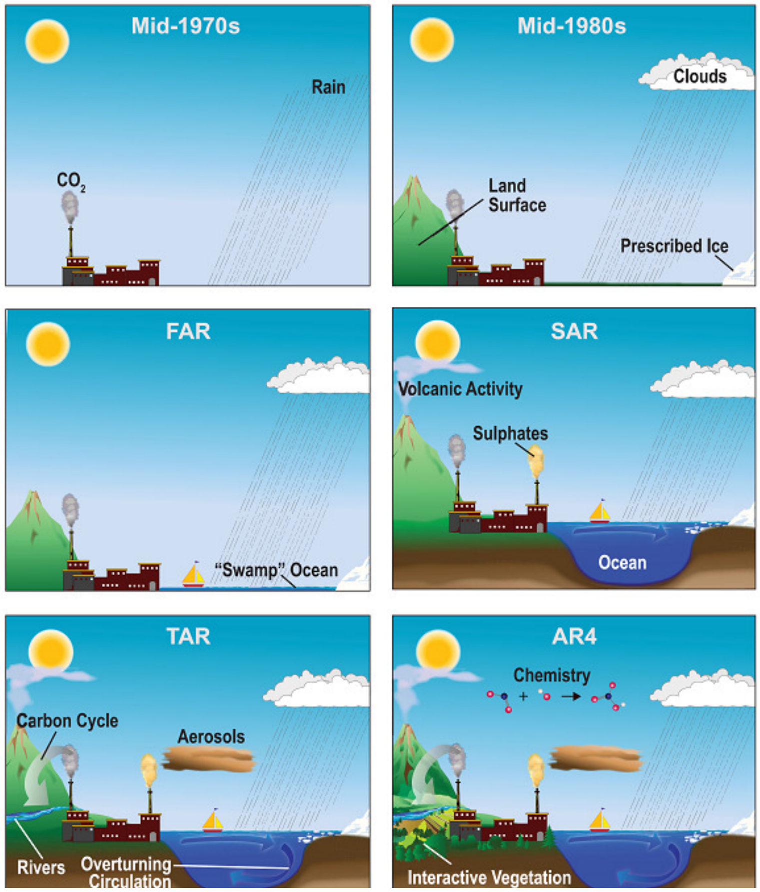

Fig 3. Recent advances in GCMs. Each box represents the evolution of our understanding of albedo. With advancements in our understanding, more variables have been taken into account (IPCC 2007)

2. GCM examples and the albedo effect

a. Parameterizations

In a recent paper by M. Zhang and C. Bretherton (2008), in which the CAM3 was accessed, several insights into the behavior of cloud feedbacks were ascertained. Because the understanding of cloud feedback is dependent on the comprehension of the physics, and parameterizations, which are methods of replacing processes that are too small-scale or complex to be physically represented in the model by a simplified process, within the clouds, the findings of this study are not only pertinent to our current textbook knowledge but they also increase our depth of knowledge of cloud feedbacks. The experiment consisted of a control experimental setup as shown in Figure 4 and a warm simulation of a two degree increase in both warm and cold sea surface temperatures (SST). The result of this experiment reinforces the theory that in order to understand cloud feedbacks multiple cloud parameterizations must be evaluated. This experiment goes one step further to say that it is not enough to know the behavior of individual parameterizations, but the interaction between the parameterizations must be evaluated in order to achieve more precise modeling. The increase in negative feedback in tropical climates, as shown in this paper, is a result of increased water vapor within the clouds, the longer lifetime of the clouds due to boundary layer turbulence, and subsidence. (Zhang et al. 2008) Turbulence is defined as a small scale irregular flow superimposed on the mean motion. Turbulence is brought forth by "eddies" also described as stochastic property changes. (Curry 1998) Subsidence instead is strictly a downward motion of air in the atmosphere. Eddies are the swirling of fluid around an obstacle.

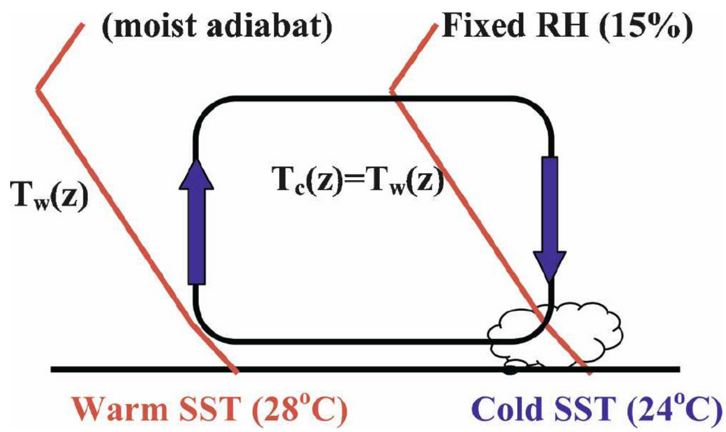

FIG. 4. Schematic of experimental setup. (Zhang et al. 2008)

A striking contribution of this experiment to the area of global climate models is the use of a negative cloud feedback. A negative feedback is significant, because it specifies that the temperature would increase at the surface, therefore increasing evaporation and cloud cover. The cloud cover increase would increase the mean global albedo, which could ultimately lead to an overall cooling effect.

Many other models have produced positive cloud feedbacks, which do not accurately reflect the process. Figure 5 shows how CAM3 and three of its precursors display negative cloud feedback as compared to the CCM0 and CCM1. The reason for this negative feedback is CAM3’s prediction of increased low cloud concentration. This model was designed to imitate the subsidence taking place in the subtropical eastern oceans. Of the increase in clouds, stratiform clouds are the most abundant and convective clouds are present at all times. (Zhang et al. 2008) In CAM3, the cloud amount is calculated from convective mass fluxes and relative humidity. Because of the low altitude of these clouds, the amount of shortwave cloud radiative forcing (CRF) is significantly larger than longwave CRF.

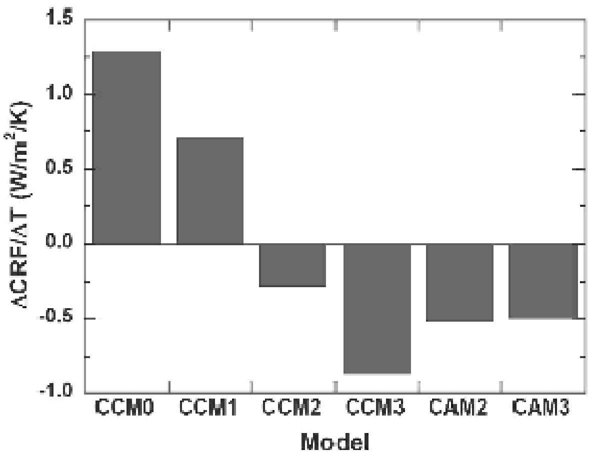

FIG. 5. Cloud Feedback in some recent GCMs. This figure exemplifies the variations that occur in different GCMs (Zhang et al. 2008)

Another conclusion drawn from these two simulations relates temperature and cloud amount. Since low cloud processes are driven by convection and, as demonstrated by the Clasius-Clapeyron equation,

$$ln\left(\frac{P_2}{P_1}\right) = -\frac{dH}{R}\left(\frac{1}{T_2} - \frac{1}{T_2}\right) \tag{4}$$

convective mass flux increases with surface temperature, then the transport of water upwards into the atmosphere increases with temperature. This causes an increase in relative humidity leading to the formation of additional clouds as a result of radiative cooling. The radiative cooling itself is the outcome of several processes, which include the Zhang-McFarlane (ZM) and Hack (HK) convection schemes, stratiform cloud scheme, radiation, and boundary layer scheme. In comparing the two temperature simulations, the warm simulation appears to have more low clouds, likely because there is more cloud water. In addition, this effect is also due to the ZM convection depositing moisture in the 900-mb layer for a longer time period.(Zhang et al. 2008) The 900-mb layer, first introduced by Zhang *et al*. (1998), represents a boundary layer between clouds, where the atmosphere is divided by convecting activity. The warmer case also exhibits larger shortwave cooling, or negative feedback as previously described.

b. Calculating Feedback Parameter

In order to determine the feedbacks induced by clouds, a cloud feedback parameter must be calculated. Perhaps the main limitation in GCMs are the methods for computing the cloud feedback parameter. Two computational approaches that have been applied over the past few decades are the Partial Radiative Perturbation (PRP) method (Wetherald *et al.* 1988) and the Cess cloud radiative forcing (ΔCRF) method (Cess *et al.* 1988).

PRP is a useful approach that can look at individual components of the total cloud feedback. The main drawback to PRP is that it cannot be experimentally verified using observational data due to the partial derivative in the calculation of Equation 4.

$$\lambda_x = -\left(\frac{\partial R}{\partial x}\right)\left(\frac{\partial x}{T_s}\right) \tag{5}$$

This describes the ratio of the change in global mean net radiative flux (*R*) to the change in mean global surface temp (T_S), with the *x* variable representing any arbitrary individual component contributing to the total feedback, such as albedo or water vapor. The calculation of a partial derivative requires all variables to be fixed, allowing only one to vary. Observations cannot recreate these conditions because in the atmosphere more than one variable is in constant flux. Even though PRP can look at separate feedback processes, there is still an uncertainty which are correct because it cannot be compared to experimental evidence.

Unlike PRP, ΔCRF can be compared directly to observational data (outside of the laboratory) because the calculation involves a simple ratio of the earth's radiative flux to its surface temperature. Despite this advantage, it too has its limitations. The method lacks the ability to separate cloud feedbacks from feedback produced by other sources such as water vapor. (Zhu *et al*.2007)

Without detailed evaluation of feedback parameters, the relation of GCMs to reality has a large degree of uncertainty. The disadvantages of PRP and ΔCRF show that it is necessary for alternative methods for feedback calculations to be found.

The limitations of PRP and ΔCRF were exemplified with GCMs developed by the National Center for Atmospheric Research (NCAR) and the Geophysical Fluid Dynamics Laboratory (GFDL). When NCAR's Community Atmosphere Model version 3 (CAM3) and GFDL's Atmospheric Model 2 (AM2) were applied to observational data, PRP and ΔCRF proved to be insufficient. To address these limitations, the Zhu *et al.* (2007) developed the Multiple Linear Regression (MLR) methodology that can be applied to GCMs to calculate feedback parameters. MLR is a useful approach because it can separate cloud feedback into three layers (low, mid, and high clouds) and other cloud properties such as optical thickness. MLR is a variation of simple linear regression, which relates two or more explanatory variables that predict changes in other variables by using a response variable and a linear equation to fit the data obtained.

A recent paper by Zhu *et al*. (2007) focused on comparing the computed cloud feedbacks using CAM3 and AM2. The comparisons were based on their response to the doubled CO_2 ($2CO_2$) and the ±2-K sea surface temperature (SST) perturbations. These two experiments are used to show a GCMs sensitivity to variations in today's climate and how the cloud albedo will change. The $2CO_2$ experiment models an atmosphere that has double the concentration of CO_2 than that of the pre-industrial atmosphere (280 ppm) and the ±2-K SST experiment takes into account monthly variations in ocean surface temperatures. .

MLR was applied to CAM3 and AM2 to simulate cloud feedbacks involving the cloud amount change and the cloud condensation change. A comparison of the results of the two different models shows the variation that can occur in different climate models, as shown in Figure 6. Before the application of MLR, CAM3 predicted a small increase in global cloud amount and cloud condensate in a warming climate, whereas AM2 predicted a large decrease in cloud amount and an increase in cloud condensate. MLR decomposed the atmosphere into three layers allowing for the analysis of separate processes, alleviating, but not eliminating, some of the large discrepancies associated with these models. By decomposing separate feedbacks, the discrepancies can be pinpointed.

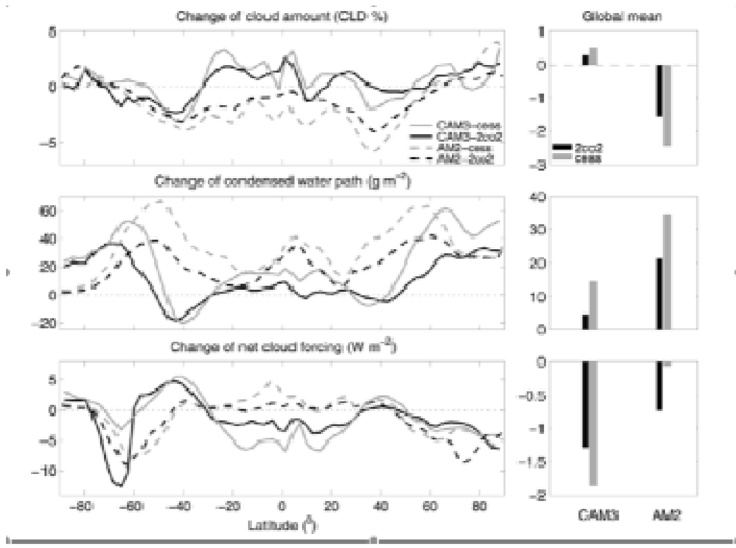

FIG. 6. Averaged mean global cloud amounts simulated by CAM3 and AM2. This shows the wide variations of the two GCMs when PRP and ΔCRF were applied (Zhu *et al*.2007)

MLR is an effective method for decomposing clouds into three different components and can be successfully applied to GCMs. Unlike PRP it can be applied to observations, and unlike ΔCRF it can look at individual components of the total feedback. Though there are advancements made with MLR, it is still not possible to determine which calculated feedbacks are correct and which are unrealistic.

The method used to calculate the feedback parameters can change the sensitivity of a model and is thus an important aspect of GCMs. GCMs will always be limited to the quality of the computation of the feedback parameter. Further work on these methods can greatly increase the progression of climate models. With the advancement of observational data and the subsequent comparison to simulations, the most realistic method of feedback analysis can be determined.

c. Limitation to Cloud Albedo Enhancement

In 2007 Lohmann et al. presented a new approach to cloud microphysics and aerosols effects in a GCM. The model, ECHAM5-HAM developed by Stier in 2005, is a 5th generation ECHAM model first proposed by Roeckner in 1996. ECHAM5-HAM is useful because it predicts cloud cover with a prognostic-statistical scheme solving equations for distribution moment of total water. (Stier 2005) ECHAM5-HAM considers the major global aerosol components, sulfate, particulate organic matter, black carbon, sea salt and mineral dust all at once while older GCM used to only consider sulfate aerosols. Aerosols greatly affect GCMs as they exert a net cooling effect on climate, which is directly proportional to mean cloud albedo enhancement, which is usually found to be in the range of −0.3 to −1.8 W m^{-2} (Lohmann et al. 2007)

The cloud albedo effect enhancement is shown, in the ECHAM5 simulations, to have the largest effect of -1.5 W m^{-2}, which is a different than the -1.8 W m^{-2} as previously believed. The introduction of the new radiation scheme also leads to more longwave cooling in the tropical upper troposphere. Combined with less absorption of shortwave radiation within the atmosphere, the atmosphere is less stable. The greater static instability requires more penetrative convection for compensation. This increases the global mean convective precipitation. (Lohmann et al. 2007)

Convective precipitation is a results of convective clouds, or cumulonimbus clouds. Cumulonimbus is a type of cloud that is tall, dense, and involved in thunderstorms and other intense weather. It is a result of atmospheric instability. Convective precipitation falls over a certain area for a relatively short time. The new radiation scheme presented in ECHAM5 simulations shows that if mean convective precipitation is to increase due to the presence of more cumulonimbus clouds, therefore the mean cloud albedo is directly affected. The mean cloud albedo will increase even if these clouds are short-lived.

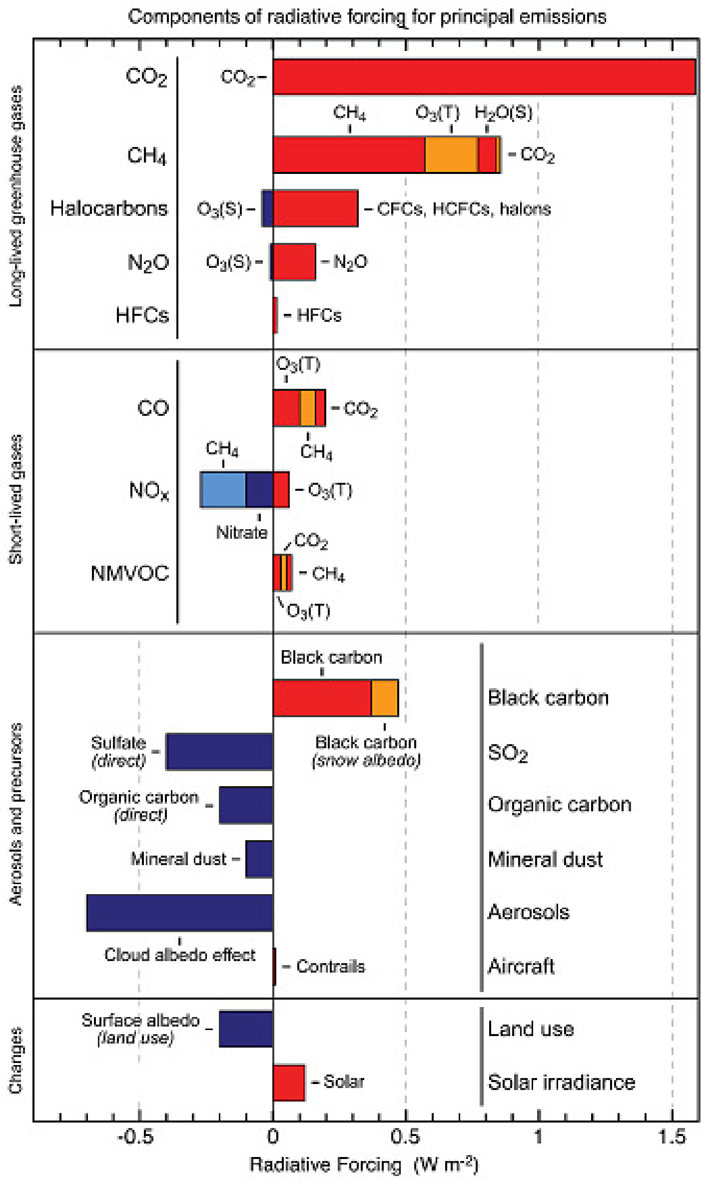

Fig. 6. Radiative forcing values from aerosols and emissions. Our level of understanding of the composition and chemistry of the atmosphere has allowed for a more detailed report (IPCC 2007)

As shown, scientists are dealing with new man-made issues that are directly affecting GCMs, but most importantly global climate. The better understanding of the atmospheric chemistry and processes, increases the accuracy of GCMs, and their ability to predict climate. But the more that is understood about climate, the greater the number of factors that need to be taken into consideration, which in turn greatly increases the uncertainty of GCMs results. All GCMs have a large degree of uncertainty that can be minimized with more accurate and complex algorithms. Some uncertainties have been greatly reduced since GCMs have been developed. Scientists are constantly creating new algorithms, in order to include more microphysical processes for properly incorporating cloud albedo in GCMs, inching closer to simulating real life observations.

d. Uncertainties in Marine Boundary Layer Clouds

In Bony and Dufresne 2005, the authors investigated the tropical cloud radiative feedback in 15 models used by IPCC's Fourth Assessment Report. The cloud type was classified by the monthly-mean mid-tropospheric (500 hPa) vertical pressure velocity ω. In Norris 1998, it was argued marine boundary clouds were poorly simulated in early GCMs, such as Soden 1992. It was shown by Bony that the latest coupled Atmosphere-Ocean General Circulation Models (AOGCMs) still do not perform well in this regime.

The last 80-year time series of cloud radiative forcing and sea surface temperature change from 30N to 30S were taken from the 1% per year increase of CO2 transient climate change simulations. After taking a linear trend over time to eliminate the short term variability, the climate response of cloud forcing S_ω for each regime with different ω was calculated. S_ω was then integrated to get a mean climate response of cloud forcing Σ in the tropics. The 15 models were divided into a high-sensitivity group with $\Sigma > 0$ (8 models) which get positive cloud feedback in the tropics and a low-sensitivity group $\Sigma < 0$ (7 models) which get negative feedback. The incoming short-wave (SW), outgoing long-wave (LW) and NET climate sensitivities in different dynamical regimes were calculated with respected to SST changes. The result is shown in Figure 7.

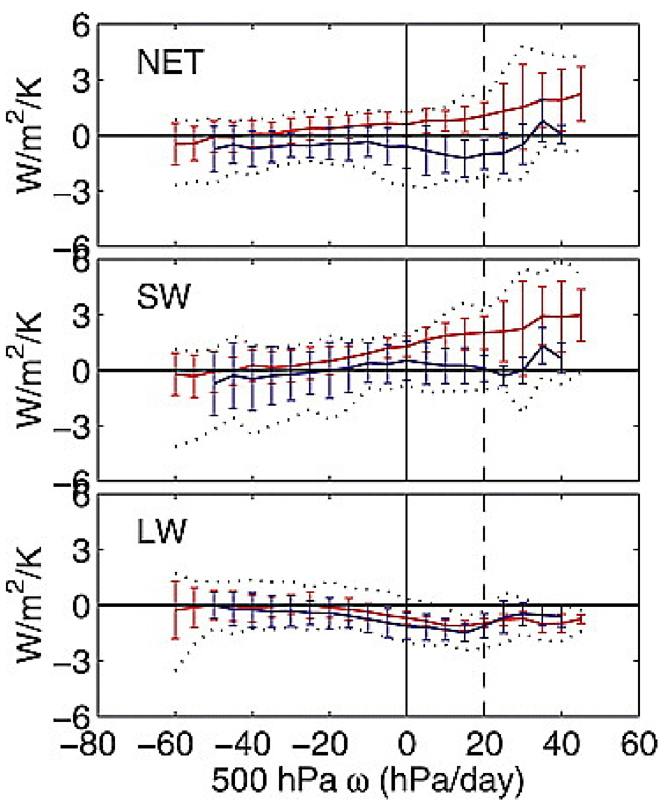

Fig. 7. Climate sensitivity of the cloud forcing to SST changes from 15 IPCC models in different dynamical regimes. Red line is HS models and blue line is LS models.

Large discrepancies of the response among different models emerged, especially in the regions of large sinking (ω > 20 hPa/day), which is dominated by marine boundary layer clouds. The HS models showed higher SW responses to the SST changes, which means an increase in SST will increase the cloud albedo significantly. Since there is no long term satellite observation to compare with, an alternative approach was used. Instead of doing a linear trend, the interannual sensitivity of cloud was calculated from models. A comparison to satellite measurements in Figure 8 showed that the models underestimated the net cloud radiative forcing in this regime, which is mainly contributed from short wave radiation forcing.

The results suggested that current uncertainties in cloud albedo are mostly from marine boundary layer clouds. The HS models showed a better agreement with observations. But whether the relationship is consistent to future climate change is still unproven.

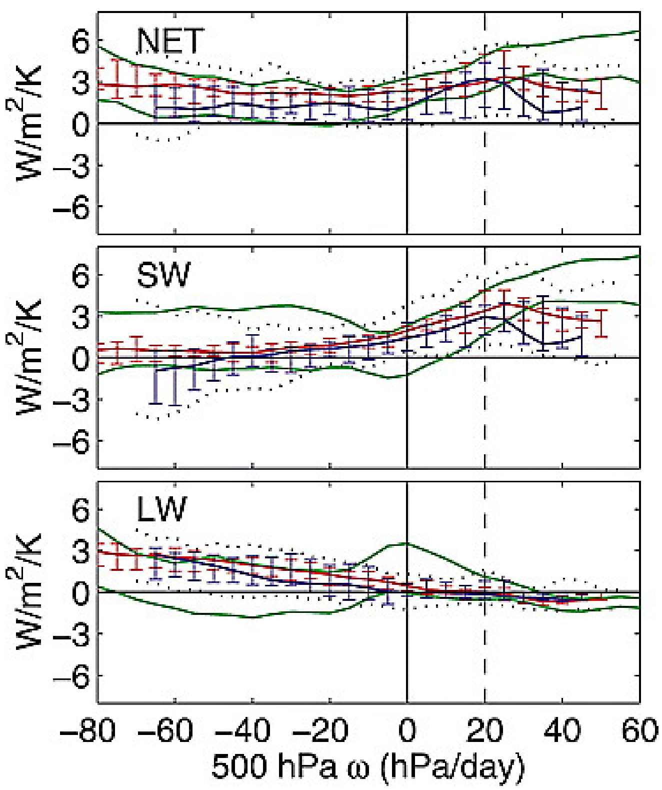

Fig. 8. Interannual sensitivity of the cloud forcing to SST changes from 15 IPCC models in different regimes. The area between the green lines showed the 5-95% confidence interval of satellite measurements.

4. Conclusion and Discussion

Feedback processes and the albedo effect involved in GCMs dealing closely with clouds, are a source of uncertainty that affect major model projections of global systems. But the recent advances in technology have helped scientists understand and apply small scale cloud processes to GCMs, therefore greatly improving predictions in cloud properties and behavior. According to Stephens *et al.* (2005) more probing and testing of model parameterizations is expected. Better cloud predictions will result, which could eventually lead to using archived observational data from previous decades to be compared with new experimental and observational data, giving scientists a broader understanding of global climate changes throughout longer periods of time. The complexity of the albedo effect stems for the fact that there are several different types of clouds all with different albedoes. The studies selected for review were representative of the challenges involved with feedback processes, cloud parameterizations, and the albedo effect, and exemplified the challenges faced by today's scientists in fine tuning GCMs. The marine boundary clouds impose largest discrepancies and uncertainties among the models and with satellite observations. In addition, artificial clouds, such as contrails, and man-made pollution, as studied by Twomey in 1977, offer other dimensions to the complexity of the problem. Extensive studies will have to be conducted to better understand all of the small processes that affect this problem, even though great improvement has been made to GCMs over the last decades. The improvement in GCMs is very important, as it could affect policy decisions for future generations, by being able to more accurately predict climate and climate change.

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