

Comparison of cloud response to CO₂ doubling in two GCMs

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Abstract

The source terms of the cloud condensate tendency equation are analyzed for two general circulation models to clarify the effect of model differences on the non-convective cloud response to CO₂ doubling. This analysis investigates the differences in the mechanism of cloud feedback between models, which is considered a major source of uncertainty in climate change projections. The two GCMs, the Hadley Centre model and MIROC, exhibit marked differences in cloud response in the mixed-phase region: cloud in middle to low latitudes decreases in the former and increases in the latter. The source terms indicate that the difference is attributable to the condensation-evaporation response. Discussions on the inter-model variance of cloud feedback may thus be assisted by developing a better understanding and evaluation of condensation-evaporation. The difference in the cloud response is also related to the relative importance of ice sedimentation compared to other microphysical processes: the former tends to increase mixed-phase cloud while the latter tends to decrease the cloud. Physically based modeling of the relevant microphysical processes is thus considered essential for having more confidence in the simulated cloud feedback.

1. Introduction

Cloud feedback remains one of the largest uncertainties in the long-term projection of climate change [Ringer et al., 2006; Soden and Held, 2006]. In order to reduce the uncertainty in the cloud feedback, processes responsible for the inter-model spread in the feedback need to be evaluated in terms of observation. The evaluation can be assisted by understanding the mechanism of model cloud response to CO₂ increase, because it enables us to focus on the specific processes responsible for the inter-model spread in the cloud feedback. Understanding the model cloud response is thus considered important, being part of the Cloud Feedback Model Inter-comparison Project (CFMIP) strategy to complement the evaluation studies.

The source term in the cloud/moisture tendency equation is expected to be a useful tool for understanding the processes contributing to cloud variations in GCMs. Mitchell and Ingram [1992] discussed the influence of large-scale condensation, convection, and other resolved motions on cloud variation in reference to the relative humidity increments derived from the temperature and moisture tendency terms. Boville et al. [2006] examined the tendency terms for cloud condensate and discussed the production of stratiform cloud in a GCM by convective detrainment and condensation-evaporation. Recently, the cloud condensate tendency terms were also used by Ogura et al. [2008, in press] to examine the cloud response to CO₂ doubling in two versions of a GCM. This study applies the approach of Ogura et al. [2008] to investigate the difference in cloud response in two GCMs with different cloud parameterizations; the

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Hadley Centre GCM and the Model for Interdisciplinary Research on Climate (MIROC). Although direct comparison of the tendency terms is difficult due to the difference in cloud schemes employed, the present analysis demonstrates the advantages of analyzing the tendency terms for discussing the mechanism of cloud response in GCMs.

2. Model and simulation

The Hadley Centre model employed in this study is the atmospheric component of HadGEM1 [Martin et al., 2005]. Simulations were run with a horizontal resolution of 3.75° longitude and 2.5° latitude (usually referred to as “N48”), setting 38 vertical levels of height based eta coordinate. The non-convective cloud scheme for liquid cloud is that of Smith [1990]. The ice cloud is treated using an updated version of the Wilson and Ballard [1999] microphysics scheme, in which the prognostic ice content is calculated based on physical process equations representing mass exchanges between water categories (ice, liquid water, vapor, and rain).

The other model examined is MIROC version 3.2 which was developed cooperatively by the Center for Climate System Research, the National Institute for Environmental Studies, and the Frontier Research Center for Global Change [K-1 Model Developers, 2004]. The model was run with a resolution of T42 (ca. 2.8° longitude and latitude) with 20 sigma levels in the vertical direction. Non-convective cloud is parameterized based on Le Treut and Li [1991]. Cloud ice content is diagnosed using a temperature-dependent splitting between ice and liquid water, which is one of the major differences between the cloud schemes of the two GCMs considered in this study. The diagnosed ice is allowed to fall following Heymsfield [1977].

The atmospheric component of each model is coupled to a 50 m slab ocean model and integrated to obtain the steady-state climate for a pre-industrial concentration of CO₂ and a doubled concentration. Output from years 1-20 and years 41-50 after the instantaneous CO₂ doubling are used to analyze the transient and the quasi-equilibrium responses, respectively.

3. Results

The cloud condensate responses to CO₂ doubling for years 41-50 in the two GCMs are shown in Fig. 1. In the figure, isotherms indicate the range of mixed-phase cloud distribution between 0 °C and -40 °C for HadGEM1, and between 0 °C and -15 °C for MIROC3.2. A marked difference between the responses of the two GCMs can be seen in the mixed-phase cloud, which has a large impact on climate sensitivity [Senior and Mitchell, 1993]. The mixed-phase cloud in the middle to low latitudes decreases in HadGEM1 and increases in MIROC3.2. Low-level cloud in the tropics (30° S-30° N) also varies between the two models. The diversity of cloud feedback among GCMs is suggestive of the dominant role of such low-level cloud [Bony and Dufresne, 2005; Webb et al., 2006; Williams and Tselioudis 2007].

The difference in cloud response between these two models is investigated using the cloud condensate

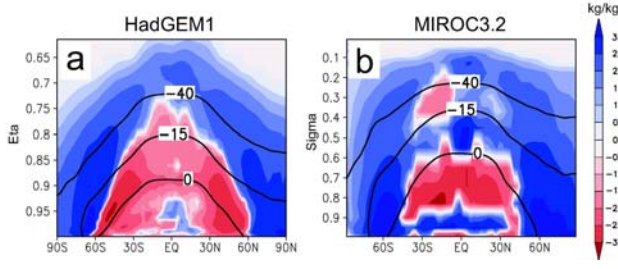


Fig. 1. Changes in zonally and annually averaged cloud condensate content, Q_c , upon CO_2 doubling (years 41-50). Values larger than 10^{-8} and smaller than -10^{-8} are plotted on a logarithmic scale offset by 8 (i.e., $\pm(\log_{10} |\Delta Q_c| + 8)$). Contours denote temperature (0°C of the normal CO_2 case, -15°C and -40°C of the doubled CO_2 case), indicating the range for the mixed phase cloud distribution with either normal CO_2 or doubled CO_2 concentration. (a) HadGEM1, (b) MIROC3.2.

tendency diagnostics (CCTD), which consist of the source terms of the non-convective cloud condensate tendency equations in the GCM. These diagnostics can be written conceptually for HadGEM1 (A) and MIROC3.2 (B) as follows.

$$\begin{aligned} \frac{\partial Q_c}{\partial t} = & [A1.\text{condensation} - \text{evaporation}] + [A2.\text{liquid precipitation}] \\ & + [A3.\text{ice sedimentation}] + [A4.\text{deposition} - \text{sublimation}] \\ & + [A5.\text{rain collection}] + [A6.\text{advection}] + [A7.\text{residual}] \quad (1) \end{aligned}$$

$$\begin{aligned} \frac{\partial Q_c}{\partial t} = & [B1.\text{condensation} - \text{evaporation}] + [B2.\text{precipitation}] \\ & + [B3.\text{ice sedimentation}] + [B4.\text{advection}] \\ & + [B5.\text{cumulus mixing}] + [B6.\text{residual}] \quad (2) \end{aligned}$$

Here, Q_c denotes the cloud condensate content in kg/kg. The terms A1 and B1 involve the condensation, evaporation, and boundary layer mixing of cloud condensate, which adjust the humidity to liquid saturation in (1), and ice saturation in (2). The terms A2 and B2 represent the formation of precipitation which falls out in one time step. The term B2 includes both solid and liquid phases (Ogura et al., in press). The A3 and B3 are the ice sedimentation which carries ice particles down to the layers below at each time step. The cloud ice content in HadGEM1 is controlled by microphysical terms, which are summarized here as [A4] and [A5] for simplicity. The term [A4] deals with mass transfer between cloud ice and water vapor through nucleation, sublimation, and evaporation, and the term [A5] corresponds to the capture of super-cooled rain by cloud ice. The term B5 represents convective mixing which is not included in (1).

Evaluating the difference between $2\times\text{CO}_2$ and control states after integrating the equations (1) and (2) from year 0 to year t' , we obtain

$$\Delta Q_c(t') \approx \Delta \int_0^{t'} \left(\frac{\partial Q_c}{\partial t} \right) dt = \sum_{i=1}^7 \left\{ \Delta \int_0^{t'} [A_i] dt \right\} \quad (3)$$

for HadGEM1, and

$$\Delta Q_c(t') \approx \sum_{i=1}^6 \left\{ \Delta \int_0^{t'} [B_i] dt \right\} \quad (4)$$

for MIROC3.2, where $\Delta = ()_{2\times\text{CO}_2} - ()_{\text{control}}$, $\Delta Q_c(0)$ is assumed zero, and $t' = 1, 2, 3, \dots, 20$. In the present study, the control state is taken to be a 10 year average of the quasi-equilibrium climate with pre-industrial CO_2 concentration. It can also be considered equivalent to

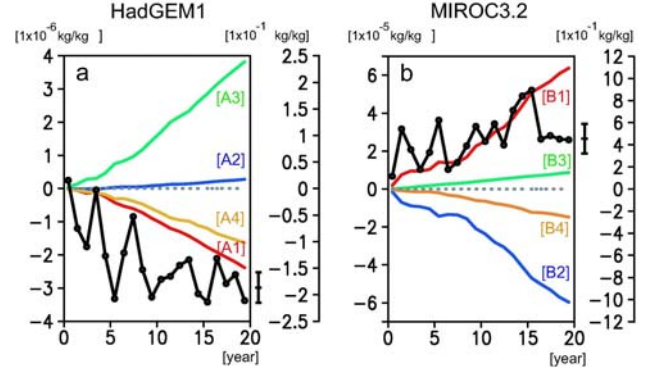


Fig. 2. Annual mean time series of cloud condensate response and the integrated tendency term responses (see text for definition) after the instantaneous CO_2 doubling at year 0. Black curves indicate the cloud condensate with scale on the left, and colored curves the integrated tendency terms with scale on the right. The black vertical bars on the right indicate the range of cloud condensate responses in quasi-equilibrium (year 41-50) estimated by the standard deviation from the mean. Grey dots indicate the sum of major terms, $\sum_{i=1}^6 \left\{ \Delta \int_0^{t'} [A_i] dt \right\}$ and $\sum_{i=1}^5 \left\{ \Delta \int_0^{t'} [B_i] dt \right\}$, respectively. The terms related to [A5], [A6], [A7], [B5], and [B6] are small and are omitted. (a) HadGEM1 at 71°W , 0°S , $\eta=0.83$, and (b) MIROC3.2 at 76°W , 1.4°S , $\sigma=0.55$.

the initial condition of the doubled CO_2 run.

The various terms in the equations (3) and (4) are considered for each model at each grid point. For example, Fig.2 shows the time series of $\Delta Q_c(t')$, $\Delta \int_0^{t'} [A_i] dt$, and $\Delta \int_0^{t'} [B_i] dt$ ($t' = 1, 2, \dots, 20$), where HadGEM1 and MIROC3.2 show a different cloud response. The cloud condensate responses show large inter-annual variations as in the pre-industrial climate. The figure also indicates that the source terms of the equations (3) and (4) (i.e., $\Delta \int_0^{t'} [A_i] dt$ and $\Delta \int_0^{t'} [B_i] dt$) roughly cancel each other out with opposite signs, making it difficult to identify the terms driving the cloud response, $\Delta Q_c(t')$. However, we might expect that the dominant terms are positively correlated with the cloud condensate response because they would have the same sign as $\Delta Q_c(t')$. Therefore, the results in Fig.2 may be interpreted that the terms $\Delta \int_0^{t'} [A1] dt$ and $\Delta \int_0^{t'} [A4] dt$ which have correlations of 0.89 and 0.89 with $\Delta Q_c(t')$ are responsible for the cloud decrease, and the terms $\Delta \int_0^{t'} [B1] dt$ and $\Delta \int_0^{t'} [B3] dt$ which have correlations of 0.87 and 0.88 with $\Delta Q_c(t')$ are responsible for the cloud increase, respectively. We note here that signs of the terms are kept the same from year 1 to 20, indicating that their contributions to the cloud change can also be inferred from the equilibrium responses.

This classification is extended to the global domain in Fig.3, deriving the temporal correlations at each grid point before taking the zonal average. We did not use zonal mean values but values at each grid point to calculate the correlation, because processes controlling the cloud response are not zonally uniform. The red and blue shading indicates where the tendency term is responsible for the cloud decrease and increase, respectively. We can see that the terms $\Delta \int_0^{t'} [A1] dt$ and $\Delta \int_0^{t'} [A4] dt$ cover most of the characteristic features of the HadGEM1 cloud response (Figs. 1(a), 3(a) and 3(c)), indicating the dominant roles of the condensation-evaporation and deposition-sublimation in driving the cloud response. In MIROC3.2, on the other hand, most of the cloud response patterns are

related to the condensation-evaporation term $\Delta \int_0^{t'} [B1] dt$ (Figs. 1(b) and 3(d)). However, the ice sedimentation term $\Delta \int_0^{t'} [B3] dt$ also has a considerable impact on the increase in mixed-phase cloud (Fig. 3(e)), consistent with the phase change feedback mechanism [Senior and Mitchell, 1993]. The correlations between $\Delta Q_C(t')$ and other terms are regionally restricted or small in the mixed phase and low level cloud region (not shown).

Comparison between the two GCMs reveals that the difference in the patterns of cloud response (Fig. 1) reflects the difference in the condensation-evaporation response (Figs. 3(a) and (d)). The difference is especially marked in the mixed phase region in the eastern tropical Pacific, where the condensation-evaporation increases in MIROC3.2 (not shown). Since the saturation vapor pressure increases following the temperature rise in both models, the condensation increase in MIROC3.2 implies a substantial increase in water vapor sources, such as from convective detrainment (Ose 1993). To clarify the difference in the condensation-evaporation responses, the linkage between cumulus convection and large

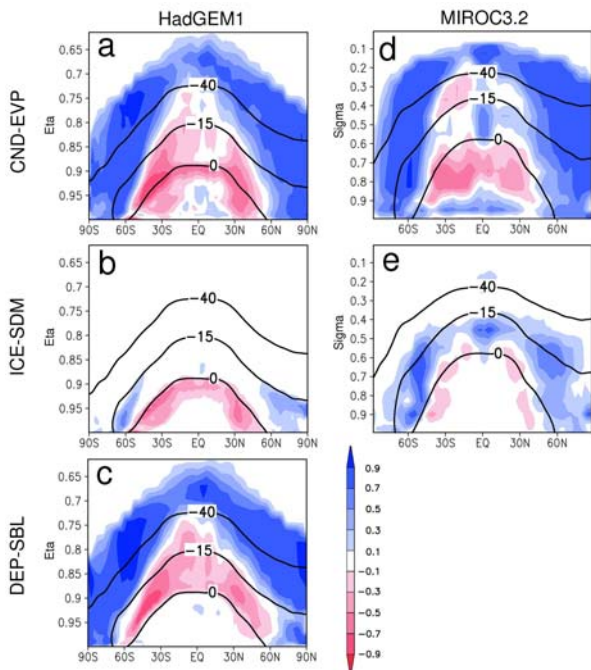


Fig. 3. Temporal correlation between cloud condensate and the integrated sources of the cloud tendency equation in response to instantaneous CO₂ doubling (years 1-20, correlations are zonally averaged). Cloud sources: (a,d) condensation and evaporation, (b,e) ice sedimentation, (c) deposition and sublimation. (a-c) HadGEM1, (d-e) MIROC3.2. The calculated correlation coefficient at each grid point is first reset to zero only where they are negative. After that, the sign of the correlation coefficients are changed from positive to negative only where the cloud response is negative. Finally, the correlation coefficients are zonally averaged as presented in the figures.

scale condensation needs to be investigated in more detail.

Another term contributing to the difference in the cloud responses is the ice sedimentation which leads to the increase in the mixed phase cloud in MIROC3.2 (Figs. 3(b) and (e)). The dissimilar roles of ice sedimentation in the two GCMs are illustrated in Fig. 4. The two models share the qualitative feature of the ice

sedimentation response, which tends to increase the mixed phase cloud by increasing the vertical ice flux convergence (Figs. 4(a) and (c)). In HadGEM1, however, the response pattern of deposition-sublimation tends to counter-balance the ice sedimentation term (Figs. 4(a) and (b)). Other terms as condensation-evaporation also contributes to the decreasing tendency of the mixed-phase cloud, which eventually outweighs the effect of ice sedimentation, as suggested by Figs. 3(a) to (c). In MIROC3.2, the increasing tendency of ice sedimentation dominates, producing an increase in mixed-phase cloud, which is further enhanced by the contribution from condensation-evaporation. Deposition-sublimation is not treated explicitly in MIROC3.2, which may have an impact on the relative importance of ice sedimentation compared to other microphysical processes.

4. Summary and discussion

The present CCTD analysis of HadGEM1 and MIROC3.2 revealed that the cloud response to CO₂ doubling differs between these two models in the mixed-phase cloud region. Cloud decreases in middle to low latitudes in HadGEM1, and increases in MIROC3.2, consistent with the response patterns of condensation-evaporation. This behavior also reflects the relative importance of ice sedimentation compared to other microphysical processes. In HadGEM1, processes such as deposition-sublimation outweigh the increasing tendency of ice sedimentation, while in MIROC3.2, ice sedimentation dominates, leading to increased mixed-phase cloud.

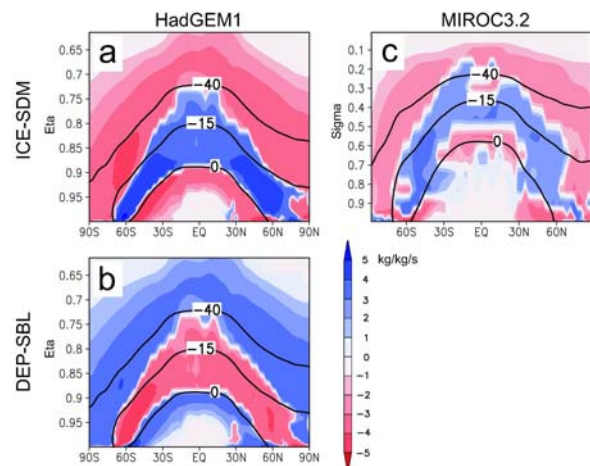


Fig. 4. Changes in zonally and annually averaged sources, Q_{src} , of the cloud tendency equation (years 41-50). Cloud sources: (a,c) ice sedimentation, (b) deposition and sublimation. (a-b) HadGEM1, (c) MIROC3.2. Values larger than 10^{-13} and smaller than -10^{-13} are plotted on a logarithmic scale offset by 13 (i.e., $\pm(\log_{10} |\Delta Q_{src}| + 13)$). Contours denote temperature (0 °C: normal CO₂, -15°C and -40°C: doubled CO₂).

Cloud phase feedback in the mixed-phase region is considered to be one of the major sources of uncertainty in climate sensitivity, being dependent on the temperature range over which the liquid-ice transition occurs [Li and LeTreut, 1992; Senior and Mitchell, 1993]. To reduce the uncertainty in long-term climate projections, it is thus desirable to constrain the mixed-phase temperature range based on observations, which are becoming increasingly available as field experiments, ground-based remote sensing, and satellite measurements become more common [Bower

et al., 1996; Hogan et al., 2003; Doutriaux-Boucher and Quaas, 2004; Naud et al., 2006]. However, the results of the present study indicate that the feedback also depends on the structure of the non-convective cloud scheme, implying that conditions other than the mixed-phase temperature range will be required in order to effectively constrain the feedback. Results of an additional sensitivity study (not shown) indicate that two versions of MIROC3.2 with different mixed-phase temperature range exhibit similar patterns of cloud response as shown in Fig1b, suggesting that the responses of mixed-phase cloud in HadGEM1 and MIROC3.2 will still differ considerably even if the same mixed-phase temperature range is used in both cases. The use of a cloud scheme that treats the microphysics affecting cloud-phase feedback explicitly is thus considered to be important. Without explicit simulation of the competing microphysical processes, it will be difficult to have confidence in the simulated cloud phase feedback.

The results obtained in this study also indicate that condensation-evaporation is the most influential term in the driving of cloud response patterns in GCMs. The response of low-level cloud in the tropics (30° S-30° N) is particularly affected by this term. Discussions on inter-model variance of cloud feedback in Assessment Report 4 of the Intergovernmental Panel on Climate Change and the CFMIP may thus be assisted by developing a better understanding of condensation-evaporation. An informative first step in clarifying the causes of changes in the condensation-evaporation response may be to separate the term into contributing processes, such as boundary layer mixing, cumulus convection, and radiation.

This study presents an example of CCTD analysis in GCMs with different cloud parameterizations. Although the definition of the diagnostic terms is model-dependent, making rigorous model inter-comparison difficult, such analyses help to understand the processes controlling the cloud response in GCMs. CCTD analyses should thus be conducted for other GCMs in order to further clarify the present findings. The present authors have also examined the cloud condensate tendency terms in three versions of one GCM, and have similarly found that the differences in cloud response can be attributed to the ice sedimentation process. This work and further CCTD analyses will be presented in subsequent papers.

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