Improvements of the Meteorological Research Institute Global Ocean-atmosphere Coupled GCM (MRI-CGCM2) and its climate sensitivity

Seiji YUKIMOTO, and Akira NODA
Meteorological Research Institute, Tsukuba, 305-0052, Japan

Abstract
A new version of the Meteorological Research Institute Coupled GCM (MRI-CGCM2) is improved in reproducing mean climate of global-mean and meridional distribution of energy budget by mainly adjusting clouds representation. In the global warming experiments, the effective climate sensitivity is evaluated and found to increase more than 1K with the improved version of the model. Decrease of negative feedback due to cloud forcing can explain the most of the change in climate sensitivity.

Keywords: climate sensitivity, climate modeling, global warming

1. Introduction

The Meteorological Research Institute global ocean-atmosphere coupled GCM (MRI-CGCM2) was developed, and its early version (referred to as MRI-CGCM2.0 or v2.0, hereafter) demonstrated sufficient performance in reproducing realistic mean climate and variability in the standard experiments with an employment of ‘flux adjustments’ (Yukimoto et al., 2001). For the global warming experiments, the model generally showed reasonable results but with a noticeably smaller warming due to the greenhouse gases compared to the results by other modeling groups (Noda et al., 2001). In the simulation by the v2.0, the energy budget was not balanced between the top and the bottom of atmosphere, and the global mean and meridional distribution of radiative flux at the top of atmosphere (TOA) had a large difference with the observation. For the new version (referred to as MRI-CGCM2.2 or v2.2, hereafter) of the MRI-CGCM2, we aimed at improving such the defects in the v2.0 by mainly refining diagnostic cloud scheme. The performance is examined with the v2.2 standard simulation for representation of cloud distribution and radiation budget. We also examine how the climate sensitivity of the model changes with the modification for the v2.2.

2. Improvements for MRI-CGCM2.0

The annual-mean radiation budgets at the TOA in the standard simulation (present-day climate simulation; see Yukimoto et al., 2001 for detailed experimental design) with the MRI-CGCM2.0 are shown in Fig. 1. The global-mean net radiation budget is 14 Wm\(^{-2}\) excessive inputs, which means the earth is heated and leads to warming trend in the deep ocean. The simulated outgoing longwave radiation (OLR) is about 20 Wm\(^{-2}\) smaller than that observed (ERBE), which is associated with the excessive high clouds especially in the tropical latitudes. Over the subtropical oceans, the model simulates excessive low-level clouds, which results in underestimation of downward solar radiation at the sea surface and overestimation of upward longwave radiation. In the MRI-CGCM2.2, we modified the diagnostic cloud scheme to control cloud amount dependent on relative humidity separately for convective clouds and layer clouds. The control parameters are also dependent on the pressure level and the surface condition (land or ocean). The control parameters are specified to make a larger cloud amount
over land than over ocean for the same relative humidity, with taking land-ocean contrast of cloud condensation nuclei number into consideration. Besides the adjustment of cloud scheme, the surface albedo over sea ice and snow cover is modified based on the seasonal variation of observed upward solar radiation. We carefully adjusted the parameters to make the meridional distributions of each longwave and shortwave radiation at the TOA close to those observed. The modified version (v2.2) simulates the radiation budgets much closer to the observation as shown in Fig. 1. The annual global-mean radiation imbalance is reduced to 4 Wm⁻² for the v2.2 from that of 14 Wm⁻² for the v2.0. The poleward energy transport of the ocean, which is required by the meridional distribution of the energy budget and the transport by the atmosphere, becomes realistic (ref. Trenberth et al., 2001). Consequently, climatic drift in the model is suppressed without employing any flux adjustments. This is a significant advantage in simulating mean climate with the new version (v2.2) compared to the older version (v2.0).

Figure 1 Meridional distributions of zonal-mean radiation budget at the TOA (upper panels) for the v2.0 (green), v2.2 (orange), and the ERBE observation (blue), and deviations from the ERBE observation (lower panels), for upward longwave (left), upward shortwave (middle), and downward net (right) radiances, respectively. The dashed lines denote global-mean deviations from the observation.
3. Climate sensitivity of MRI-CGCM2.2

3.1 Experiments

In order to examine climate sensitivity of the models, we made the standard experiments and the CO2 increase experiments for both the v2.0 and v2.2. In the standard experiments, the CO2 concentration is fixed at 348ppmv level during the whole model integration of 250 years for v2.0 (exp. v2.0-c2) and 350 years for v2.2 (exp. v2.2-a2). In the CO2 increase experiments, the atmospheric CO2 concentration is increased at a rate of 1%/year compound, where the concentration is doubled at 70 years. The CO2 increase experiments with the v2.2 are extended with keeping the CO2 concentration at constant after the doubled (exp. v2.2-g2) and the quadrupled (exp. v2.2-g1). These extended stabilization experiments are used for analyzing ‘effective climate sensitivity’ which is discussed later. In order to examine equilibrium climate sensitivity, we made a pair of doubled CO2 equilibrium experiments with the 50m slab ocean coupled to the same atmospheric GCM (SGCM) corresponding to each version of CGCMs. The experimental design is summarized in Table 1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Model version</th>
<th>Period (years)</th>
<th>CO2 concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>v2.0-c2</td>
<td>CGCM v2.0</td>
<td>250</td>
<td>1xCO2 (=348ppmv, constant)</td>
</tr>
<tr>
<td>v2.0-b1</td>
<td>CGCM v2.0</td>
<td>140</td>
<td>1% increase</td>
</tr>
<tr>
<td>v2.0sf0</td>
<td>SGCM v2.0</td>
<td>55</td>
<td>1xCO2 (constant)</td>
</tr>
<tr>
<td>v2.0sf1</td>
<td>SGCM v2.0</td>
<td>55</td>
<td>2xCO2 (constant)</td>
</tr>
<tr>
<td>v2.2-a2</td>
<td>CGCM v2.2</td>
<td>350</td>
<td>1xCO2 (constant)</td>
</tr>
<tr>
<td>v2.2-g1</td>
<td>CGCM v2.2</td>
<td>140 + 160</td>
<td>1% increase _ 4xCO2 stabilize</td>
</tr>
<tr>
<td>v2.2-g2</td>
<td>CGCM v2.2</td>
<td>70 + 230</td>
<td>1% increase _ 2xCO2 stabilize</td>
</tr>
<tr>
<td>v2.2s-d0</td>
<td>SGCM v2.2</td>
<td>60</td>
<td>1xCO2 (constant)</td>
</tr>
<tr>
<td>v2.2s-d1</td>
<td>SGCM v2.2</td>
<td>60</td>
<td>2xCO2 (constant)</td>
</tr>
</tbody>
</table>

Figures 2a and 2b show the temporal variations of the CO2 concentration and radiative forcing for the v2.2-a2, v2.2-g1 and v2.2-g2 experiments, respectively. Figure 2c shows the global-mean annual surface air temperature change for the CO2 increase experiments relative to the average of corresponding standard experiments. At the time of doubled CO2 (70 years after the start), the temperature change is +1.1K for the v2.0 (Table 2), whereas for the v2.2, it becomes 64% larger and to be about +1.8K. It is suggested that the v2.2 has a larger climate sensitivity compared to the v2.0. For the transient CO2 increase experiment, however, the temperature change at the time of doubling does not directly reflect the climate sensitivity at the equilibrium state. The temperature change for the v2.2-g2 shows moderate increase even after stabilized CO2 level at doubling, and appears to reach near the equilibrium around +2.3K at 300 years. It is considered that the additional temperature change > ~0.5K reflects an effect of oceanic thermal inertia. Since the temperature increase is delayed in deeper ocean due to its large heat capacity, there are persistent oceanic heating as shown by downward energy flux at the TOA (Fig. 2d) gradually decreasing from 1.1 Wm$^{-2}$ at 70 years to about 0.4 Wm$^{-2}$ at 300 years.

3.2 Effective Climate Sensitivity

By considering transient temperature change and oceanic heating rate, we can estimate ‘effective climate sensitivity’ (Murphy, 1995) in which the effect of oceanic thermal inertia is
Figure 2 (a) CO₂ Concentration, (b) radiative forcing due to the increase of CO₂ concentration, (c) global-mean annual surface air temperature change relative to the average of corresponding standard experiments, and (d) global-mean annual net radiation budget at the TOA, for the v2.2-a2 (black), v2.2-g1 (blue), and v2.2-g2 (green), respectively.

removed. Consider the climate system with thermal capacity $C$, temperature change $\Delta T$ under radiative forcing $F_0$ is

$$C \frac{d \Delta T}{dt} = F_0 - \alpha \Delta T = \Delta F,$$

where $\alpha$ is climate feedback parameter and $\Delta F$ is net (downward) radiative flux change at the TOA. The equilibrium climate sensitivity $\Delta T_{eq}$ is defined as the temperature change in the equilibrium state ($d\Delta T / dt = 0$) under the radiative forcing $F_{2xCO2}$ due to doubling of CO₂;

$$\Delta T_{eq} = \frac{F_{2xCO2}}{\alpha}.$$

Since the thermal inertia of the atmosphere and land is very small compared to that of the ocean and can be neglected, the variation of the oceanic thermal inertia $H_{ocean}$ is written as
\[ C \frac{d\Delta T}{dt} = \frac{dH_{\text{net}}}{dt} = \Delta F. \]

When the climate system is not in equilibrium, by using the transient temperature change \( \Delta T \) and energy flux change \( \Delta F \), the effective climate sensitivity can be estimated as

\[ \Delta T_{\text{eff}} = \frac{F_{2\times\text{CO}_2}}{\alpha_{\text{eff}}} = \frac{F_{2\times\text{CO}_2}}{F_{2\times\text{CO}_2} - \Delta F} \Delta T. \]

Assuming that the climate feedback parameter \( \alpha = (F_{2\times\text{CO}_2} - \Delta F)\Delta T^{-1} \) changes very small and is close to that in equilibrium state, \( \Delta T_{\text{eff}} \) will be equal to \( \Delta T_{\text{eq}} \). We calculated \( \alpha \) for each year for the transient CO2 experiments (not shown), and found it is very stable during the period of stabilized CO2 forcing. This implies the effective climate sensitivity is a good approximation for the equilibrium climate sensitivity in our model.

The effective climate sensitivity and feedback parameter estimated with the above procedure are shown in Table 2 together with the equilibrium values for the SGCM experiments. Those values are calculated for the average of the last 20 years of each experiment. For the experiment v2.2-g1, note that the values of radiative forcing are those from the quadrupled CO2 forcing. For the model v2.2 including SGCM (v2.2s), the effective climate sensitivity is about 2.5-2.7K, while that for the experiment v2.0-b1 is much smaller (1.4K). The climate feedback parameters \( \alpha \) (defined as positive values suppress temperature change) of 1.4-1.5 for the experiments with the v2.2 and v2.2s are 53-58% of the value of 2.6 for the experiment v2.0-b1.

<table>
<thead>
<tr>
<th>Model-experiments</th>
<th>v2.2-g1</th>
<th>v2.2-g2</th>
<th>v2.2s-d1</th>
<th>v2.0-b1</th>
<th>v2.0s-f1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta T ) at the time of 2\times\text{CO}_2 (K)</td>
<td>+1.8</td>
<td>+1.8</td>
<td>_</td>
<td>+1.1</td>
<td>_</td>
</tr>
<tr>
<td>Climate feedback ( \alpha ) (Wm(^{-2})K(^{-1}))</td>
<td>1.51</td>
<td>1.39</td>
<td>1.51</td>
<td>2.61</td>
<td>1.57</td>
</tr>
<tr>
<td>Effective climate sensitivity ( \Delta T_{\text{eff}} ) (K)</td>
<td>2.45</td>
<td>2.66</td>
<td>2.45</td>
<td>1.38</td>
<td>2.29</td>
</tr>
<tr>
<td>Radiative forcing ( \Delta F_{2\times\text{CO}_2} ) (Wm(^{-2}))</td>
<td>+7.4*</td>
<td>+3.7</td>
<td>+3.7</td>
<td>+3.6</td>
<td>+3.6</td>
</tr>
<tr>
<td>SW cloud forcing ( CF_{\text{sw}} ) (Wm(^{-2}))</td>
<td>_0.64*</td>
<td>_0.51</td>
<td>_1.03</td>
<td>_1.61</td>
<td>_1.77</td>
</tr>
<tr>
<td>LW cloud forcing ( CF_{\text{lw}} ) (Wm(^{-2}))</td>
<td>_1.97*</td>
<td>_0.85</td>
<td>_0.44</td>
<td>_2.11</td>
<td>_0.64</td>
</tr>
<tr>
<td>Net cloud forcing ( CF_{\text{net}} ) (Wm(^{-2}))</td>
<td>_2.60*</td>
<td>_1.36</td>
<td>_1.46</td>
<td>_3.73</td>
<td>_2.41</td>
</tr>
<tr>
<td>Cloud feedback ( \alpha_{\text{CLD}} ) (Wm(^{-2})K(^{-1}))</td>
<td>0.63</td>
<td>0.60</td>
<td>0.64</td>
<td>1.68</td>
<td>1.15</td>
</tr>
</tbody>
</table>

* values are for 4\times\text{CO}_2 for the v2.2-g1.

From the above analysis with effective climate sensitivity, it is shown that most of the difference of temperature change between the models v2.0 and v2.2 is attributable to the difference of the magnitude of climate feedback, and the difference of the effect of oceanic thermal inertia is relatively small between the models.

### 3.3 Feedback due to cloud forcing

It has been frequently argued that effects of cloud are very important in the climate feedback. We examined how the climate feedback due to cloud forcing is changed with the modification of cloud scheme in our model. The climate feedback parameter \( \alpha \) can be
divided into the contribution from clear sky $\alpha_{CS}$ and that from cloud forcing $\alpha_{CLD}$. These parameters are obtained by

$$\alpha_{CS} = \frac{F_0 - \Delta F_{CS}}{\Delta T}$$

$$\alpha_{CLD} = -\frac{CF}{\Delta T}$$

where $\Delta F_{CS}$ is the net (downward) radiative flux change for clear sky, and $CF$ is the cloud forcing defined as $CF = \Delta F - \Delta F_{CS}$. Figure 3 shows these parameters for each model experiments. The magnitude of clear sky feedback parameter $\alpha_{CS}$ is similar between all the experiments except the SGCM experiment v2.0s-f1. In the standard experiment with SGCM v2.0s-f0, a climatic drift was found in sea ice distribution, which leads erroneous clear sky feedback through the surface albedo change. This result suggests a possible problem in equilibrium experiments with SGCMs, which have no feedback for sea ice variation associated with ocean dynamics. Besides the experiment v2.0s-f1, the major difference of the overall feedback $\lambda$ is contributed from the cloud forcing feedback $\alpha_{CLD}$. While the cloud forcing feedback parameters are 0.60-0.64 for the experiments with the model v2.2 including SGCM (v2.2s), those for the models v2.0 and v2.0s are much larger.

![Figure 3](image-url)

Figure 3  Feedback parameters with contributions from clear sky ($\alpha_{CS}$), and from cloud forcing ($\alpha_{CLD}$), for each experiments.

Figure 4 shows the changes of zonal-mean cloud amount normalized by global-mean surface air temperature change for each experiment. In the tropical and subtropical latitudes, the cloud amount generally decreased at middle level and high level (except near the tropopause) for the both models. With the models v2.0 and v2.0s, however, the experiments shows large increase in tropical and subtropical compared to the model v2.2 and v2.2s. The larger increase of the tropical low-level cloud has larger negative effect on shortwave forcing
Figure 4  Zonally averaged annual-mean cloud amount change normalized by global-mean surface air temperature change for each experiment, (a) v2.2-g1, (b) v2.2-g2, (c) v2.2s-d1, (d) v2.0-b1, and (e) v2.0s-f1.

(Table 2). Furthermore, it is noted that the reduction of middle level clouds in the tropics is larger for the v2.0 and v2.0s than for the v2.2 and v2.2s. The larger reduction of middle level cloud probably contributes to the larger negative effect on longwave forcing. These differences of cloud amount change are the major contribution to make the difference in overall climate feedback through both shortwave and longwave cloud forcing feedback. In the high latitudes, the both models show increase of cloud amount throughout the troposphere. There seems some differences between the models in the cloud changes in the high latitudes and in the tropical tropopause, however, these has relatively smaller impact on the overall cloud feedback, since clouds in these regions have very small cloud water (that is diagnostic variable in the model).
4. Summary and discussion

A new version of the Meteorological Research Institute coupled GCM (MRI-CGCM2) is improved in reproducing mean climate of global-mean and meridional distribution of energy budget by mainly adjusting clouds representation. In the global warming experiments with the improved version of the model, the effective climate sensitivity is evaluated and found to increase more than 1K. It is shown that the decrease of negative feedback due to cloud forcing can explain the most of the change in climate sensitivity. The major difference of cloud feedback can be explained by the change in tropical low-level clouds for shortwave forcing and in tropical middle level clouds for longwave forcing. Associated with the tropical low-level clouds, the stratus and stratocumulus clouds over the eastern part of the oceans (especially over the eastern Pacific) have large impact on shortwave forcing. The change in the tropical middle level clouds is associated with the change in deep convective clouds. Generally, the qualitative pattern of these cloud change is reasonable and roughly agrees with the results from many other modeling group. However, the climate sensitivity of the model is shown to be very sensitive to the mean climate and magnitude of the response of cloud in the global warming experiment. For global warming experiments, it is suggested that very careful treatments are needed for the clouds and associated parameterizations in the model, particularly in simulating the mean climate and variation of marine stratus and stratocumulus clouds and middle level clouds in the convective region. Modeling accurately these clouds is a very important subject in the future studies.

References


Contact Person

Yukimoto, S. Phone:(+81)298-53-8610 Facsimile:(+81)298-55-5525 E-mail:yukimoto@mri-jma.go.jp