Improved Representation of Clouds in Climate Model MRI-ESM2

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1. Introduction

The previous version of the climate model of MRI MRI-CGCM3 (Yukimoto et al. 2012; TL159L48 in the standard configuration), which was used for CMIP5 simulations, had various limitations in terms of representation of clouds. In the updated version of our climate model, MRI-ESM2 (TL159L80), which is planned for use in CMIP6 simulations, the representations of clouds and aerosol–cloud interactions are improved. Figure 1 shows that the biases in shortwave cloud radiative effect are substantially reduced in the new version. The main improvements are briefly summarized herein.

2. Improvements and Results

(i) New Stratocumulus Parameterization

New stratocumulus parameterization based on a stability index that considers a cloud-top entrainment criterion (Kawai 2013; Kawai et al. 2017) was introduced. Vertical mixing at the top of a boundary layer is suppressed when the stability is high, promoting stratocumulus occurrence. There was a significant shortwave radiative flux bias (underestimated reflection of solar insolation) over the Southern Ocean in the old version, as observed in the case of many climate models. However, the bias was considerably reduced mainly due to the increased low-level cloud cover by the introduction of new stratocumulus parameterization (figure is not shown; see Kawai 2013).

(ii) Supercooled Water

In the old model, excessive ice-phase clouds and rare supercooled liquid clouds were observed over the Southern Ocean, as compared with CALIPSO satellite observation data. In the new version, the treatment of the Wegener–Bergeron–Findeisen process was modified, taking into account a relationship between liquid:ice ratio and temperature derived by Hu et al. (2010). This modification resulted in an increase in the ratio of supercooled liquid clouds in the new version, and this result is consistent with the satellite data (Fig. 2). The change in the phase ratio also contributed to the increase in the reflection of solar insolation and reduction in shortwave radiation bias over the area. This is because the effective radius of a cloud droplet is much smaller than that of ice crystals and the optical thickness of the clouds increased because of the change.

(iii) Vertical Resolution

The vertical resolution was increased from L48 to L80, and the number of vertical layers in an atmospheric boundary layer was nearly doubled in MRI-ESM2 (from 5 to 10 layers below 900 hPa). This increase helped in resolving the problem of excessive geometric thickness of low-level clouds that have extremely high albedo (Fig. 3).

(iv) Stratocumulus to Cumulus Transition

In the old model, the vertical structures of low-level clouds transition from stratocumulus to cumulus off Peru were unrealistic. However, they were significantly improved in the new version (Fig. 4) by preventing the occurrence of shallow convection over the area where the conditions for stratocumulus occurrence [see Item (i)] are met.

(v) Cloud Overlap

In the old version, the treatment of cloud overlap in the shortwave radiation calculation caused excessive reflection of solar radiation, particularly for deep convection towers topped by anvil clouds. In the new version, a more realistic cloud overlap became available in the shortwave radiation calculation because of the introduction of practical independent column approximation (PICA; Nagasawa 2012). This new cloud overlap scheme enabled the drastic alleviation of excess reflection of shortwave radiation over the tropics (figure is not shown).

(vi) Horizontal Resolution for Radiation

Though the horizontal resolution is TL159 for both models, in the old version, full radiation computations were

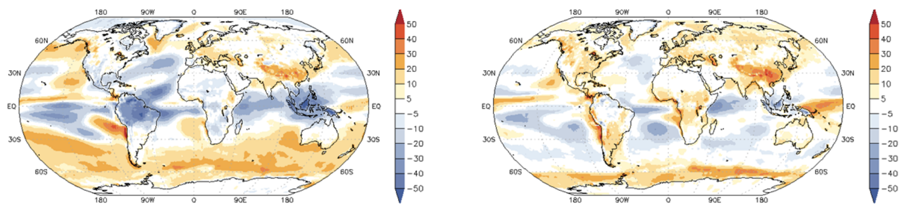

Fig. 1: Biases in shortwave cloud radiative effect (W/m^2) based on historical CMIP simulations using MRI-CGCM3 (left) and MRI-ESM2 (right). Annual means for the period 1986–2005. Observation is CERES-EBAF.

performed for every two grids in the zonal direction. In the new version, these calculations are performed for each model grid. The low-level clouds in the subtropics and mid-latitudes slightly increased because of this change (Fig. 5), presumably due to the improvement in the cloud–radiation interactions.

(vii) Bug Fixes

The old version had a bug associated with the prognostic equations of number concentrations of the cloud particles. This bug caused the problem of large number concentrations of cloud particles, particularly, for stratocumulus and stratus over the subtropics and northern Pacific region. In addition, the bug caused a large decrease in the number concentration of cloud droplets and large positive cloud feedback for such clouds in warmer climate simulations. This bug was fixed in the new version.

(viii) Aerosol Mode Radii

Aerosol mode radii were modified based on recent observations. Consequently, appropriate number concentrations of cloud particles were achieved. In particular, the increase in the mode radii of organic carbon from 0.0212 to 0.1 μm caused a significant decrease in the cloud droplet number concentration that originated from organic carbon. This modification significantly decreased the aerosol–cloud interactions associated with organic carbon.

(ix) Cloud Ice Fall

The calculation method of cloud ice fall in the old version was inappropriate, and it caused unrealistic calculation of ice fall and large time-step dependency of ice water content. The main problem was that the ratio of snow, which is removed from the ice water content at each time step and falls down to the surface within one time step, was not proportional to the time step. The treatment of cloud ice fall was improved based on the study of Kawai (2005), and the time-step dependency was alleviated (figure is not shown).

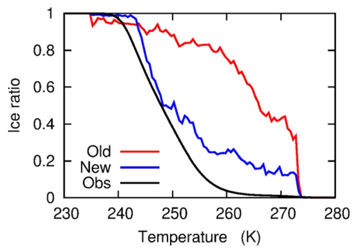

Fig. 2: Ice ratio in MRI-CGCM3 (old version; red line), MRI-ESM2 (new version; blue), and Hu et al. (2010) (observation; black). Global mean at 700 hPa for January.

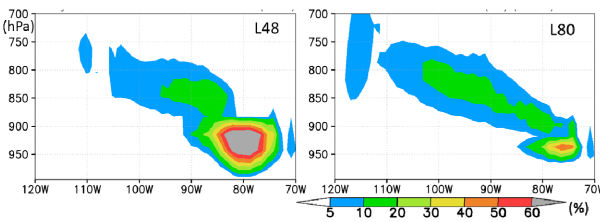

Fig. 3: Cross sections of cloud fraction along 20°S using models with vertical resolution L48 (left) and L80 (right) for January.

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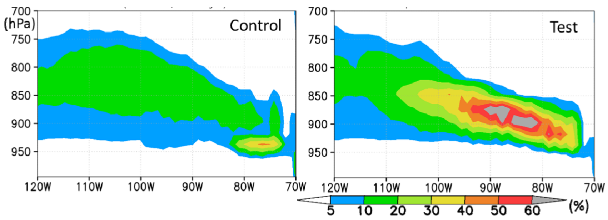

Fig. 4: Same as Fig. 3; however, this figure shows a comparison between using original shallow convection calculation (left) and a treatment of shallow convection suppressed under stratocumulus condition (right), which is calculated by a model with L80 vertical resolution.

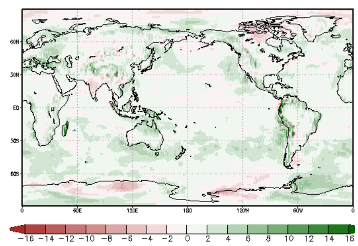

Fig. 5: Impact on the low-level cloud cover (%) by a change in radiation computation from every two grids to every grid in the zonal direction (annual mean).