Underestimated tropical stratiform precipitation in the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3)

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The ratio between stratiform and convective precipitation simulated by the NCAR CCM3 is examined. Stratiform rain only accounts for about 1.5% of the total rain amount in CCM3 between 20°N and 20°S, far lower than 40% estimated from Tropical Rainfall Measuring Mission (TRMM) data. Preliminary study suggests that the serious underestimation of stratiform precipitation in CCM3 could be responsible for failed simulations of intraseasonal oscillation (ISO) and seasonal migration of the intertropical convergence zone (ITCZ) precipitation across the equator. Sensitivity experiment with artificially enhanced stratiform precipitation indicates that increase of stratiform rain fraction can improve the simulations of ISO and seasonal migration of the ITCZ precipitation. This study suggests that reasonable partition of stratiform and convective precipitation is crucial for a climate model to project realistic climate features.

INDEX TERMS: 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology.


1. Introduction

Many observations in the tropics indicated that stratiform precipitation covers great areas and accounts for a large portion of the tropical rainfall [e.g., Cheng and Houze, 1979; Leary, 1984; Short et al., 1997]. Since December 1997, the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) has provided high-resolution three-dimensional precipitation data between 35°N and 35°S, which are so far the best available data to differentiate regions of convective and stratiform precipitation in the tropics [Schumacher and Houze, 2003]. Reasonable agreement has been found between various airborne and ground-based radar convective-stratiform classifications and instantaneous PR convective-stratiform statistics [Heymsfield et al., 2000; Schumacher and Houze, 2000]. Using the TRMM PR data in the tropics (20°S–20°N), Schumacher and Houze [2003] showed that stratiform precipitation accounts for 40% of the total rain amount and 73% of the area covered by rain over a 3-year period (1998–2000). Moreover, recent study based on 5 years (1998–2002) of TRMM PR data further showed that anomalous stratiform precipitation contributes about 60% to the anomalous precipitation in the Madden–Julian oscillation (MJO) more than the climatological fraction of stratiform precipitation [Lin et al., 2004]. From comparison of the observed anomalous heating profiles with those in seven models, Lin et al. [2004] suggested that the models’ difficulty in simulating the MJO might due to systematic lack of stratiform-like heating process in the MJO. In this study, we examined the ratio between the convective and stratiform precipitation simulated by the National Center for Atmospheric Research (NCAR) Community Climate Model Version 3.6 (CCM3.6, hereafter CCM3 [Kiehl et al., 1998]) and performed a sensitivity experiment with artificially enhanced stratiform precipitation to discuss the role of the stratiform condensation in the global climate model (GCM). This experiment indicates that increase of stratiform rain fraction can significantly improve simulations of the intraseasonal oscillation (ISO) and seasonal migration of the intertropical convergence zone (ITCZ) precipitation.

2. Stratiform Precipitation Fraction in the NCAR CCM3

In general, tropical precipitation can be divided into two types: convective and stratiform [Houze, 1997; Schumacher and Houze, 2003]. Convective precipitation regions are characterized by strong vertical motions (>1 m/s), small horizontal scale (~1–10 km), high precipitation rate (>5 mm/h), and horizontally inhomogeneous radar echo. The latent heating profile associated with convective rain is positive throughout the troposphere. In contrast, stratiform precipitation areas are characterized by small vertical motions (<1 m/s), large horizontal scale (~100 km), low precipitation rate (<5 mm/h), and horizontally homogeneous radar echo. The latent heating associated with stratiform rain is characterized by cooling in the lower troposphere and heating in the upper troposphere.

In GCMs, precipitation is usually estimated by two separate schemes: subgrid scale convective parameterization scheme and non-convective condensation parameterization scheme. In CCM3, Zhang and McFarlane’s [1995] scheme is used to represent deep penetrative convection and Hack’s [1994] scheme is used for shallow and middle-level convection. In general, stratiform rainfall may occur within mesoscale convective systems. However, the mesoscale effects have not been incorporated to the convective
schemes in CCM3, thus the two convective schemes in CCM3 consequentially produce convective rain. The non-convective condensation parameterization represents stable condensation processes, which are associated with weak updraft. The precipitation produced by non-convective condensation primarily depends on grid box relative humidity. In CCM3, a saturation adjustment scheme is used for non-convective condensation process. Since this scheme is applied to grid point fields, it produces the grid-scale (~300 km) precipitation. The weak vertical motion and large horizontal scale suggest that the precipitation is stratiform rain. We further examined the regionally averaged non-convective latent heating profile for 10-year (1980–1989) simulation with CCM3 (Figure 1). The heating profile is very similar to those observed in areas of stratiform rain, which is characterized by heating in the upper troposphere and cooling in the lower troposphere, indicating that the precipitation produced by non-convective condensation parameterization in the model is comparable to the observed stratiform rain. Therefore, the stratiform rain to which this study refers is produced by non-convective (stratiform) condensation parameterization, while the convective rain refers to that produced by convective parameterizations.

[5] In order to examine the stratiform rain fraction simulated in the NCAR climate model, we conducted a 11-year (1979–1989) standard control simulation with CCM3. The simulation used the standard initial conditions datasets provided with the model and was forced with the standard observed monthly average SSTs at T42 horizontal resolution. Figure 2 shows the 10-year (1980–1989) mean simulated stratiform rain fraction between 20°S–20°N. Similar to the work of Schumacher and Houze [2003], regions that have annual mean rainfall less than 0.6 m were excluded in order to decrease uncertainty from sampling. From Figure 2 it is evident that the stratiform rain estimated by the model appears very small. The stratiform rain fraction in most areas is less than 1% except for few grid boxes in which it is greater than 15%. Across the tropics (20°S–20°N), the mean stratiform rain fraction for the 10-year period is 1.5%, far lower than 40% estimated from TRMM PR data [Schumacher and Houze, 2003]. To examine the contribution of anomalous stratiform precipitation to the anomalous precipitation in the MJO, standard deviation of 20–100-day band-pass-filtered precipitation was calculated. Stratiform precipitation can only explain 1.2% of the variance of total precipitation in the region 5°S–5°N and 60°E–180°E. It is clear that the low fraction of climate mean stratiform precipitation result in the low contribution of stratiform precipitation in the MJO.

3. Role of Stratiform Condensation Process in the GCM

[6] The aforementioned analysis implies that the effect of the stratiform condensation is significantly underestimated in CCM3. However, observational study shows that the stratiform condensation process can affect the radiative and latent heating, which has a significant impact on tropical convolutions and intraseasonal oscillations [Lin et al., 2004]. In order to investigate the effect of stratiform condensation process on simulation, a sensitivity experiment was performed with CCM3. The sensitivity run is similar to the standard control run except that the convective parameterizations were turned off. Thus convective rain is disappeared and precipitation is produced only by stratiform condensation scheme. Then the role of stratiform condensation can be examined by comparing sensitivity simulation to control simulation and through comparison with the observations. In this section, the simulations of ITCZ precipitation and ISO were compared to examine the role of stratiform condensation.

[7] The climatology simulated by the sensitivity simulation, in general, is in good agreement with the observations. However, tropical troposphere is systematically colder than observed and those in control simulation. This is most likely due to the lack of convective mixing. It is worth to note that precipitation in control simulation tends to be too lower than observed over the western Pacific in summer. However, sensitivity simulation tends to produce excessive precipitation over the Indian Ocean and the western Pacific. It seems like that increasing stratiform rain fraction could improve the precipitation simulation over the western Pacific in summer.

[8] The ITCZ is a prominent component of the general circulation of the atmosphere, and is characterized by a belt of low-level convergence and upper-level divergence. In precipitation field, the ITCZ is consistent with the regions of maximum precipitation in the tropics. Figure 3 shows the 10-year (1980–1989) mean annual cycles of zonal mean precipitation rate. The Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) observations (Figure 3a) from Xie and Arkin [1997] indicate that the ITCZ precipitation has a distinct seasonal migration across the equator, characterized by precipitation maximum shifts from 8°S in boreal winter to 8°N in boreal summer.

Figure 1. 1980–1989 mean non-convective latent heating profile simulated by CCM3, averaged between 5°S–5°N and 145°E–165°E.

Figure 2. 1980–1989 mean stratiform rain fraction simulated by CCM3. Areas with annual mean rainfall less than 0.6 m were excluded. The contour interval is 5% above 1%. Areas with stratiform rain fraction greater than 1% are shaded.
However, the control simulation (Figure 3b) is unable to reproduce this observed feature. The precipitation maximum in control simulation remains north of the equator throughout the year. In contrast, although slightly higher, the sensitivity simulation (Figure 3c) reproduced the observed feature quite well. The precipitation peak shifts from south of equator in November–March to north of equator in April–October and the relative minimum occurs in April.

[9] To examine the effect of stratiform condensation process on the simulation of ISO, daily outgoing longwave radiation (OLR) and 200-mb zonal wind from the simulations for 1980–1989 were filtered with a 20–100-day band-pass filter and then averaged from 10 S to 10 N at every longitude. To isolate the intraseasonal time scale the first two annual harmonics were removed before the filter was applied. Hereafter, these mean band-passed data will simply be referred to as intraseasonal anomalies. Daily 200-mb zonal wind from National Centers for Environmental Prediction (NCEP)-NCAR reanalysis [Kalnay et al., 1996] and daily OLR data from the National Oceanic and Atmospheric Administration (NOAA)-CIRES/Climate Diagnostics Center (CDC) [Liebmann and Smith, 1996] for the same period were used as validation data in this study. Figure 4 shows the time-longitude sections of intraseasonal OLR anomalies for 1986. It is clear that the notable differences do exist between the control and sensitivity simulation (Figures 4c and 4b). The intraseasonal variability in control simulation is weaker and disjointed. In contrast, sensitivity simulation produces prominent eastward-propagating intraseasonal signals with high amplitude. Comparing to the observation (Figure 4a), the sensitivity simulation produces slightly slower phase speeds and stronger amplitudes, while the control simulation produces much weaker signals with some indications of westward propagation. The sensitivity simulation produces more realistic intraseasonal signals than those in the control simulation. Figure 5 shows the time-longitude sections of intraseasonal 200-mb zonal wind anomalies for 1986. Similar to Figure 4, sensitivity simulation produces more realistic eastward-propagating intraseasonal zonal wind signals than control simulation, with slightly stronger amplitudes and more realistic phase speeds, while control simulation produces much weaker signals than observed. We tested all of the 10-year simulations. Although the interannual differences do exist, the conclusions do not change.

[10] It should be noted that the motivation of sensitivity experiment is not to get a realistic simulation, but to understand the role of stratiform condensation in GCM. The sensitivity simulation indicates that when stratiform precipitation is dominant, the simulated seasonal migration of ITCZ precipitation is reasonably good, but both ITCZ precipitation and ISO are stronger than those observed. While the control simulation indicates that when convective precipitation is dominant, the simulated seasonal migration of ITCZ precipitation and the ISO are too weak. It indicates that the excessive lack of stratiform rain in CCM3 may be the possible cause for the failed simulations of the ISO and seasonal migration of ITCZ precipitation. This conclusion supports the speculation of Lin et al. [2004] that the difficulty in simulating the MJO might due to lack of stratiform-like heating process.

Figure 3. 1980–1989 mean annual cycles of precipitation rate (mm/day) from (a) CMAP observations, (b) the standard CCM3 simulation (CCM3 CTL), and (c) the CCM3 simulation without using convective parameterizations (CCM3 NCP).

Figure 4. Time-longitude sections of 20–100-day band-pass filtered OLR averaged between 10 S and 10 N in 1986 from (a) NOAA observations, (b) the CCM3 simulation without using convective parameterizations (CCM3 NCP), and (c) the standard CCM3 simulation (CCM3 CTL). Units are W/m².

Figure 5. As in Figure 4 except for 200-mb zonal wind. (a) NCEP reanalysis. Units are m/s.
tary features between convective and stratiform condensation also suggest that a reasonable partition of stratiform and convective precipitation is important to a reasonable climate simulation. Observations indicated stratiform rain is comparable to convective rain in tropics. However, the convective rain is dominant in CCM3, it suggests that increase of stratiform rain fraction can improve the simulations of the ITZC precipitation and ISO. The more closer stratiform rain fraction is to those observed, the more closer simulation is to the reality.

4. Summary and Discussion

In this study, we examined the stratiform rain fraction simulated by the NCAR CCM3.6 and discussed the role of stratiform condensation in climate simulation.

In general, the criterions for stratiform precipitation used in observational studies are different to that used in GCMs, but our analysis indicates that the precipitation produced by stratiform condensation scheme in CCM3 has the basic observational features of stratiform precipitation, so it is comparable in quality to that of observed stratiform rain. In tropics (20°S–20°N), stratiform rain fraction estimated from 10-year simulation with CCM3 is about 1.5%, far lower than 40% estimated from TRMM PR data. The excessive lack of stratiform precipitation indicates that the model significantly underestimate the effect of stratiform condensation. So we conducted a sensitivity simulation in which the stratiform rain is artificially enhanced to investigate the effect of stratiform condensation on the simulation. The comparison between control and sensitivity simulations and the observations suggests that the serious underestimation of stratiform precipitation in CCM3 could be responsible for failed simulations of ISO and seasonal migration of the ITZC precipitation. It also indicates that the increase of stratiform rain fraction could improve the climate simulation of CCM3. The complementary features between convective and stratiform condensation suggest that both stratiform and convective condensation have important effect on simulation. The reasonable partition of stratiform and convective precipitation is crucial for a climate model to project realistic climate features.

The underestimation of stratiform precipitation in CCM3 is partially due to the fact that the model convection is so active that it consumes most of the moisture transported from the boundary layer. The neglect of several other important factors such as detrainment of cloud water/ice from convection, the effect of wind shear and mesoscale cloud processes in the current schemes could also contribute to this problem.

Note that the conclusion in this study is only based on one model simulation, using different GCMs to confirm this finding is useful. The physical mechanism of how the stratiform condensation process affects climate simulation is unclear, although the latent heat feedback may be one of the most possible mechanisms for it. Further studies are needed to clarify this issue.

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