Evaluation of RegCM4.6 Simulations with Two Cumulus Parameterization Schemes over East Asia: A Postprint

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Date: 2023-02-27T00:00:00+00:00

Abstract

The new-generation regional climate model RegCM4.6 has introduced the Mix cumulus parameterization scheme, which can combine the Emanuel and Grell schemes from previous versions to compensate for the deficiencies of individual parameterization schemes. Using 2016 MODIS (Moderate-resolution Imaging Spectroradiometer) data, a preliminary evaluation was conducted of East Asian cloud fraction (CF), ice water path (IWP), and liquid water path (LWP) simulated by the Mix and Emanuel cumulus parameterization schemes in RegCM4.6. The correlation coefficient (r), mean absolute error (MAE), mean bias error (MBE), and root mean square error (RMSE) were calculated to provide a reference for selecting cumulus parameterization schemes in related research. The results show that: (1) The MBE of simulated CF is roughly bounded by the Hu Line, with slight overestimation in the northwestern part and general underestimation in the southeastern part. Both schemes perform best in summer and worst in winter. The absolute values of MAE, MBE, and RMSE for the Mix scheme are generally smaller than those of the Emanuel scheme across all four seasons. (2) The model significantly underestimates IWP over East Asia. Except for summer, the IWP simulated by both schemes shows a significant negative correlation with MODIS data, indicating that the model has difficulty accurately simulating physical processes related to ice crystals in clouds. (3) The LWP simulated by both schemes is underestimated over the Tibetan Plateau and eastern sea areas, but overestimated in southern, central, and northern China, with the bias of the Mix scheme being closer to zero. In winter, the evaluation metrics of the two schemes are similar; in other seasons, the absolute values of MAE, MBE, and RMSE for the Mix scheme are all smaller than those of the Emanuel scheme, with MAE differing by 21–39 $g \cdot m^{-2}$. Therefore, the Mix scheme is more suitable for simulation research on cloud water resources in East Asia.

Full Text

Abstract

The new generation regional climate model RegCM4.6 combines the Emanuel and Grell cumulus parameterization schemes into a Mix scheme to compensate for deficiencies in individual parameterizations. Previous validation studies have primarily focused on temperature and precipitation, with few evaluations of cloud physical properties. This study uses MODIS satellite products from January 1 to December 31, 2016, as a reference to evaluate simulated cloud fraction (CF), ice water path (IWP), and liquid water path (LWP) over East Asia from the Emanuel and Mix schemes in RegCM4.6 at various temporal scales. Statistical metrics including correlation coefficient (r), mean absolute error (MAE), mean bias error (MBE), and root mean square error (RMSE) were calculated. Results show: (1) Simulated CF is slightly overestimated in northwestern regions but generally underestimated in southeastern regions, roughly bounded by the Hu Huanyong Line. Both schemes perform best in summer and worst in winter. Across all seasons, the absolute values of MAE, MBE, and RMSE for the Mix scheme are generally smaller than those for the Emanuel scheme. (2) Systematic IWP biases are negative across East Asia. Except in summer, IWP from both simulations shows significant negative correlation with MODIS data in the other three seasons, indicating challenges in accurately simulating ice particle-related physical processes. (3) LWP is underestimated by both schemes over the Qinghai-Tibet Plateau and eastern ocean areas, and overestimated in southern, central, and northern China, but the annual MBE of the Mix scheme is closer to zero. The two schemes show similar performance in winter, but in the other three seasons, the absolute values of MAE, MBE, and RMSE for the Mix scheme are smaller than those for the Emanuel scheme, with MAE differences of 21-39 $g \cdot m^{-2}$. Therefore, the Mix scheme is more suitable for simulating cloud water resources in East Asia.

Keywords: regional climate model; East Asia; cloud fraction; ice water path; liquid water path

Introduction

East Asia is one of the most freshwater-scarce regions in the world. With the development of artificial precipitation enhancement technology, exploiting atmospheric cloud water resources has become an important approach to alleviating water shortages. Cloud formation and distribution result from the combined effects of various atmospheric thermodynamic and dynamic processes and surface processes. Many scholars have used ground observations and satellite-retrieved cloud data to analyze the spatiotemporal distribution of cloud physical properties such as cloud fraction, cloud equivalent temperature, and ice water path, as well as their relationships with precipitation. However, ground stations are unevenly distributed, polar-orbiting satellite observations are temporally discontinuous for any given region, and geostationary satellite data are limited by observation range. Therefore, further assessment and prediction of cloud water resources require numerical models.

Regional climate models (RegCM) can be used for regional climate simulation and prediction, with cumulus convection being the most commonly used parameterization scheme for cloud water numerical simulation and forecasting. Studies based on previous versions show that the Emanuel cumulus parameterization scheme in RegCM simulates temperature well but has large biases in precipitation, while the Grell scheme performs better overall in simulating temperature and precipitation in East Asia. Consequently, the new generation regional climate model RegCM4.6 combines the Emanuel and Grell schemes into a Mix cumulus parameterization scheme that can use different cumulus parameterizations over land and ocean to compensate for individual scheme deficiencies. However, few studies have evaluated the simulation performance of these two cumulus parameterization schemes for cloud physical properties. This study uses MODIS satellite products to validate simulated cloud fraction (CF), ice water path (IWP), and liquid water path (LWP), providing a reference for cloud water resource development and prediction research in East Asia and surrounding regions.

1. Study Area Overview

East Asia covers approximately 12.5×10^{6} km^2, including China, Mongolia, Japan, South Korea, and North Korea, with complex terrain and significant topographic variation. The western region features the Qinghai-Tibet Plateau with highland climate; the northwest inland areas are dry with arid and semi-arid conditions; and the eastern region faces the Pacific Ocean, where large land-sea thermal differences create a typical monsoon climate.

Based on climate characteristics and referencing *Physical Geography of China*, East Asia is divided into five sub-regions plus the entire study area, totaling six research regions: entire East Asia, Northwest region, Qinghai-Tibet Plateau, North region, South region, and Eastern Ocean (Fig. 1). This subdivision facilitates investigation of the applicability of the Emanuel and Mix cumulus parameterization schemes.

[Figure 1: see original paper]

2. Data and Methods

2.1 Data Sources

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a passive radiometer onboard Terra and Aqua satellites with multi-channel and high temporal resolution characteristics. This study uses MODIS Level 3 products MOD08_{M3} and MYD08_{M3} with monthly temporal resolution and $1^\circ\times1^\circ$ spatial resolution to evaluate simulated CF, IWP, and LWP.

2.2.1 RegCM4.6 Model Description and Configuration

Originally developed by the National Center for Atmospheric Research (NCAR) and later improved by the International Centre for Theoretical Physics (ICTP), RegCM4.6 is the latest version of the regional climate model. This study designs two experimental schemes with identical settings except for cumulus parameterization: Experiment 1 uses the Emanuel scheme, while Experiment 2 uses the Mix scheme (Emanuel over ocean and Grell over land). Detailed descriptions of the Emanuel and Grell schemes can be found in references [19-20, 24-25].

The simulation domain covers all of East Asia (10°-58°N, 37°-158°E) with a horizontal resolution of 25 km. The integration period is from January 1 to December 31, 2016, with the first month as spin-up. Initial and lateral boundary conditions are provided by ECMWF reanalysis data, sea surface temperature from the OISST dataset, and terrain from GMTED data. Main parameterization schemes include: Community Land Model (CLM) land surface scheme, Holtslag planetary boundary layer scheme, Community Climate Model version 3 (CCM3) radiation transfer scheme, and Explicit Moisture large-scale precipitation scheme.

2.2.2 Statistical Metrics

Although satellite retrieval data contain errors, they provide valuable validation under current technological constraints with limited cloud physical property observations. MODIS and model data are averaged annually and seasonally on a 1°$×$1° grid, then differenced at each grid point to obtain spatial bias distributions. Regional average biases are calculated for each sub-region. To further evaluate simulation performance, we compute correlation coefficient (r), mean absolute error (MAE), mean bias error (MBE), and root mean square error (RMSE) as follows:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|\mathrm{Model}(i) - \mathrm{MODIS}(i)|$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}[\mathrm{Model}(i) - \mathrm{MODIS}(i)]$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[\mathrm{Model}(i) - \mathrm{MODIS}(i)]^2}$$

where n is the number of grid points; $\mathrm{Model}(i)$ and $\overline{\mathrm{Model}}$ are the modeled physical quantities and their mean; $\mathrm{MODIS}(i)$ and $\overline{\mathrm{MODIS}}$ are the MODIS-derived quantities and their mean.

3. Results

3.1 Annual Mean Cloud Fraction, Ice Water Path, and Liquid Water Path

Figure 2 shows the spatial distributions of annual mean CF, IWP, and LWP from MODIS and the two schemes, along with their MBE. Annual mean CF is generally below 0.6 in the Northwest region and Qinghai-Tibet Plateau, and 0.4–0.6 in the North region, Eastern Ocean, and South region. Both Emanuel and Mix schemes significantly underestimate CF along the northern coast, Eastern Ocean, and South region. The Mix scheme shows a slight overestimation in the Qinghai-Tibet Plateau and central North region, with MBE around 0.1, while the Emanuel scheme shows underestimation in these areas.

The spatial distributions of IWP from both schemes are similar, with significant underestimation across most of East Asia. Overestimation occurs only in parts of Mongolia, Xinjiang, Inner Mongolia, Qinghai, and Tibet, with MBE around 25 $g \cdot m^{-2}$. The Mix scheme' s positive bias is larger than Emanuel' s because the Emanuel scheme considers automatic conversion of cloud water to rain or ice crystals, assuming convection occurs when mid-level buoyancy exceeds bottom-level buoyancy with mixed entrainment, which often overestimates cumulus and convective precipitation over land.

Both schemes underestimate LWP across East Asia, particularly in the southeastern coastal areas and Eastern Ocean where underestimation exceeds 200 $g \cdot m^{-2}$. In the Northwest region, the simulation is better with underestimation within 150 $g \cdot m^{-2}$. The Mix scheme' s MBE is closer to zero than Emanuel' s.

Table 1 shows the annual statistics for East Asia. Both schemes underestimate CF, with the Mix scheme showing higher r (0.55) and smaller absolute MBE (0.06) and RMSE (0.18) compared to Emanuel (r=0.53, MBE=-0.08, RMSE=0.20). For IWP, both schemes show significant negative correlation with MODIS, indicating difficulties simulating ice crystal-related processes. For LWP, both schemes show significant positive correlation with MODIS, with the Mix scheme performing better as its MBE absolute values are smaller and closer to zero.

3.2 Seasonal Mean Cloud Fraction

Figure 4 shows seasonal CF distributions and MBE. In spring, autumn, and winter, East Asian CF exhibits a "low in northwest, high in southeast" pattern, with low values in the Northwest region and Qinghai-Tibet Plateau, and high values in the North region, South region, and Eastern Ocean. This pattern results from higher atmospheric moisture in these regions providing conditions for low cloud formation, while low temperatures prevent moisture transport to high altitudes. Summer shows a "low in northwest, high in southwest" pattern.

Both schemes significantly underestimate CF across East Asia in all seasons, with performance best in summer and worst in winter. The Mix scheme' s absolute MBE values are generally smaller than Emanuel' s. In the Eastern Ocean, systematic underestimation is particularly severe, likely due to insufficient lateral boundary conditions and the lack of air-sea coupling in the model, which cannot fully represent interactions between cumulus convection and ocean processes.

Table 2 shows seasonal statistics for East Asia. Both schemes underestimate CF in all seasons, with the smallest MBE in winter (-0.04 to -0.05) and largest in summer (-0.11 to -0.12). The Mix scheme shows smaller absolute MBE values than Emanuel across all seasons.

3.3 Seasonal Mean Ice Water Path

Figure 6 shows seasonal IWP distributions and MBE. In spring, autumn, and winter, IWP shows a "low in northwest, high in southeast" pattern, with high values exceeding 400 $g \cdot m^{-2}$ in the South region and low values within \$$\pm 100 g \cdot m$^{-2}\$ in the Northwest region and Qinghai-Tibet Plateau. Summer shows a more uniform distribution with values mostly 150–250 $g \cdot m^{-2}$.

Both schemes underestimate IWP across East Asia in all seasons, with performance best in winter and worst in summer. The Mix scheme generally performs better than Emanuel, particularly in the South region and Eastern Ocean. In the Northwest region, North region, and Qinghai-Tibet Plateau, both schemes show similar performance.

Table 3 shows seasonal statistics for East Asia. Except in summer, IWP from both simulations shows significant negative correlation with MODIS, indicating the model cannot adequately describe subgrid cloud processes related to ice particle generation, development, and dissipation. This may be related to uncertainties in cloud ice particle size, irregular shapes, and scattering properties.

3.4 Seasonal Mean Liquid Water Path

Figure 8 shows seasonal LWP distributions and MBE. In spring, autumn, and winter, LWP exhibits a "low in northwest, high in southeast" pattern. Spring values are relatively small (50–300 $g \cdot m^{-2}$), while winter values are larger, exceeding 350 $g \cdot m^{-2}$ in northern Northwest region. Summer shows a different pattern with high values in the eastern Qinghai-Tibet Plateau (200–300 $g \cdot m^{-2}$) and a zonal low-value band near 35°N.

Both schemes underestimate LWP in the Qinghai-Tibet Plateau and Eastern Ocean, and overestimate it in southern, central, and northern China. The Mix scheme's MBE is generally within \$$\pm 100 g \cdot m$^{-2}\$, closer to zero than Emanuel' s. Winter shows the worst performance with systematic underestimation, while other seasons show mixed overestimation and underestimation patterns.

Table 4 shows seasonal statistics for East Asia. For LWP, both schemes show significant positive correlation with MODIS in all seasons. The Mix scheme has smaller absolute MBE values than Emanuel in all seasons, with the smallest differences in winter (\$$\pm 50 g \cdot m^{\{-2\})andlargestinsummer(exceeding 100 g \cdot m}${-2}\$).

4. Conclusions

Based on MODIS satellite data and simulations from RegCM4.6 using Emanuel and Mix cumulus parameterization schemes over East Asia, this study evaluates simulated cloud fraction, ice water path, and liquid water path. The main conclusions are:

1. Both schemes simulate CF reasonably well, with slight overestimation in the northwest and underestimation in the southeast, roughly bounded by the Hu Huanyong Line. Performance is best in summer and worst in winter. The Mix scheme shows smaller errors than Emanuel, with annual MBE of -0.06 versus -0.08, and RMSE of 0.18 versus 0.20.
2. Both schemes significantly underestimate IWP across East Asia, with the largest underestimation in summer (exceeding 200 $g \cdot m^{-2}$ in southeastern China and the Eastern Ocean). Winter and spring simulations are relatively better. Except in summer, simulated IWP shows significant negative correlation with MODIS, suggesting the model cannot accurately describe ice particle-related physical processes.
3. Both schemes underestimate LWP in the Qinghai-Tibet Plateau and Eastern Ocean (within 150 $g \cdot m^{-2}$) and overestimate it in other regions (mainly within 100 $g \cdot m^{-2}$). The Mix scheme's MBE is closer to zero. Both schemes show significant positive correlation with MODIS in all seasons, with the Mix scheme performing better.

In summary, the Mix cumulus parameterization scheme in RegCM4.6 is more suitable for simulating cloud water resources in East Asia. This study provides a reference for selecting and improving cumulus convection parameterization schemes in regional climate models.

References

[1] References section contains citations to various studies on cloud properties, RegCM applications, and parameterization schemes in Chinese and English journals.

[2] Additional references on regional climate modeling, cumulus parameterizations, and MODIS validation studies.

[3] Technical references for RegCM4.6 model documentation and parameterization scheme details.

[4] Studies on cloud vertical distribution and microphysical properties over China’ s mountainous regions.

[5] Research on cloud radiative forcing and climate change projections using RegCM.

[6] Sensitivity studies of cumulus parameterizations over the Tibetan Plateau and East Asian monsoon region.

[7] Validation studies using MODIS and CloudSat/CALIPSO data for cloud property retrievals.

[8] References on numerical weather prediction and model parameter tuning.

[9] Studies on warm cloud properties and their relationships with meteorological conditions in eastern China.

[10] Technical documentation for MM5 and RegCM model formulations.

[11] Research on convection suppression criteria and air-sea system phase relationships.

[12] Climate change projections and ensemble simulations using RegCM4 over China and Xinjiang.

[13] Studies on glacial surface effects on cloud structure and cloud water content.

[14] Analysis of seasonal cloud variations over Asian monsoon regions using satellite data.

[15] Parameter calibration and performance evaluation of RegCM3 with different cumulus schemes.

[16] Evaluation of RegCM4 performance over major river basins in China.

[17] Assessment of net shortwave radiation simulation over China using RegCM.

[18] Recent advances in regional climate modeling and applications.

[19] The quiet revolution of numerical weather prediction and its implications for regional climate modeling.

[20] Spatiotemporal distribution of cloud liquid water over Xinjiang' s mountainous regions.

[21] Vertical distribution of ice water content during heavy rainfall events around Tianshan Mountains.

[22] Cloud parameter characteristics of mesoscale short-term rainstorms in northern Tianshan slopes.

[23] Seasonal distribution characteristics of precipitating ice clouds in Beijing-Tianjin-Hebei region.

[24] Effects of glacial surface on summer cloud structure and water content in Qilian Mountains.

[25] Seasonal variations of ice particle microphysical properties for stratus and stratocumulus in Xinjiang.

[26] Sensitivity of regional climate model to different cumulus parameterization schemes in Tibetan Plateau simulation.

[27] Influence of cumulus parameterization on air-sea system phase relationship simulation in East Asian summer monsoon region.

[28] Features of cloud overlapping in East Asia and effects on cloud radiative forcing.

[29] Seasonal variation of single-layer low cloud properties and radiative forcing in East Asia.

[30] Spatial and temporal distributions of warm cloud properties in eastern China and adjacent oceans.

[31] Modern climate over East Asia simulated by regional climate model nested in global circulation model.

[32] Climate change in China in the 21st century as simulated by high-resolution regional climate model.

[33] Numerical simulation analysis of precipitation and temperature in Xinjiang using RegCM3.

[34] Future climate change projection over Xinjiang based on ensemble regional climate model simulations.

[35] Climate change of the 21st century over China from RegCM4 ensemble simulations.

[36] Performance of RegCM4 over Central America and Caribbean using different cumulus parameterizations.

[37] Validation of MODIS retrieved cloud fractions using whole sky imager measurements.

[38] Spatial and temporal distribution of clouds observed by MODIS onboard Terra and Aqua satellites.

[39] Development and evaluation of a convection scheme for use in climate models.

[40] Description of the fifth-generation Penn State/NCAR mesoscale model (MM5).

[41] Numerical prediction of convectively driven mesoscale pressure systems.

[42] Regional climate model RegCM reference manual version 4.6.

[43] Convection suppression criteria applied to the MIT cumulus parameterization scheme.

[44] Parameter tuning and calibration of RegCM3 with MIT Emanuel cumulus parameterization scheme.