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$2\times CO_2$ Eastern Asia regional responses in the RSM/CCM3 modeling system

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Abstract

A global to regional modeling system has been developed to evaluate precipitation under doubled CO_2. The National Centers for Environmental Prediction (NCEP) regional spectral model (RSM) is initialized and forced by current and doubled CO_2 simulations from the NCAR community climate model (CCM3). Three RSM simulations, RSM0, RSM1, and RSM2, with resolution of 280, 50 and 15 km, are examined. The RSM0 setup resolution matches the T42 CCM3 simulations. The RSM2 simulation is centered over Taiwan. Due to incompatibility of the model physics, noticeable differences between RSM0 and CCM3 are found, especially in wintertime, which suggests that simulation from RSM0, rather than CCM3, should be used to contrast high-resolution regional variations produced by RSM1 or RSM2 simulations.

While the spatial distributions of RSM1 and RSM2 simulations over Taiwan are greatly improved over the CCM3 simulation, the intensity of the unique wintertime drizzle is overestimated, especially in RSM2. There is also a spurious northward extension of the precipitation pattern from the subtropical warm-pool region. Thus the regional response to doubled CO_2, which consists of more summerlike wintertime precipitation characteristics over the northeastern and eastern sides of Taiwan, with increased intensity mostly in the extreme events, is still in doubt and must be examined with improved global and regional models.

Keywords: Global change; Precipitation; Climate dynamics; Mesoscale meteorology

1. Introduction

Developing regional applications of climate simulations has been difficult, in part due to the uncertainty of interpreting coarse resolution global model simulation to regional scales. This downscaling problem has been attacked by attempting to resolve some of the small-scale climatic features with a regional model (e.g., Giorgi and Bates, 1989; Marinucci and Giorgi, 1992; Horel et al., 1994; Soong and Kim, 1996; Chen et al., 1999; Takle et al., 1999; Roads and Chen, 2000; Anderson et al., 2001). Despite problems, Dickinson et al. (1989) and Giorgi et al. (1992) have developed studies of regional changes with doubled CO_2 over the US and Europe.

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These previous studies have demonstrated the difficulty distinguishing features generated by regional model high-resolution dynamics from those generated by the incompatibility of the model physics in the global and the embedded regional model. One recurring problem is that most regional models have physical parameterization schemes that differ from the driving global model causing a large mismatch. The resulting regional circulation and most importantly the precipitation have a systematic bias in response to the constant large-scale forcing, even when the forcing is only applied on the lateral boundary. The consequence of this bias is that it can give rise to a spurious regional bias, which is not necessarily small scale. This bias makes the interpretation of regional downscaling variations confusing. This uncertainty is especially severe for global change regional assessment when there is no data to validate the simulation.

To study the uncertainty arising from the use of different physical parameterizations in the global and regional models, we use the latest NCAR community climate model global climate change scenario simulations to drive the NCEP regional spectral model over Eastern Asia. Evaluation of the regional simulation involves regional model runs at 280, 50 and 15 km resolutions. The 15-km simulation is validated in terms of spatial as well as statistical characteristics against observed station precipitation over the island of Taiwan.

2. Global to regional modeling system

Interested readers should refer to Kiehl et al. (1998) for a full description of the NCAR community climate model (CCM3), and Hack et al. (1998) for comparisons of this model to observations. Briefly, CCM3 is a global spectral model with triangular 42 (~ 280 km) resolution. CCM3 employs state-of-the-art atmospheric physics and has been coupled to a simple mixed-layer ocean model. As discussed by Marshall et al. (1997), CCM3 has an improved hydrologic cycle. Kothavala et al. (1999) further suggest that in comparison to previous NCAR models, CCM3 has a somewhat reduced sensitivity in surface temperature in response to the increase of atmospheric CO_2 concentration.

The regional spectral model (RSM) was originally developed at the National Centers for Environmental Prediction (NCEP) by Juang and Kanamitsu (1994). We have already used this model for various regional climate studies (Chen et al., 1999; Roads and Chen, 2000; Anderson et al., 2001). Interested readers should refer to these papers for more details. Briefly, the model physical parameterizations are identical to the NCEP's global spectral model (GSM) which has been used for the NCEP/NCAR reanalysis (Kalnay et al., 1996). A sigma model vertical coordinate, unlike the hybrid vertical coordinate in the driving GSM, is used. Since all model variables are expressed as a sum of the imposing large-scale (global or coarser regional) model field and its perturbation, in absence of any regional forcing (e.g., higher resolution orography), the total RSM solution should be identical to the GSM.

Multi-nesting of the RSM simulation was utilized. Fig. 1 shows all three regional domains, referred to as RSM0, RSM1, and RSM2. The largest domain, RSM0, has a 280-km resolution similar to the driving CCM3. Due to the Mercator grid of the regional model, the regional grids away from the center region are slightly different from those in the T42 CCM3 (marked with " + "s). However, this difference is rather small and the RSM0 can be considered as a regional simulation with T42 resolution over this area. The RSM1 domain with 50-km resolution covers southeastern China and is centered over Taiwan. Both RSM0 and RSM1 simulations are driven by the imposing twice daily CCM3 circulation at the boundary and interior (see Chen et al., 1999 for discussion). The RSM2 nested within RSM1 has a resolution of 15 km, and is initialized and forced by the RSM1 simulation.

The nesting method for the CCM3/RSM system (as well as for the multi-nesting system) is a one-way noninteractive system. Because the RSM was originally developed to use the NCEP GSM output, a number of technical difficulties had to be hurdled to allow the RSM to utilize the CCM3 output, which does not provide the same variables nor have the same vertical coordinates and structure as the RSM. As a result, atmospheric variables were re-interpolated first from CCM3's hybrid vertical coordinate to RSM's sigma coordinate.

A number of other techniques were applied to overcome the inherent mismatches between the global and regional models. Due to the original simple linear

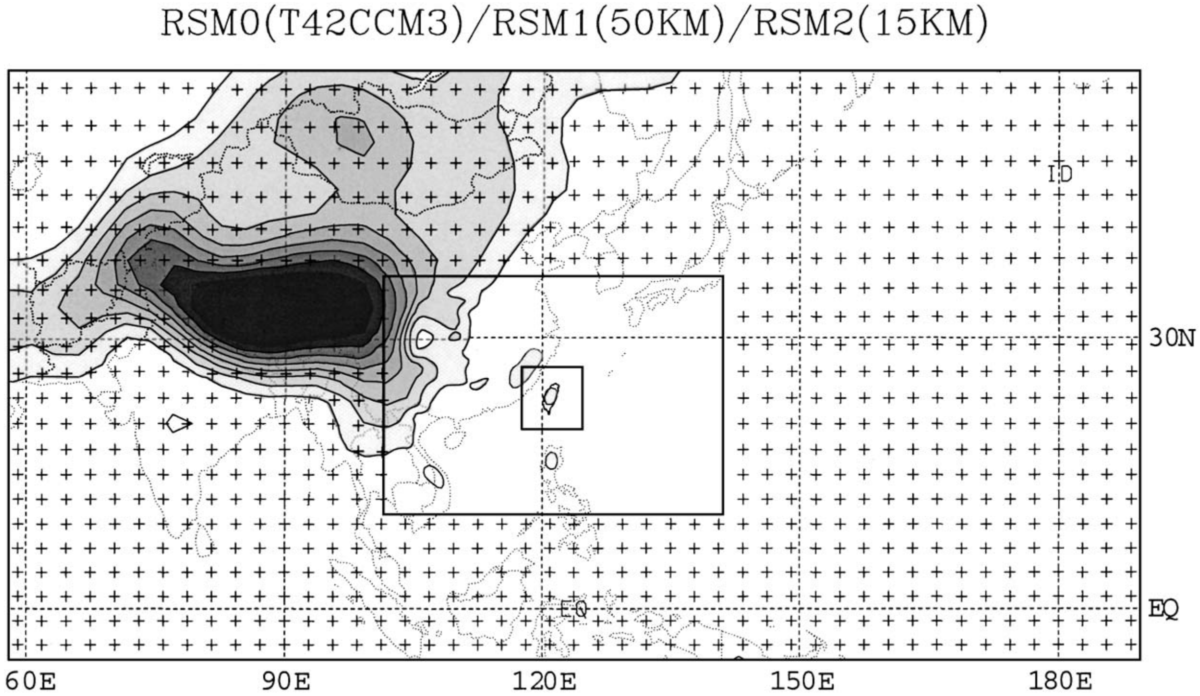

Fig. 1. The regional domain of RSM0, RSM1, and RSM2, centered around Taiwan Island, with resolution of 280, 50, and 15 km, respectively. The outer most RSM0 domain has an effective T42 CCM3 resolution with the T42 grids marked with " + "s. The corresponding orography is plotted with 500-m contour interval.

interpolation to regional grids, the sharp land–sea contrast of the surface variables was poorly represented; a newer interpolation scheme has now been implemented to better include the high-resolution land–sea interface. An unrealistic high bias ground and deep soil temperature in the regional model, caused by the changes of surface elevation, was dry-adiabatically adjusted. Again, the physical parameterizations in CCM3 are equivalent but not exactly the same as those of the RSM.

All RSM runs are initialized at the beginning of each corresponding season, and continuously integrated for a season by updating the large-scale circulation every 12 h. Due to the immense regional model computing time required, we only used the last 10 summer and 10 winter seasons from two equilibrium 30 years runs of control (at present day CO_2 concentration 355 ppmv) and $2 \times CO_2$ (710 ppmv) CCM3 experiments to initialize and force the regional model. Hereafter, we refer to these two experiments as CTL and 710 runs. This may be insufficient to study the interannual or longer climate variability under doubling CO_2 scenarios; however, it is quite sufficient to establish climatology, sensitivity experiments, and some examination of the regional modeling problems.

3. Control simulation

Fig. 2 shows the December–January–February (DJF) precipitation and the vertically integrated moisture flux from reanalysis (Kalnay et al., 1996), and CTL simulations of CCM3, RSM0, and RSM1. The CCM3 CTL run shows an anticyclonic gyre of moisture transport over southeastern Asia and a broad precipitation feature, especially over subtropical ocean, which is similar to the reanalysis shown in Figure 2a. The RSM0 run has moisture transport and precipitation patterns, except a bit more intense precipitation in the subtropical ocean and northward extension. The RSM1 (Fig. 2d) moisture fluxes are similar to that of CCM3/RSM0, the precipitation

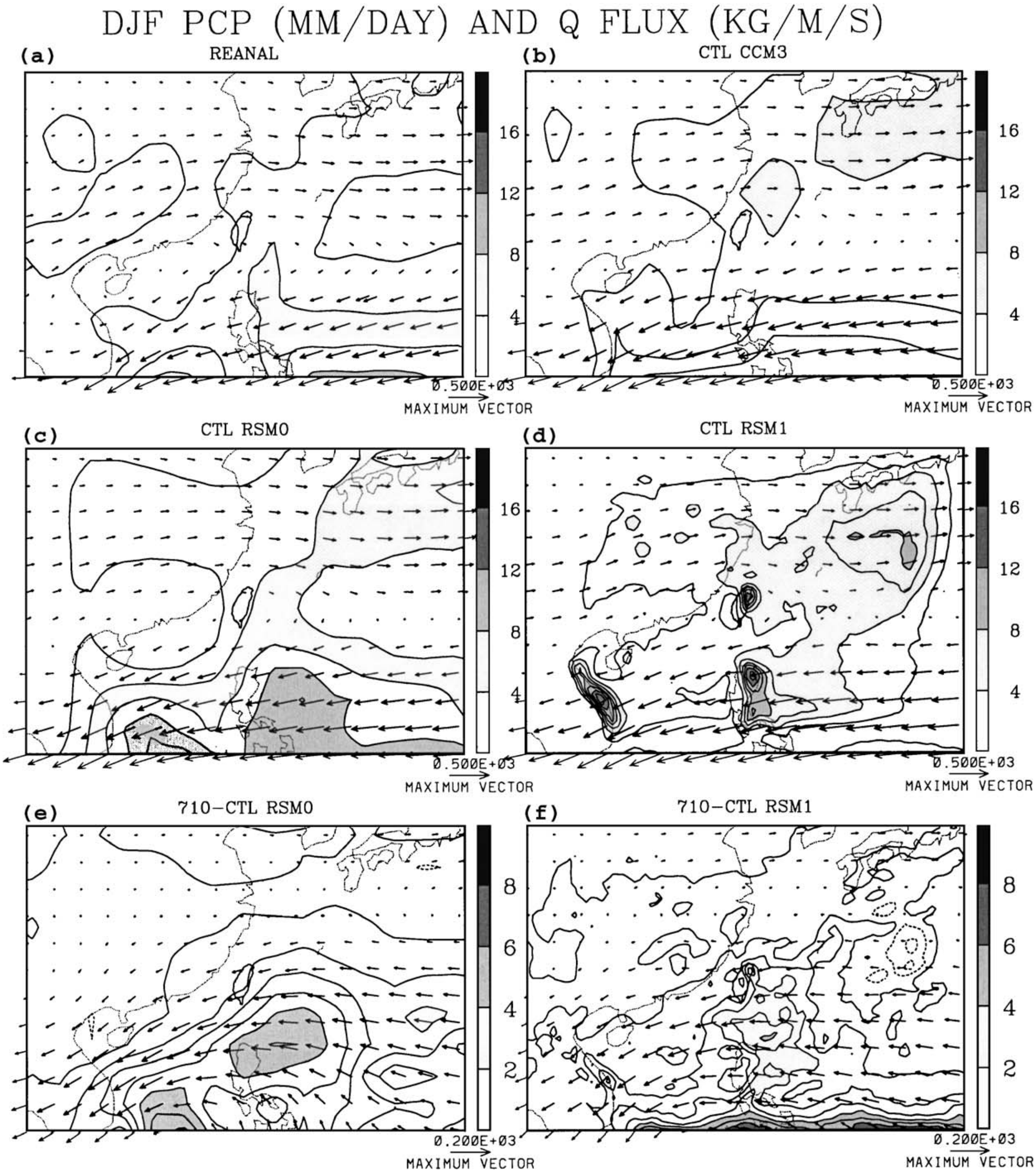

Fig. 2. December–January–February (DJF) precipitation and vertical integrated moisture flux over RSM1 domain for (a) reanalysis; (b) CTL CCM3; (c) CTL RSM0; (d) CTL RSM1; (e) differences between 710 and CTL runs in RSM0; and (f) in RSM1. The precipitation contour interval is 2 mm day^{-1} with 4 mm day^{-1} shading interval. The unit of the moisture flux vector is kg m^{-1} s^{-1}.

patterns merely demonstrate regional variations. Heavy precipitation centers are evident where the easterly moisture flux impinges on the regional orography (e.g., northeastern Taiwan, eastern Philippines, eastern Vietnam). The wintertime storm tracks in the area from just offshore China to Japan have also been intensified.

Obvious wintertime simulation defects occur along the oceanic lateral boundary where the RSM1 has less precipitation, in part because the nudging process forces the RSM circulation fields, but not precipitation, toward those of CCM3's. However, there could be other problems associated with the divergent circulation. Summertime simulations (not shown) reveal more problems. The center of the CCM3 southerly moisture transport moves inland of China in the RSM, instead of along the east coast. The RSM0 and RSM1 were not able to improve this poorly simulated CCM3 feature. They faithfully emulate the CCM3 and even enhance the easterlies just north of the southern boundary.

4. Sensitivity experiment

Sensitivity simulations with $2 \times CO_2$ are shown in Fig. 2e, f. Fig. 2e clearly shows that the $2 \times CO_2$ RSM wintertime runs intensify the easterly fluxes along with a northward extension of excess precipitation reaching Taiwan. The RSM1 simulation reveals a similar picture but with more regional details.

While taking the difference of the 710 and CTL runs is a common and logical methodology for the global modeling sensitivity experiment, the method is

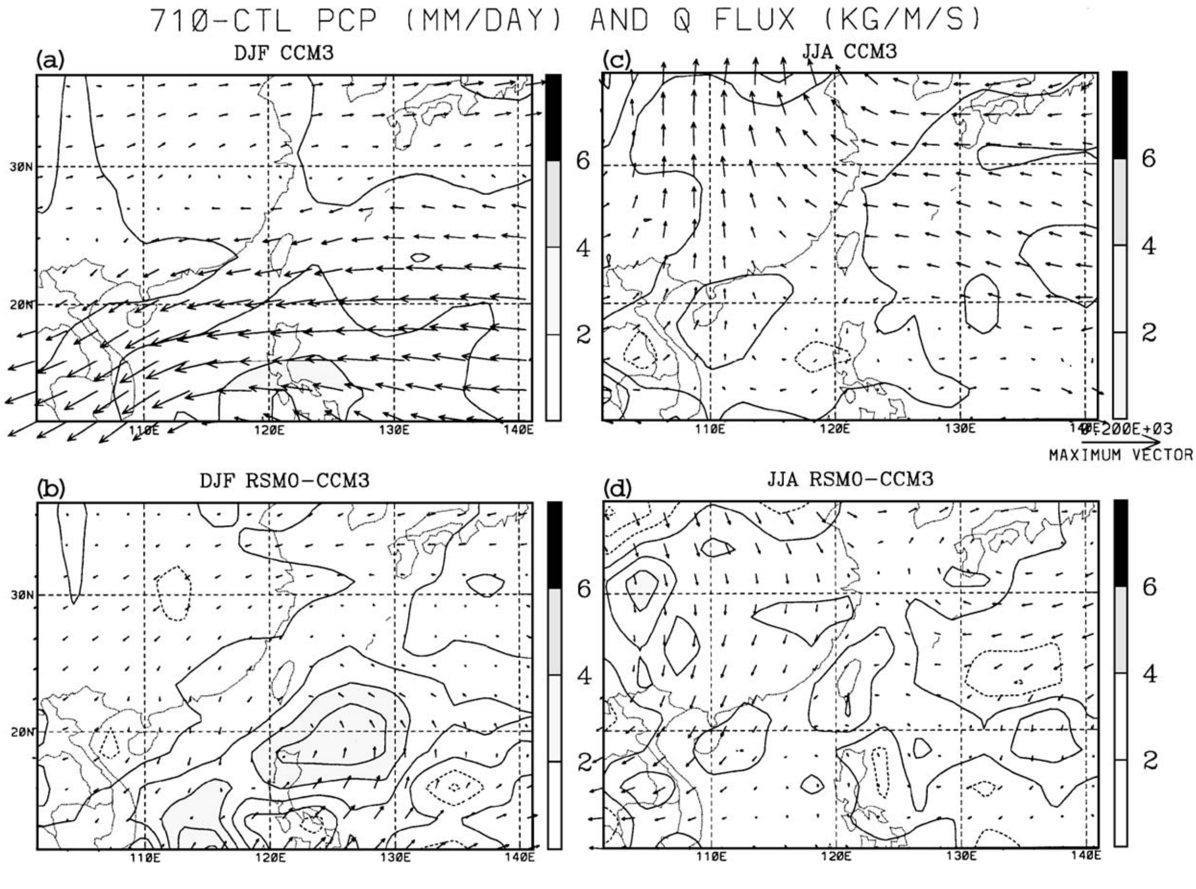

Fig. 3. The DJF simulated precipitation and vertical integrated moisture flux difference between the 710 and CTL runs for (a) CCM3; and (b) the systematic difference between RSM0 and CCM3. Those for JJA are given in (c) and (d).

rather questionable in regional modeling. Since all models are subject to modeling bias, it is thus assumed that the bias in the control and experiment runs is similar, and hence the bias difference is relatively small compared to the sensitivity signal we are trying to identify. As shown in Fig. 3, this is not the case when two models (global and regional), whose physical parameterization schemes are different in many aspects, are compared. For example, for DJF, the 710 minus CTL runs in CCM3 (Fig. 3a) has a maximum precipitation difference over central Philippines. However, this center is displaced northward

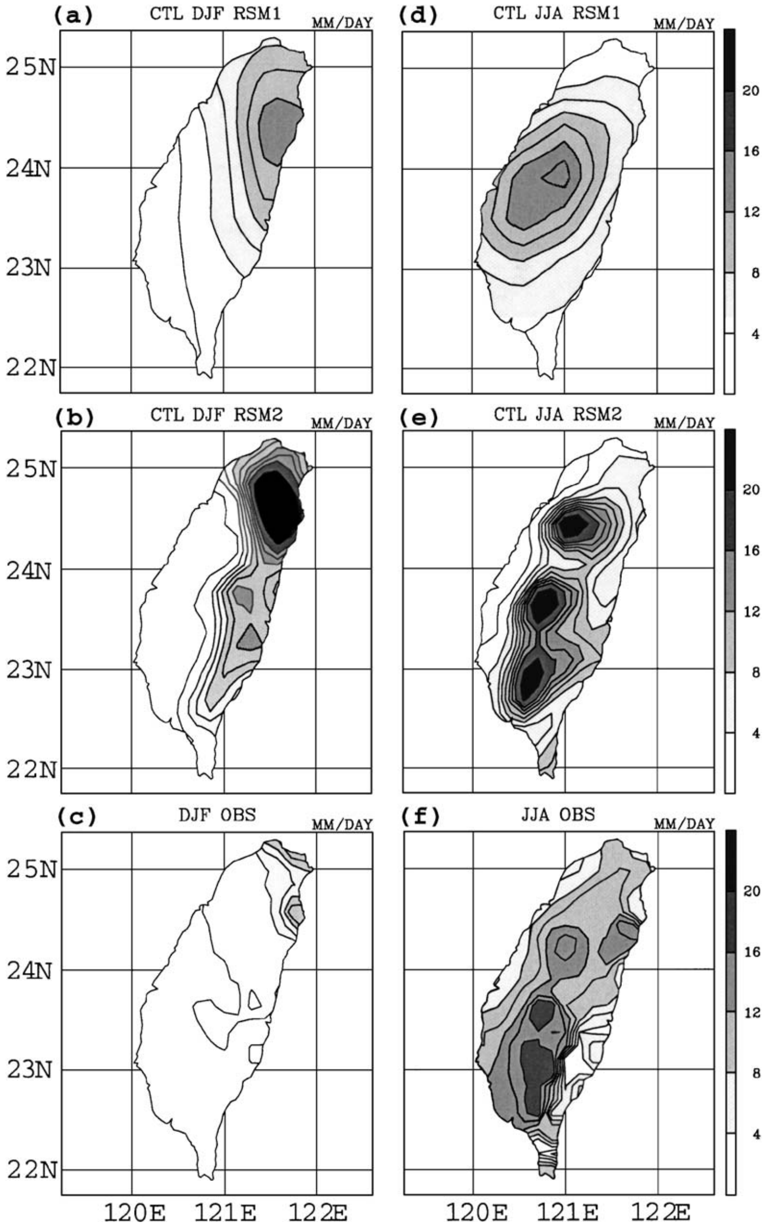

Fig. 4. DJF precipitation over Taiwan Island for (a) CTL RSM1; (b) CTL RSM2; and (c) DJF station observation. Those for JJA are given in (d), (e) and (f). The contour interval is 2 mm day^{-1} with shading interval of 4 mm day^{-1}.

and offshore in RSM0 (Fig. 2e). As a result, the differences of the CO_2 sensitivity in RSM0−CCM3 (Fig. 3b) indicates a maximum center, which is supported by a southerly transport of moisture, as large as the original signal in Fig. 3a. The implication of this is that RSM1 (Fig. 2f) is actually the regionally enhanced model bias (Fig. 3b), rather than the regional enhancement of the $2 \times CO_2$ signal. In summertime the $2 \times CO_2$ signal is weak in Fig. 3c as well as in Fig. 3d.

5. Validations

Despite the obvious problems in the RSM0 and RSM1 regional simulations, comparisons of RSM2 results with the available observation can reveal additional model capabilities and problems. Fig. 4 shows the precipitation of RSM1 and RSM2 from the CTL runs, along with the observed station observation over the region of Taiwan. There are 365 surface stations throughout the island. Simple aggregation of available

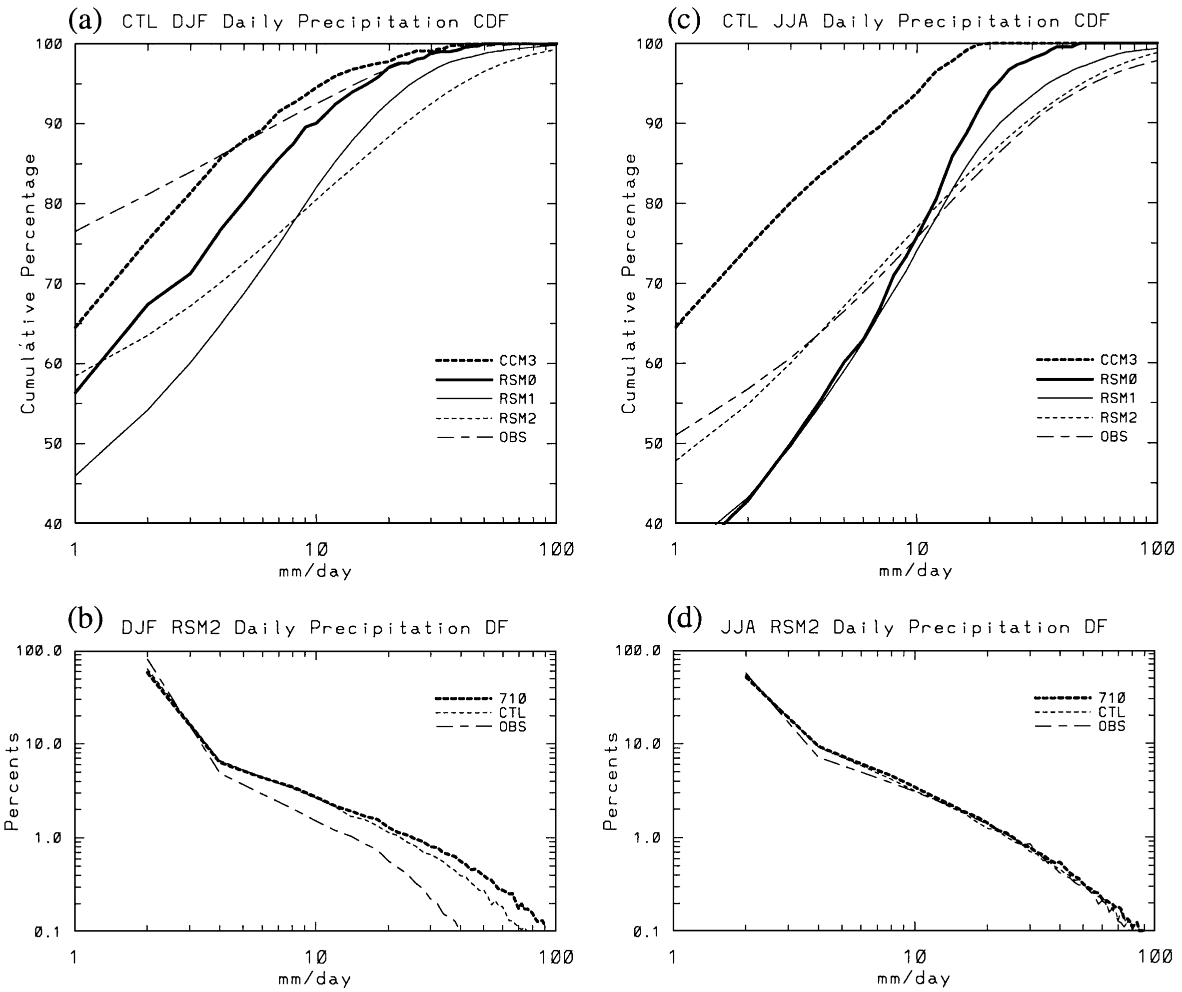

Fig. 5. DJF (a) cumulative distribution function (CDF) of daily precipitation for CCM3 (thick dashed line), RSM0 (thick solid line), RSM1 (thin solid line), RSM2 (thin dashed line), and station observation (thin dash-dotted line); (b) density function (DF) for RSM2 from 710 (thick dashed line), CTL (thin line), and station observation (thin dash-dotted line). The threshold precipitation rate on the logarithmic abscissa is in units of mm day^{-1}. Those for JJA are given in (c) and (d).

station hourly precipitation within a RSM2 grid box are averaged and assigned to the RSM2 grid. Data was available for the period of 1987 through 1999 for the evaluation. Compared to observations, both simulated seasons show correct seasonal variation of precipitation patterns. Taiwan has a north–south elongated central mountain range in the center (barely visible in Fig. 1). During the wintertime, shallow northeasterly (not shown) surface winds impinge upon the mountains, producing a windward side drizzle. In summertime, most of the rainfall is convective, particularly in the mountains. Note that both CCM3 and RSM0 cannot properly resolve this spatial distribution of rainfall since there is only one grid point over the entire island (see Fig. 1). The higher resolution simulation clearly improves the spatial distribution of rainfall patterns. However, there are some noticeable modeling deficiencies. For example, the precipitation was overestimated when the resolution increased. This might be due to the use of horizontal diffusion on constant model sigma surface. Warm, humid air is artificially piled up over the mountain summit and induces excess precipitation by the large-scale condensation scheme of the model. We intend to improve this simulation by replacing the sigma surface diffusion by pressure surface diffusion in future simulations.

To examine characteristics of the precipitation intensity, Fig. 5 shows the cumulative percentage of the daily precipitation over the island of Taiwan for all runs as well as station observation. During the summer (Fig. 5c), the higher resolution RSM simulations improve the precipitation intensity distribution. The comparison of the 710 and CTL RSM2 runs (Fig. 5d) basically shows no changes under the doubled CO_2 scenarios. However, during the wintertime (Fig. 5a), none of the simulations (CCM3, RSM0, RSM1 and RSM2) agree well with the observation. In fact, all RSM runs show more rainy days (lower intercept at 1 mm day^{-1}) than actually observed. It is not clear at this point that this is a bias due to the northward displacement of the Philippines precipitation maximum (Fig. 2c), or due to the overestimated diffusion physics, mentioned previously. Ironically, the wintertime RSM2 precipitation (Fig. 5b) shows a more summerlike rainfall, under the doubled CO_2 scenario, despite a large bias in the extreme rainfall part of the distribution.

6. Conclusions

A global CCM3 to regional RSM modeling experiment was developed in order to investigate Eastern Asia regional impacts under doubled CO_2. Three RSM setups, RSM0, RSM1, and RSM2, which had resolutions of 280, 50 and 15 km, respectively, were used. The RSM0 setup had effective resolution similar to the T42 CCM3 simulations. RSM2 simulations over the Taiwan Island were used to examine seasonal precipitation characteristics caused by the underlying complex terrain and large-scale patterns.

It was shown that the embedded regional model was useful to translate the global large-scale patterns of circulation and precipitation into more regional details. However, since there were different model physical parameterizations in the global and the regional models, it was difficult to tell whether the regional details were produced by the high-resolution model and topographic resolutions or by a mismatch of models' physics. We tried to demonstrate why it was critical to quantify this incompatibility from the regional model results before attempting to interpret the regional model sensitivity experiments. We found, with the help of RSM0, that the high resolution, 50 km or even 15 km, doubled CO^2 regional impacts could be spurious.

Validation of the control precipitation simulation over the RSM2 domain further revealed that geographical distribution, seasonal transition, and rainfall intensity distribution were largely improved when the resolution becomes higher. However, the defects from the regional model physics or the intrinsic incompatibility between the regional and global models are clearly illustrated by the simulations of excessive precipitation at high resolution. Given this clear model deficiency, the increased wintertime heavy rainfall—found in the doubled CO_2 high resolution runs—remains doubtful. Further analysis and simulation is needed.

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