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On the role of resolution and topography in the simulation of East Asia precipitation

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With 9 Figures

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Summary

In this paper, we investigate the role that horizontal resolution plays in the simulation of East Asia precipitation. Two sets of numerical experiments are performed using the Regional Climate Model (RegCM2) nested in one-way mode within the CSIRO global coupled atmosphere-ocean model. In the first set we use the actual RegCM2 topography at the selected model resolutions, which are 45, 60, 90, 120, 180, 240 and 360 km. In the second set of the experiments, the same coarse CSIRO model topography is used in all simulations using the different resolutions of the first set. The results demonstrate that the simulation of East Asian precipitation improves as the horizontal resolution is increased. Moreover, it is shown that the simulations using a higher resolution along with the coarse CSIRO topography perform better than the simulations using a coarser model resolution with corresponding model topography. This suggests that over East Asia adequate spatial resolution to resolve the physical and dynamical processes is more important than topography. Lastly, the results indicate that model resolutions of 60 km or higher are needed to accurately simulate the distribution of precipitation over China and East Asia.

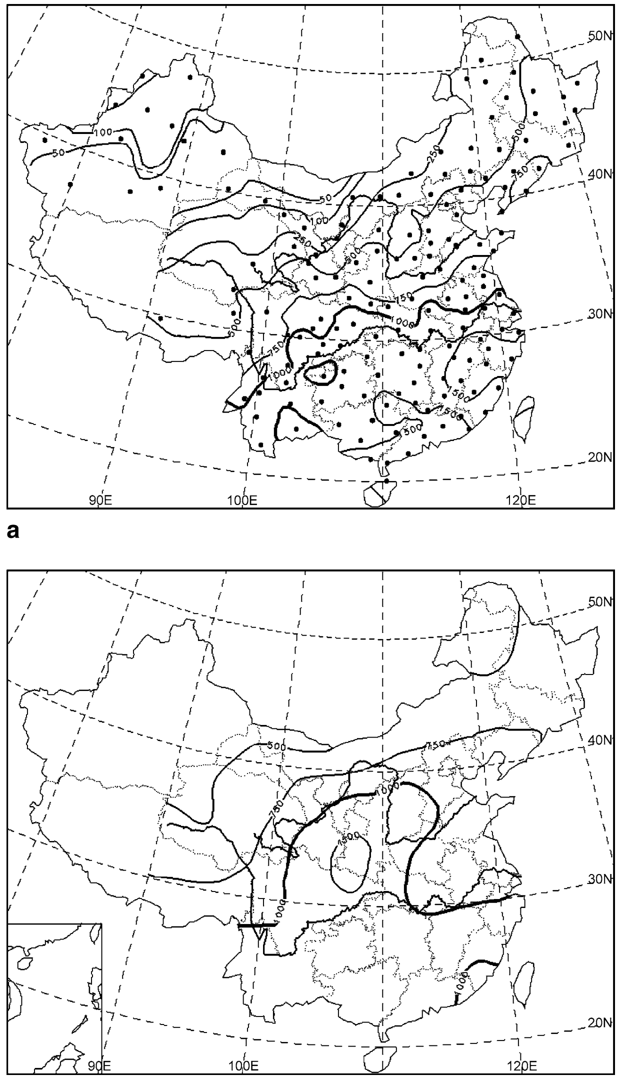
1. Introduction

The need to provide fine scale regional climate information usable for impact assessment studies has recently given a strong impetus to the development of global and regional climate models (RCMs) with increasing horizontal resolution (e.g. Giorgi et al., 2001). The horizontal resolution of numerical models is extremely important for the simulation of surface climate. The surface climate signal is in fact strongly influenced by fine scale forcings, such as topography and land use distribution (Giorgi and Mearns, 1991). In addition, higher resolution allows to better simulate the fine scale structure of synoptic and mesoscale systems which characterize the climate of a region (e.g. Leung et al., 1996; Machenhauer et al., 1998; Christensen and Kuhry, 2000).

The increase in resolution of global atmospheric models has been shown to improve the representation of major features of the general circulation, such as mid-latitude storm tracks, the positioning and seasonal migration of the Intertropical Convergence Zone (ITCZ), or the genesis and evolution of tropical storms (e.g. Boville, 1991; Bengtsson et al., 1995; Stratton, 1999). Because of their potential to reach relatively high horizontal resolutions, RCMs have today become a widely used tool for regional climate studies (Giorgi and Mearns, 1999). Similarly to GCMs, increasing resolution in RCMs generally leads to a better description of surface climate features as forced by topographical detail (Marinucci et al., 1995; Christensen and Kuhry, 2000; Leung and Qian, 2003). On the other hand, previous studies have indicated that the RCM sensitivity to resolution is due not only to the description of topographical detail, but also to the direct sensitivity of the model physics and dynamics to resolution (Giorgi and Marinucci, 1996a). Because models are used at a wide range of spatial scales for different applications it is thus important to understand the importance of resolution in a climate simulation and within this context, the relative role played by the description of forcings (e.g. topography) vs. the dynamics and physics of the model.

In this paper we present a study of the effect of horizontal resolution in a nested regional climate simulation of precipitation over East Asia. This precipitation is mostly controlled by the development of the East Asia monsoon. Between October and April the rain belt over East Asia is usually stationary, with its center located around 28° N over southeast China. In May and June the precipitation band moves quickly to the Yangtze and Huai River Region (around 32–34° N) where it resides until July. This time period is usually called the Meiyu or Baiu season. In August the rain belt shifts to northern China where the rain season begins. Finally, towards the end of August the rain belt retreats quickly back to southeast China. Precipitation in May–June–July–August–September accounts for 60–85% of the annual total over most of China. The mean annual precipitation over China is shown in Fig. 1a (1961–1990 mean), based on 160 Chinese station observations (black dots indicate the location of the stations). This precipitation is characterized by maxima over south and south-east China and a decrease towards the north and northwest. In the figure, the 1000 mm isoline is located slightly north of the Yangtze River while the 1500 mm isoline lies over the south and southeast coastal areas.

Traditionally, General Circulation Models (GCMs) have shown a poor performance in simulating the East Asia monsoon precipitation patterns. The precipitation center simulated by GCMs is usually located too far north over central China. For example, this behavior can be observed in simulations performed with the CSIRO R21L9 GCM (Fig. 1b, from Gao et al., 2000) and the NCAR CCM3 model (Gao et al.,



a

b

Fig. 1. Annual mean precipitaion in China (unit: mm). **a** Observation (1961–1990, black dots are locations of the 160 Chinese stations used in the paper). **b** Simulation by CSIRO AOGCM

2004). Figure 1b shows that the eastward extension of the 1000 mm precipitation isoline simulated by the CSIRO GCM is located near the lower reaches of the Yangtze River, but it reaches too far north and west. In addition, the simulated precipitation maximum (1500 mm isoline) is located over central China rather than south China.

To what extent is this problem related to the model's horizontal resolution and can a nested high resolution RCM improve the simulation of East Asia precipitation? In this paper we investigate this question by performing a series of nested RCM simulations at increasingly high horizontal resolutions driven by large scale fields obtained from the CSIRO AOGCM. We then investigate the relative role of the topography representation by repeating this set of experiment with the RCM using the coarse scale CSIRO topography and comparing results from the two sets of simulations. We focus on the RCM sensitivity because demonstrating the capability of RCMs to improve upon the driving GCM provides useful information on the issue of the "added value" of using nested RCMs for downscaling purposes (Giorgi et al., 2001).

In the next section we first describe the models and experiment design, which is crucial for our study. In Sect. 3 we then analyze our results, with particular emphasis on the elucidation of the role of topography vs. resolution. Summary and concluding remarks are finally presented in Sect. 4.

2. Model description and experiment design

In this study, we use a modified version of the National Center for Atmospheric Research's (NCAR) Regional Climate Model version 2 (RegCM2) to investigate the key questions brought forth in the introduction. The original model was developed by Giorgi et al. (1993a, b) and includes some of the modifications presented in Giorgi and Shields (1999).

The dynamical core of RegCM2 is based on the hydrostatic version of the Penn State/NCAR Mesoscale Model version 5 (Grell et al., 1994). The atmospheric radiative transfer computations are performed using the package from the NCAR Community Climate Model CCM2 (Briegleb, 1992), and the planetary boundary layer computations employ the non-local formulation of Holtslag et al. (1990). Surface processes are carried out with the Biosphere–Atmosphere Trans-

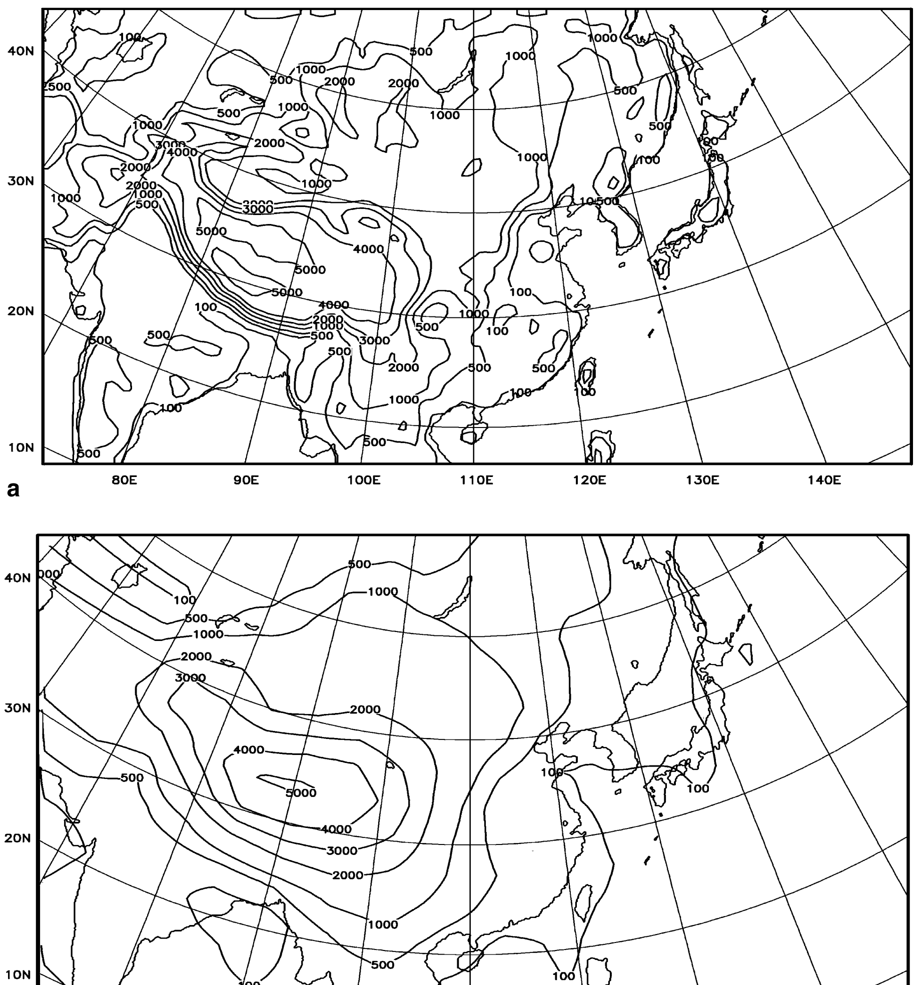


Fig. 2. Model domain and 60 km resolution topography for real topography (**a**) and GCM topography (**b**) (unit of topography: m)

fer Scheme (Dickinson et al., 1993) and resolvable scale precipitation is represented via the simplified explicit scheme described by Giorgi and Marinucci (1996b) and Giorgi and Shields (1999), which includes a prognostic equation for cloud water content. Lastly, the mass flux scheme of Grell (1993) with the Arakawa and Schubert (1970) closure assumption is used to describe convective precipitation.

The model domain used in the simulations is shown in Fig. 2. It encompasses a large area including East Asia, most of India and the Himalayas. This domain is much larger than in previous studies such as by Giorgi et al. (1999). This is because large domains better allow the nested model to develop its own circulation structure in the interior of the domain (Giorgi et al., 2001) and are thus more suitable to study the model sensitivity to resolution and topography. The model also employs sixteen vertical sigma layers and a model top of 10 hPa. This is the same model configuration originally used by Gao et al. (2000).

The initial conditions and time-dependent (12-hourly) lateral boundary conditions used to drive the RegCM are derived from present day climate simulations performed with the CSIRO AOGCM version R21L9 as in the previous work of Gao et al. (2001, 2002, 2003). The atmospheric component of the CSIRO AOGCM has a horizontal spectral resolution of R21. In one of its climate change simulations, it was integrated for the period 1881–2100 using observed GHG forcing until 1990 and a 1% per year GHG concentration increase between 1990 and 2100 (Gordon and O'Farrel, 1997). Out of this 220 year simulation period, the 5-year period of 1986–1990 was selected for the present sensitivity experiments. Note that the 5-year precipitation climatology of the CSIRO model over this region is very close to its 30-year climatology (1961–1990), as shown by Xu et al. (2002).

To investigate the role of horizontal resolution, two sets of RegCM2 numerical experiments are performed. In the first set, we use horizontal grid point spacings of 45, 60, 90, 120, 180, 240 and 360 km to cover approximately the same domain as described above. Hereafter these experiments are referred to as RT45, RT60, RT90, RT120, RT180, RT240, and RT360, respectively. RegCM2 model topography and land use calculated for each model grid and resolution are used in the different experiments, which are therefore referred to as "RCM Topography" experiments.

In the second set of simulations, hereafter referred to as "GCM Topography" experiments, the coarse CSIRO model topography is used in place of the RCM model topography for each of the different resolutions (except for the 45 km one, which was not performed because of computer resource limitations). These experiments, which therefore all use the same GCM topography, are referred to as GT60, GT90, GT120, GT180, GT240, and GT360, respectively. Comparison of the RCM Topography and GCM Topography experiments therefore allows us to identify the role of topography vs. resolution in the simulations. As illustrative examples, the topography fields of the RT60 and GT60 experiments over the domain are compared in Fig. 2.

All the model settings are kept the same in the experiments except for the grid spacing and time step. The lateral buffer zone has approximately the same extension in all experiments (about 900 km) and all simulations are 5 years in length and are driven at the lateral boundaries by the same fields from the CSIRO model. For convenience of data analysis, the model output is interpolated onto the 160 Chinese station locations used by Gao et al. (2001, 2002, 2003), where we have available accurate long-term climatological data (see Fig. 1a).

3. Analysis of the results

3.1 Simulated annual mean spatial precipitation patterns in the RCM topography experiments

Figure 3 shows the simulated annual mean precipitation for each of the RCM Topography experiments (except for RT45, which was similar to RT60). At the coarsest resolution (RT360, Fig. 3f), the precipitation distribution resembles that of the CSIRO simulation (Fig. 1b); the precipitation center is located over Central China which, as mentioned above, is considerably north and west of the observed (Fig. 1a). However, as the resolution increases (RT360 to RT60, Fig. 3f to 3a), the rain center shifts gradually to south/southeast China and becomes much closer to the observed. The highest resolution simulation

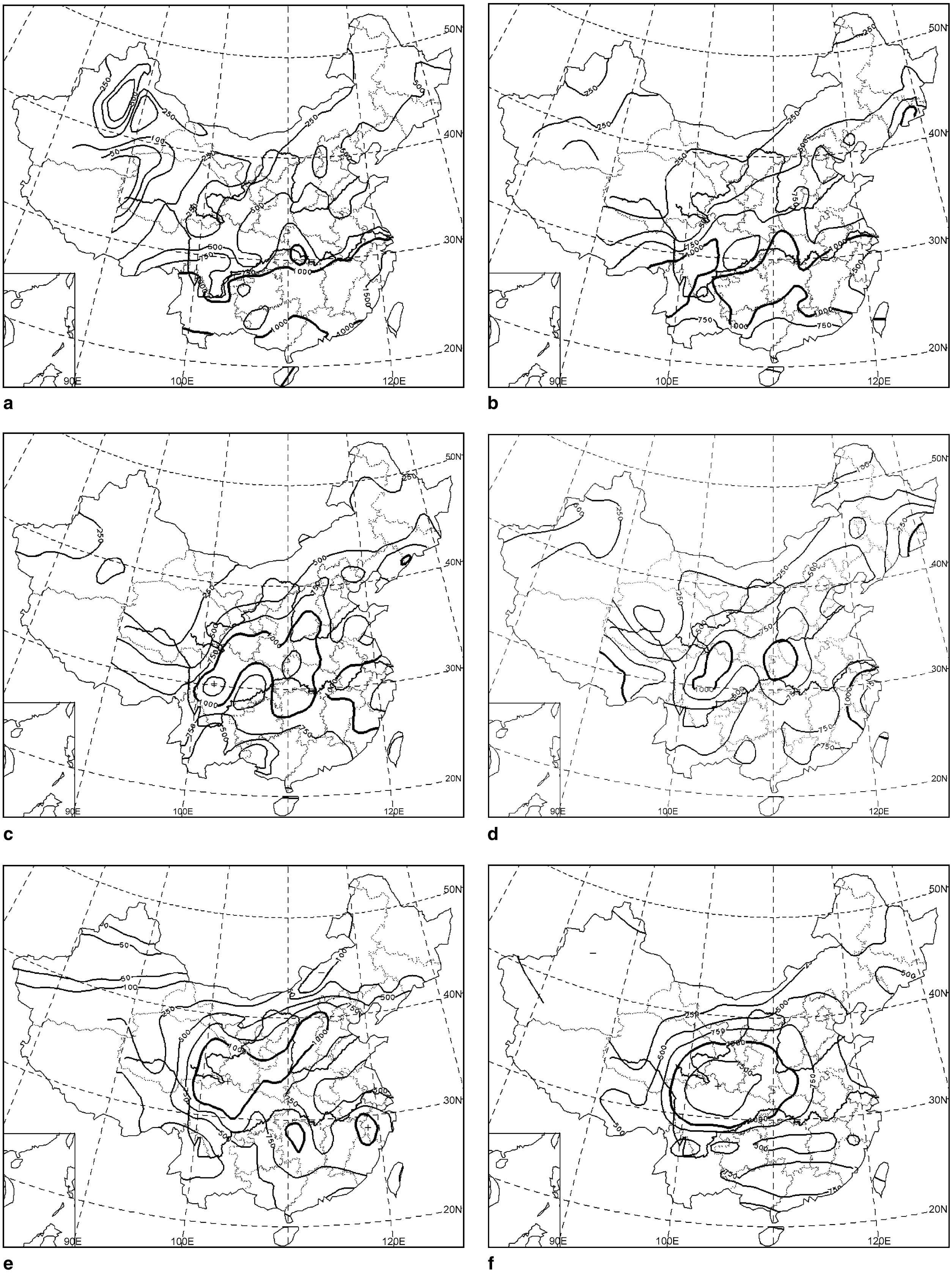
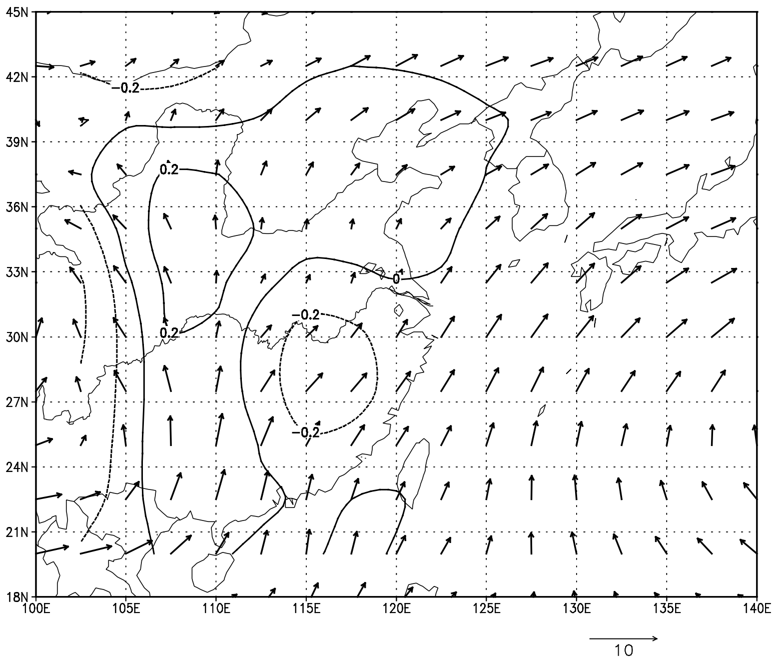


Fig. 3. Simulated annual mean precipitation by different resolutions of RegCM using real topography (unit: mm). **a** RT60; **b** RT90; **c** RT120; **d** RT180; **e** RT240; **f** RT360

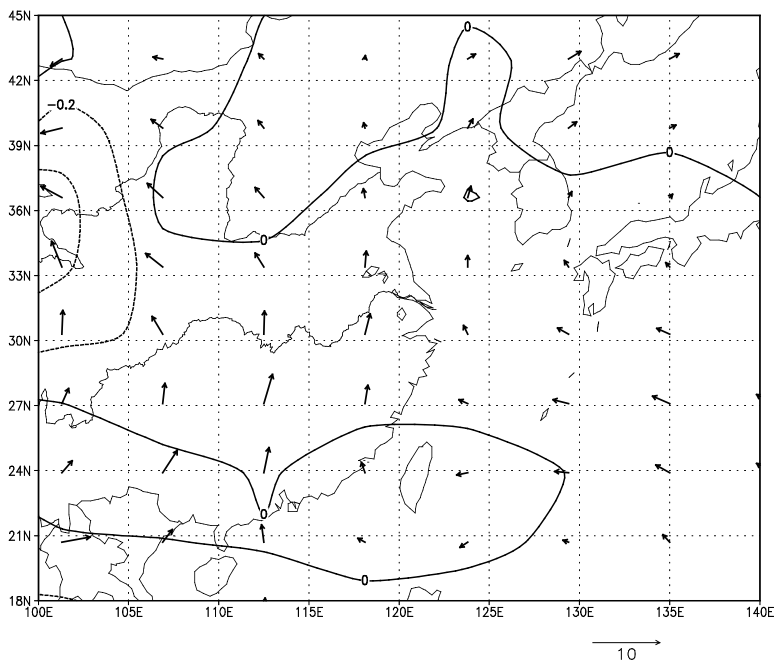
in the figure (RT60) clearly best reproduces the observations (Fig. 1a). In addition, it can be seen that increasing the resolution generally leads to an increase in spatial detail of the simulated precipitation distribution.

The improvement of the simulation can be partly explained by the improvement of the dynamical fields. Figure 4 shows the summer (JJA) mean 850 hPa wind field and the convergence field in the NCEP/NCAR Re-analysis (1971–2000 mean, a) and the simulations by the CSIRO, RT60 and RT180 (c–d). Concerning the constrain of the reanalysis by upper air observations, it is noted that there are about 130 rawinsonde stations in China, which are distributed evenly across the above mentioned 160 stations.

The Western Pacific Subtropical High (or anticyclone), which controls the monsoon weather

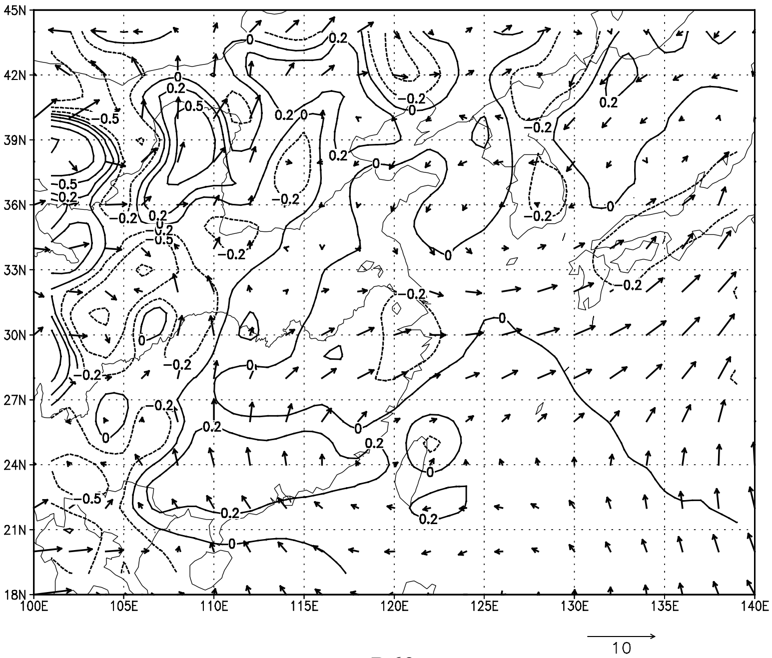


a NCEP/NCAR

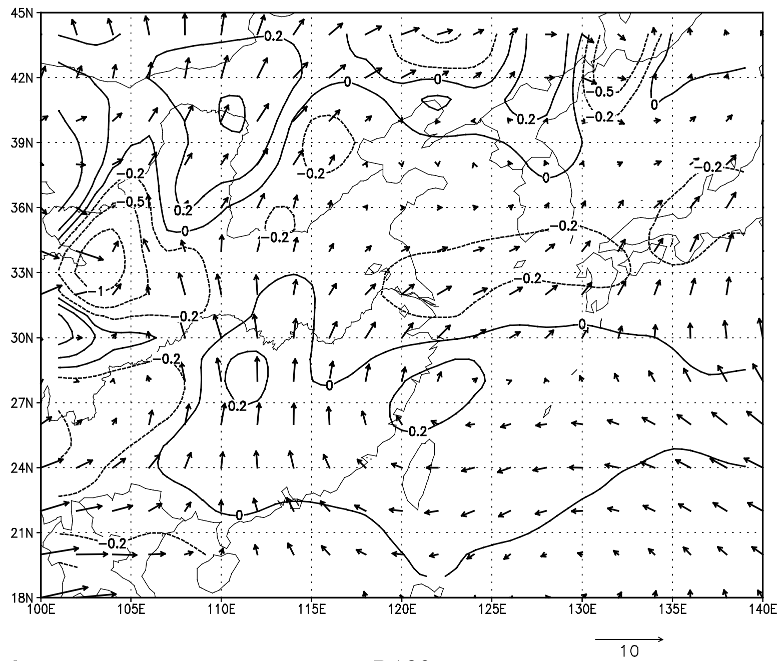


b CSIRO

Fig. 4. Summer (JJA) mean 850 hPa wind field by NCEP Reanalysis (1971–2000 mean, (**a**)), and simulation of CSIRO model (**b**), R60 (**c**) and R180 (**d**) (unit for wind: m/s; unit for convergence: $10^5\,s^{-1}$)



c R60



d R180

Fig. 4 (*continued*)

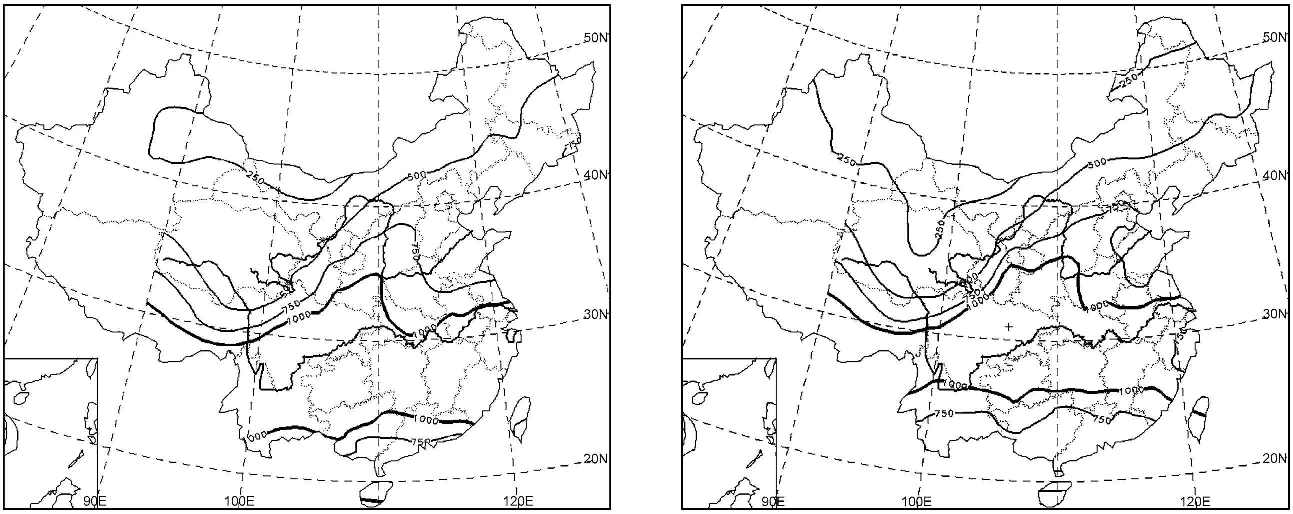
in China, can be found in the southeastern region of the NCEP/NCAR Re-analysis field of Fig. 4a. The southerly jet reverses to a south-east direction over the region 27–30° N, 115–120° E of China and generates a convergence center that leads to maximum precipitation over Central-east and Southeast China (Fig. 1a).

The anticyclone and the corresponding convergence center is not well reproduced by the CSIRO model (Fig. 4b). The southerly jet in the CSIRO simulation does not show a significant change of direction over eastern and south-east China and therefore moisture is transported too far north into central China. This causes high precipitation in correspondence of a simulated convergence center there, and lower precipitation to the south. By comparison the anticyclone and the convergence center are well simulated in the RT60 experiment (Fig. 4c), although the position of the convergence center is shifted somewhat to the north compared to the NCEP reanalysis. In the RT180 simulation (Fig. 4d), the anticyclone and the convergence center are still simulated but their locations are further north compared to the experiment RT60. A comparison across experiments indicates that, as the resolution becomes coarser, the southerly wind becomes increasingly stronger, the anticyclone weakens, and the convergence center moves to the north and northwest.

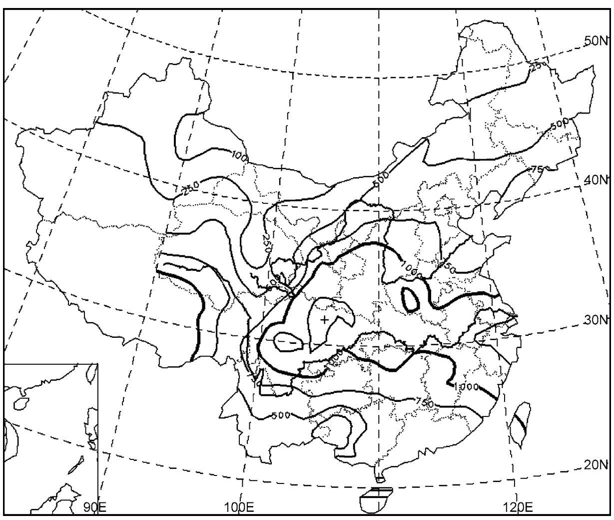
It is difficult to identify whether the impact of resolution on the dynamics is via direct mechanisms or via indirect mechanisms related to the physics. However, since summer is the main rain season over China, precipitation is probably mainly caused by sub-GCM grid mesoscale convective systems. Coarse resolution does not allow the description of these systems and therefore the moisture from the sea is not efficiently removed over the coastal regions and can more easily reach the interior of the continent (central China) and precipitate there. Further work is however needed to better elucidate this process.

3.2 Simulated annual mean spatial precipitation patterns in the GCM topography experiments

Moving to the GCM Topography experiments, the simulated annual mean precipitation for the GT60, GT90 and GT120 simulations are shown in Fig. 5. The other experiments (GT180, GT240, GT360) are not shown because at resolutions beyond 120 km the results from the GCM to-



a GT60 **b** GT90



c GT120

Fig. 5. Simulated annual mean precipitation by different resolutions of RegCM, using GCM topography (unit: mm)

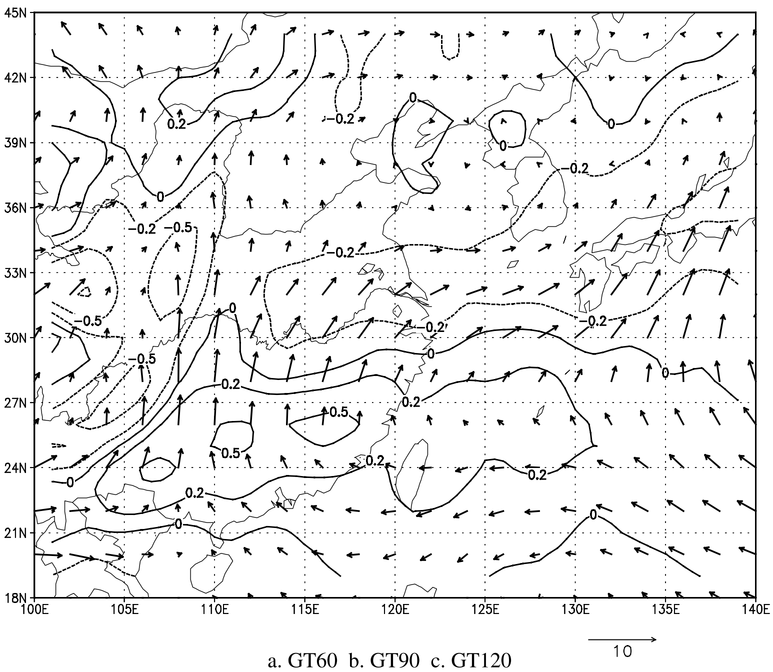


Fig. 6. Summer (JJA) mean 850 hPa wind field simulated by GT90 (unit for wind: m/s; unit for convergence: $10^5\ s^{-1}$)

pography and RCM Topography experiments resemble each other since they have similar topographies. In a way similar to the RCM Topography experiments in the GCM Topography ones, the precipitation center over central China shifts to the south as the horizontal resolution increases. However, comparison with Fig. 4 shows that at the same resolution the RCM Topography simulation provides a more accurate representation of precipitation than the equivalent GCM Topography simulation.

On the other hand, a somewhat better level of quality is seen in a GCM Topography experiment than an RCM Topography one when the horizontal resolution is one step higher. For example, the distribution of precipitation in the GT90 experiment is slightly better than that of RT120. This indicates that a model with smoothed topography but high resolution can give a better simulation than a model with lower resolution but finer scale topography. This indicates that model resolution itself, regardless of the accuracy of the topographic representation, has a strong impact on the model physics and/or dynamics which leads to a better simulation of precipitation.

Figure 6 shows the summer (JJA) mean 850 hPa wind field simulated in GT90. The anticyclone and the convergence center over southern China are simulated in a similar way as in RT60 and RT180 (Fig. 4c, d), suggesting that using a high resolution even with the coarse GCM Topography, leads to an improvement in the dynamical and physical fields compared to the CSIRO simulation (Fig. 4b).

It is interesting to note that for all resolutions, the GCM Topography runs tend to push the 1000 mm precipitation isoline towards Northern China (near the Yellow River), which appears to be a behavior associated with low resolution. By contrast the RCM Topography runs tend to keep the 1000 mm isoline contour around the Yangtze River, at least at the highest resolutions. It thus appears that the topographic forcing is important in correctly placing this precipitation feature.

It is also noted that the RCM Topography runs also simulate higher precipitation amounts over southern China, which is in closer agreement with observations.

3.3 Spatial correlation

To more quantitatively analyze the model simulation of precipitation spatial patterns, we calculate the spatial correlation coefficients between simulated and observed precipitation at the 160 stations.

3.3.1 Annual mean precipitation

The spatial correlation coefficient between the simulated and observed annual mean precipita-

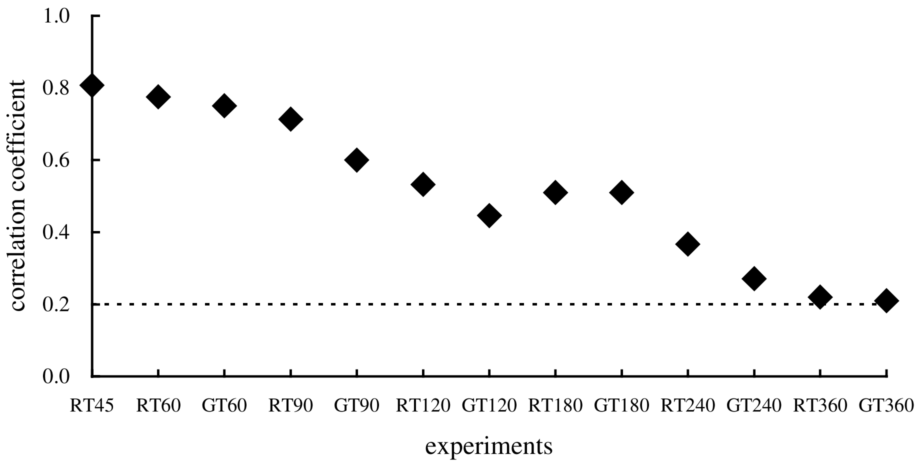


Fig. 7. Spatial correlation coefficient between simulated and observed annual mean precipitation. (Dashed line is 0.99 significant level, same as below)

tion for each of the simulations is presented in Fig. 7. In general, it can be seen that the coefficient increases as the model resolution increases. The RT45 simulation gives the best performance with a high correlation coefficient (0.81), indicating a very good performance in reproducing the observed spatial patterns of precipitation. As discussed in the previous section, when using the same resolution, the RCM Topography simulations tend to perform better than the corresponding GCM Topography simulations (e.g. the correlation coefficient for RT60 is greater than for GT60, RT90 greater than for GT90, etc.). In addition, a higher resolution GCM Topography simulation generally performs better than the RCM Topography simulation at a resolution one step coarser (e.g. GT60 > RT90, GT90 > RT120, etc.).

3.3.2 Monthly mean precipitation

Because of the strong seasonality of East Asia precipitation it is also important to examine the precipitation simulation for each month. The spatial correlation coefficients between the simulated and observed monthly mean precipitation for the RCM Topography experiments RT45, RT60, RT90, RT120, RT360 are presented in Fig. 8. Most notably, the correlations range from values near 0.8 during the cold season months (November through March) to values less than 0.4 during the mid to late monsoon months (July through September). The improvements due to increased resolution occur primarily in the summer monsoon months.

In fact, at resolutions coarser than 90 km, the correlation coefficients in September are not significant at the 99% confidence level. Note that the annual precipitation is dominated by the summer monsoon in China. Our results therefore suggest that relatively high resolutions (60 km or higher) are required to accurately simulate the East Asia monsoon when convective precipitation is dominant. The model resolution is less of a factor during the winter months when non-convective precipitation is dominant.

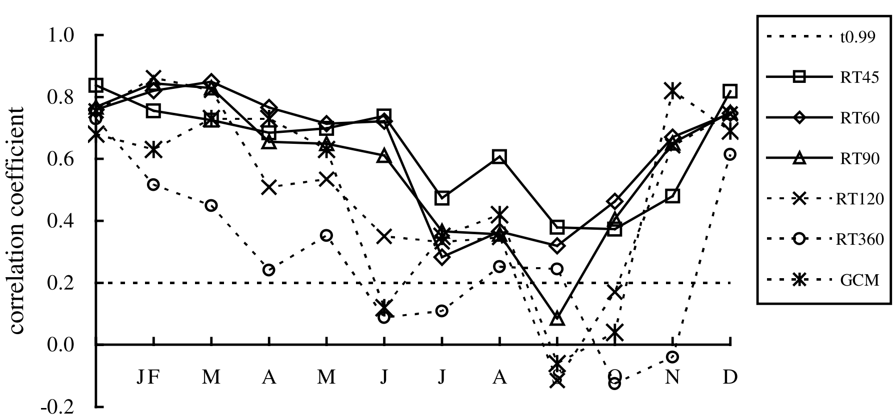


Fig. 8. Spatial correlation coefficient between simulated and observed monthly mean precipitation for RT45, RT60, RT90, RT120, RT360 resolution using real topography and GCM

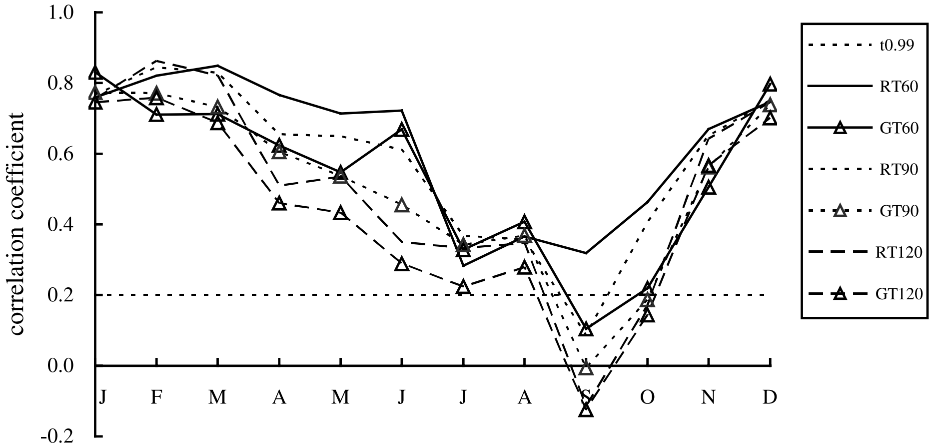


Fig. 9. Spatial correlation coefficient between simulated and observed monthly mean precipitation for RT60, GT60, RT90, GT90, RT120, GT120

To evaluate the role of the RCM Topography, the spatial correlation coefficients between the simulated and observed monthly mean precipitation for the experiments RT60, GT60, RT90, GT90, RT120 and GT120 are compared in Fig. 9. This comparison shows the effect of high resolution topography as a function of season. In all the months, the RCM Topography simulations perform at least as well and generally better than the corresponding GCM Topography experiments. In most of the months, the improvement in correlation is around 0.1. Although this improvement is not very large, it is found consistently across the range of resolutions examined.

4. Summary and discussions

The effects of horizontal resolution and topography representation on the simulation of precipitation in East Asia are investigated in a series of five year RegCM simulations nested within the CSIRO R21L9 GCM. Two sets of RegCM experiments are performed and intercompared: in one set both topography and resolution change across the range of $dx = 60$ to 360 km; in the second set only the resolution changes while the topography remains the same as the one of the CSIRO GCM. Our main conclusions can be summarized as follows:

1) The simulated East Asia large-scale precipitation patterns are significantly affected by resolution. More specifically, simulated precipitation is increasingly realistic with increasing resolution. We indeed find that a grid point spacing of at least 60 km is needed to reproduce the observed precipitation patterns reasonably well. For coarser resolutions the precipitation maximum is displaced too far north and west compared to observations. It is noted that even though higher resolution appears to improve the simulation of convective precipitation, 45 km is still too coarse to resolve all the important dynamics of a mesoscale convective system (e.g. Cotton et al., 1989).
2) The effect of resolution is most important during the mid to late monsoon months, when smaller scale convective processes dominate. During the winter months, the model reproduces well the large scale distribution of precipitation over East Asia regardless of resolution.
3) The high resolution RegCM simulations with the smooth GCM Topography perform surprisingly well compared to those employing the RegCM topography at the selected model resolution. Use of RCM Topography only adds a relatively small level of performance to the simulations. This suggests that the impact of resolution on model physics and/or dynamics is more important than the impact of topography.

Especially the last conclusion above has important implications concerning the use of fine scale models to simulate regional climates. It is well known that in areas characterized by complex topographical features, such as Europe or the western United States, complex topography plays a dominant role in determining the precipitation signal (e.g. Giorgi and Mearns, 1991). However, our results indicate that resolution itself plays an important role, especially when summer convection is a dominant process. A similar result was also found by Giorgi et al. (1998) for a simulation over the Central Plains of the U.S., another region of relatively smooth topography and summer-dominated precipitation. Evidently, during the summer sufficiently high resolution is needed to simulate convective precipitation processes.

Another important result of our study is that, in this case also confirming the findings of Giorgi et al. (1998), a nested model can indeed improve also the large scale patterns of the driving GCM. This is related to two specific features of our experiments. The first is that we used a relatively large domain, so that the large scale lateral boundary forcing is less effective in the domain interior. The second is that for summer processes the boundary dynamical forcing is less effective than for winter and local physics processes (e.g. convection and land-atmosphere exchanges) play a more important role. This result adds some useful material to the discussion of "added value" of RCM nesting (Giorgi et al., 2001).

We finally stress that our results are obviously limited to the selected region and experiment design and might not apply to other regions (where topography has a stronger effect) or climate regimes (when precipitation is dominated by cold season processes). Also, we did not change the land-use in our simulations, so that we could not evaluate the possible role of land use resolution information on the simulated climate of East Asia. We are indeed planning to carry out a more extended set of experiments to examine the possible effects of land-use distribution and land-use change on the climate of East Asia.

References

Arakawa A (1972) Design of the UCLA general circulation model. Numerical simulation of weather and climate, Tech. Rep. No. 7. L. A., CA: Dept. of Meteorology, University of California

Bengtsson L, Botzet M, Esch M (1995) Hurricane-type vortices in a general circulation model. Tellus 47A: 175–196

Boville BA (1991) Sensitivity of the simulated climate to model resolution. J Climate 4: 469–485

Briegleb BP (1992) Delta-Eddington approximation for solar radiation in the NCAR community climate model. J Geophys Res 97: 7603–7612

Christensen JH, Kuhry P (2000) High resolution regional climate model validation and permafrost simulation for the East-European Russian Arctic. J Geophys Res 105: 29647–29658

Cotton WR, Lin M, McAnelly RL, Tremback CJ (1989) A composite model of mesoscale convective complexes. Mon Wea Rev 117: 765–783

Dickinson RE, Henderson-Sellers A, Kennedy PJ (1993) Biosphere atmosphere transfer scheme (BATS) version 1e as coupled to the NCAR Community Climate Model, NCAR Tech. Note, NCAR/TN387 + STR

Gao XJ, Zhao ZC, Ding YH, Huang RH, Giorgi F (2001) Climate change due to greenhouse effects in China as simulated by a regional climate model. Adv Atmos Sci 18: 1224–1230

Gao XJ, Zhao ZC, Giorgi F (2002) Changes of extreme events in regional climate simulations over East Asia. Adv Atmos Sci 19: 927–942

Gao XJ, Luo Y, Lin WT, Zhao ZC, Giorgi F (2003) Simulation of effects of landuse change on climate in China by a regional climate model. Adv Atmos Sci 20: 583–592

Gao XJ, Lin WT, Zhao ZC, Kucharsky F (2004) Simulation of climate and short-term climate prediction in China by CCM3 driven by observed SST. Chinese J Atmos Sci 28: 63–76

Giorgi F, Mearns LO (1991) Approaches to regional climate change simulations: a review. Rev Geophys 29: 191–216

Giorgi F, Mearns LO (1999) Introduction to special section: regional climate modeling revisited. J Geophys Res 104: 6335–6352

Giorgi F, Marinucci MR, Bates GT (1993a) Development of a second-generation regional climate model (RegCM2). Part I: Boundary-layer and radiative transfer processes. Mon Wea Rev 121: 2794–2813

Giorgi F, Marinucci MR, Bates GT, DeCanio G (1993b) Development of a second-generation regional climate model (RegCM2). Part II: convective processes and assimilation of lateral boundary conditions. Mon Wea Rev 121: 2814–2832

Giorgi F, Shields C (1999) Tests of precipitation parameterizations available in the latest version of the near regional climate model (RegCM) over the continental U.S. J Geophys Res 104: 6353–6376

Giorgi F, Hewitson B, Christensen JH, Hulme M, et al. (2001) Regional climate information – evaluation and projections. In: Houghton JT et al (eds) Chapter 10 of Climate Change 2001: The Scientific Basis, Contribution of WGI to the Third Assessment Report of IPCC. Cambridge, U.K.: Cambridge University Press

Giorgi F, Marinucci MR (1996a) Improvements in the simulation of surface climatology over the European region with a nested modeling system. Geophys Res Lett 23: 273–276

Giorgi F, Marinucci MR (1996b) An investigation of the sensitivity of simulated precipitation to model resolution and its implications for climate studies. Mon Wea Rev 124: 148–166

Giorgi F, Mearns LO, Shields C, McDaniel L (1998) Regional nested model simulations of present day and 2xCO_2 climate over the Central Plains of the U.S. Clim Change 40: 457–493

Gordon HB, Farrell PO (1997) Transient climate change in the CSIRO coupled model with dynamic sea ice. Mon Wea Rev 125: 875–907

Grell GA (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. Mon Wea Rev 121: 764–787

Grell GA, Dudhia J, Stauffer DR (1994) A description of the fifth-generation Penn State/NCAR Mesoscale Model(MM5) Tech. Rep. NCAR/TN-398 + STR, National Center for Atmospheric Research, Boulder, Colorado

Holtslag AAM, Bruijn EIFD, Pan H-L (1990) A high resolution air mass transformation model for short-range weather forecasting. Mon Wea Rev 118: 1561–1575

Leung LR, Qian Y (2003) The sensitivity of precipitation and snowpack simulations to model resolution via nesting in regions of complex terrain. J Hydrometeorol 4: 1025–1043

Leung LR, Wigmosta MS, Ghan SJ, Epstein DJ, Vail LW (1996, 2001) Application of a subgrid orographic precipitation/surface hydrology scheme to a mountain watershed. J Geophys Res 101: 12803–12817

Machenhauer B, Windelband M, Botzet M, Christensen JH, Deque M, Jones R, Ruti PM, Visconti G (1998) Validation and analysis of regional present-day climate and climate change simulations over Europe. MPI Report No. 275, MPI, Hamburg, Germany

Marinucci MR, Giorgi F, Beniston M, Wild M, Tschuck P, Ohmura A, Bernasconi A (1995) High resolution simulations of January and July climate over the western alpine region with a nested regional modeling system. Theor Appl Climatol 51: 119–138

Stratton RA (1999) A high resolution AMIP integration using the Hadley Centre model HadAM2b. Clim Dyn 15: 9–28

Xu Y, Ding Y, Zhao Z (2002) Detection and evaluation of effects of human activities on climate change in East Asia in resent 30 years. Quart J Appl Meteor 13: 513–525 (in Chinese with English abstract)

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