Dynamical Downscaling of Global Analysis and Simulation over the Northern Hemisphere

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ABSTRACT

As an extreme demonstration of regional climate model capability, a dynamical downscaling of the NCEP–NCAR reanalysis was successfully performed over the Northern Hemisphere. Its success is due to the use of the scale-selective bias-correction scheme, which maintains the large-scale analysis of the driving global reanalysis in the interior of the domain where lateral boundary forcing has very little control. The downscaled analysis was found to produce reasonable regional details by comparison against 0.5° gridded analysis from the Climatic Research Unit of the University of East Anglia. Comparisons with smaller-area regional downscaling runs in India, Europe, and Japan using the same downscaling system showed that there is no degradation of quality in downscaled climate analysis by expanding the domain from a regional scale to a hemispherical scale.

1. Introduction

Kanamaru and Kanamitsu (2007a, hereafter KK), developed a spectral nudging technique (e.g., von Storch et al. 2000) for the Regional Spectral Model (RSM) named scale-selective bias correction (SSBC) for dynamical downscaling of large-scale atmospheric reanalysis. The SSBC suppresses the large-scale error whose spatial scale is greater than a specified value within the regional model domain. KK demonstrated that the use of SSBC reduced the dependency of the downscaled analysis on the domain size over the United States. More recently, SSBC was successfully applied to a long-term 10-km resolution downscaling of the National Centers for Environmental Prediction– National Center for Atmospheric Research (NCEP–NCAR) reanalysis over California (Kanamitsu and Kanamaru 2007; Kanamaru and Kanamitsu 2007b) and the contiguous United States.

In this short note we demonstrate that by using SSBC, it is possible to downscale over an extremely large domain for which lateral boundary forcing has very little influence on the interior. For this purpose, we chose the Northern Hemisphere (NH) domain with lateral boundaries placed over the tropics. We will show that the SSBC can maintain the large-scale analysis of the driving coarse-resolution reanalysis within a hemispheric domain and produces regional-scale detail over the entire hemisphere, which agrees better with small-scale observations than the coarse-resolution reanalysis.

In section 2, the model, data, and experiment design are described. Section 3 discusses SSBC and its damping coefficient. Section 4 focuses on three areas in the NH and compares the NH downscaling with observation and smaller-area regional downscaling runs. Section 5 concludes the paper.

2. Experiment

The Regional Spectral Model (Juang and Kanamitsu 1994; Juang et al. 1997; Kanamitsu et al. 2005) is used in this study. The lateral forcing is NCEP–NCAR global reanalysis (hereafter referred to as NNR; Kalnay et al. 1996). The approximate 200-km resolution global reanalysis is directly downscaled to 30-km resolution in this study. The 6-hourly reanalysis at model sigma lev-

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els is used to force the regional model. For sea surface temperature, the analyses of the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (Uppala et al. 2005) are used.

The model domain covers the entire NH with the polar stereographic projection centered at the North Pole with a resolution of 30 km (true at 60°N; 840 × 799 grid points). The initial condition of atmosphere and land is taken from the global reanalysis at 0000 UTC 1 June 2001 and the downscaling was performed for one month.

The 0.5° TS 2.1 gridded dataset of near-surface temperature and precipitation from the Climatic Research Unit (CRU) of the University of East Anglia (Mitchell and Jones 2005) is used for comparison. In addition to the NH downscaling run, we ran the regional model over several smaller focus regions: India (120 × 115 grid points), Europe (120 × 115 grid points), and Japan (264 × 195 grid points), for the same period at the same 30-km horizontal resolution with the same downscaling system.

3. Damping coefficient

The most important component of the SSBC scheme is the reduction of the large-scale error of the wind components. Within the regional domain the growth of wind perturbations whose spatial scale is greater than a cutoff value is damped in the spectral space. The average distance of radiosonde observations in the United States is approximately 250 km (Archer and Jacobson 2003), and the resolution of the NCEP–NCAR reanalysis is about 200 km. Based on these estimates, a cutoff scale of 1000 km is chosen, although observation accuracy may be worse in other NH continents and over the ocean. The SSBC also adjusts area-averaged temperature, moisture, and surface pressure, which KK describes in more detail.

KK empirically determined the damping coefficient for nudging of winds based on the integration over the United States. The value of 0.9 was found to be optimum, which reduced the tendency of wind perturbation of the selected scale to roughly half in one time step. For the hemispheric domain, we ran several one-day downscaling runs with different damping coefficients to determine the optimum coefficients for a much larger domain than the United States.

To assess the SSBC's ability to reduce the large-scale error in the domain, the root-mean-square difference (RMSD) of 500-hPa height from the base field is calculated after scales smaller than 500 km are filtered out. Table 1 shows the 500-hPa RMSD for 8 November 2002 from different damping coefficient runs. The RMSD increases with values of the damping coefficient that increases from 10 to 100. Strong damping adversely affects the large-scale errors for the NH domain. A damping coefficient of 10, which reduces the tendency of wind perturbation by roughly one-tenth in one time step, resulted in the smallest RMSD, so this value was used for this study.

TABLE 1. The 500-hPa height root-mean-square difference between the regional field and the base reanalysis field.

Damping coef	500-hPa height RMSD (m)
0.9	12.0
10	9.5
20	11.6
30	13.9
100	20.2

Using a damping coefficient of 10, 5-day (3–7 June 2001) mean NH downscaling runs with and without SSBC were compared with the NNR (not shown). RSM without SSBC produces large-scale errors of considerable magnitude with a maximum peak 500-hPa height difference of more than 100 m from the NNR. The 500-hPa height RMSD is 34.9 m, which is the accumulated large-scale error without SSBC. In the NH run with SSBC, the large-scale errors are reduced to less than 15 m over most of the domain. The RMSD is 14.4 m in the SSBC run. Thus, SSBC successfully reduces the regional model 500-hPa height forecast error to approximately the level of observational error of radiosondes (Xu et al. 2001).

4. Regional comparisons

a. India

Figure 1 shows estimated precipitation over India from regional downscaling, NH downscaling, CRU, and the NNR during June 2001. NNR (Fig. 1d) underestimates monsoon rainfall, but the NH run (Fig. 1b) and the regional Indian downscaling run (Fig. 1a) both produce precipitation at the right places on the western coast of India along the Western Ghats. Observed precipitation (Fig. 1c) is small in the southeastern region, and NNR and the two downscaling runs simulate it correctly. However, the downscaling runs do not produce enough precipitation in the central region. NNR is not able to capture the atmospheric analysis that produces rain in the region, and the downscaling runs seem to have inherited the deficiency. The RMSD of precipitation between the two downscaling runs is 4.8 mm

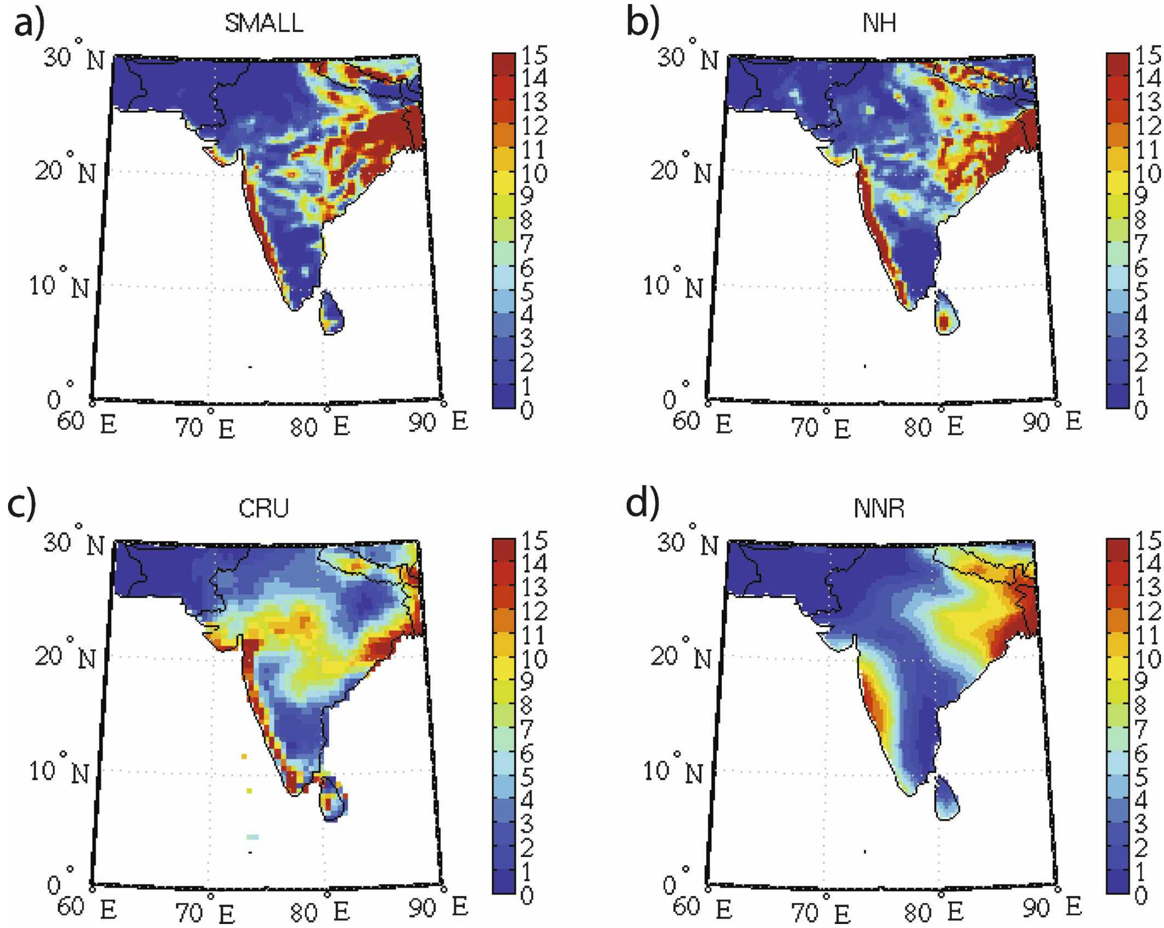

FIG. 1. Precipitation (mm day^{-1}) in June 2001. (a) SMALL: downscaling run over India, (b) downscaling run over the NH, (c) gridded observation from CRU, and (d) NNR.

day^{-1}. Overall, the two downscaling runs produce quite similar spatial precipitation patterns.

b. Europe

In this section, the European region that includes several high mountain ranges from the NH downscaling run is compared with the regional European downscaling run, the NNR, and the CRU observations. Figure 2 shows near-surface temperature for June 2001. There is a good agreement between the two downscaling runs (RMSD is 0.8°C; Figs. 2a,b), and the downscaled temperature fields look similar to the CRU observations (Fig. 2c). The downscaled runs are a little warmer in the north and colder in the south than the observation. However, the spatial pattern of near-surface temperature is very realistic over the Pyrenees, the Alps, and the Carpathians due to more realistic topography.

To estimate the magnitude of uncertainty within a downscaling system, we performed a five-member ensemble run of the smaller-area regional Europe downscaling with different initial conditions (dating back one each day from 1 June 2001). Figure 3 compares the standard deviation of near-surface temperature from the ensemble runs (Fig. 3b) and the difference between the regional Europe run and the NH run (Fig. 3a). The temperature difference between these two downscaling runs is smaller than the uncertainty in a downscaling system. An exception is the lateral boundary zone where the regional area run is susceptible to errors.

The precipitation difference between the two downscaling runs (Fig. 3c) is comparable to the uncertainty estimated from the ensemble runs (Fig. 3d) over most of the domain but the difference can be large over high elevations and the lateral boundary zone.

To demonstrate the regional model's finescale simulation over a complex terrain, Fig. 4 compares the surface wind fields of the two downscaled analyses (Europe and the NH) over the Alps for 1200 UTC mean during June 2001. Both analyses show similar profiles of important circulations near the mountains such as

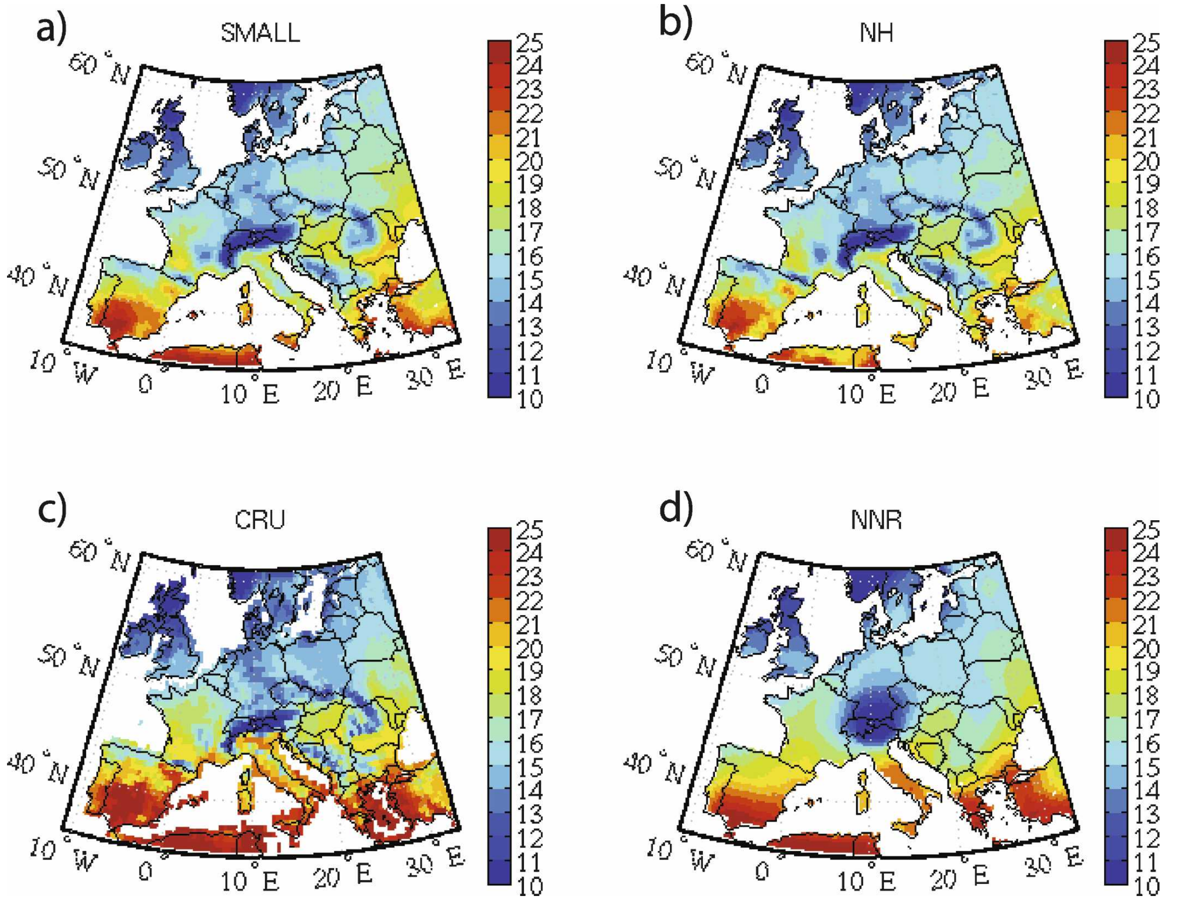

FIG. 2. Near-surface temperature (°C) in June 2001. (a) SMALL: downscaling run over Europe, (b) downscaling run over the NH, (c) gridded observation from CRU, and (d) NNR.

daytime upvalley winds. The two downscaling runs produce similar analyses on a monthly time scale.

c. Japan

The CRU observation (Fig. 5c) shows heavy precipitation associated with the Baiu front in the southern Korean Peninsula and the southern island of Kyushu. Precipitation decreases toward the north along the islands of Japan. NNR (Fig. 5d) produces more rain over central Japan and the northern Korean Peninsula than the precipitation areas identified in the observation. The two downscaling runs (RMSD is 3.9 mm day^{-1}; Figs. 5a,b) produce more precipitation in the Korean Peninsula and Kyushu Island than the NNR, and they agree better with observations. However, Honshu Island also gets large precipitation in scattered areas. Hokkaido Island receives much less precipitation than the rest of Japan but the gradient of the precipitation amount from the southwest to the northeast along Honshu Island is not as clear as observation.

The amount of rain over the Korean Peninsula is different between the regional downscaling and the NH downscaling runs. A comparison of the 500-hPa height field between the two analyses shows the NH run has higher pressure, centered to the west of the peninsula (not shown). Although SSBC reduces large-scale errors, it cannot remove them completely, and precipitation differences of this magnitude still remain in the current downscaling system. Further refinement of the damping coefficient may be able to reduce this deficiency. As we discussed in section 4b, dynamically downscaled temperature fields are less sensitive to small differences in large scale than precipitation (Fig. 3).

Overall the downscaling runs significantly improve the amount and placement of precipitation from NNR in areas where NNR provides reasonable large-scale analysis.

5. Summary and discussion

In this study, NCEP–NCAR reanalysis was dynamically downscaled to 30-km horizontal resolution over

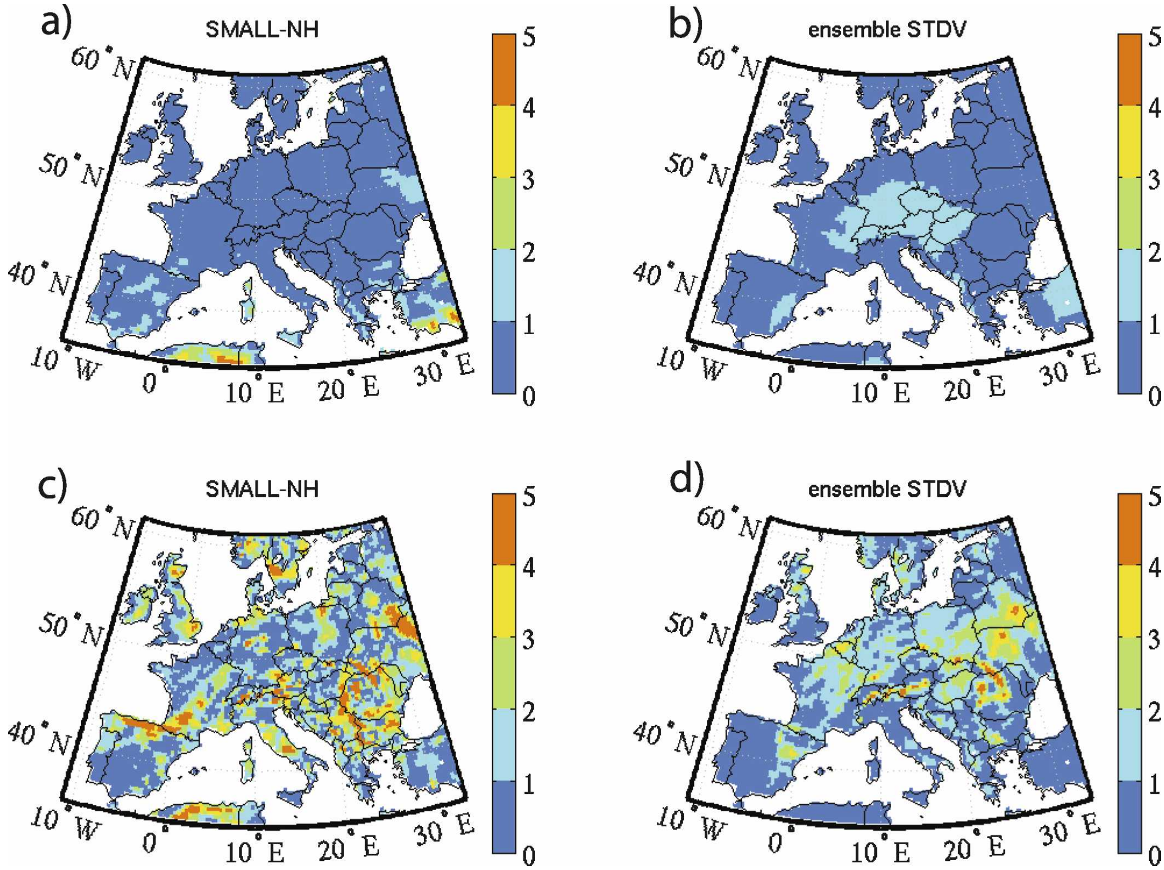

FIG. 3. Comparison of uncertainties in dynamical downscaling: (a) difference of near-surface temperature (°C) between the Europe run and the NH run (absolute values); (b) standard deviation of near-surface temperature from the ensemble European runs with different initial conditions; (c) difference of precipitation (absolute values, mm day^{-1}); and (d) standard deviation of precipitation.

the entire NH using the Regional Spectral Model. It was demonstrated that SSBC is a powerful method for making the dynamical downscaling of analysis and simulation independent of the domain size, even in an extreme case of hemispheric domain. This was accomplished by reducing the large-scale forecast errors within the regional domain toward zero.

Downscaled climate analyses of near-surface tem-

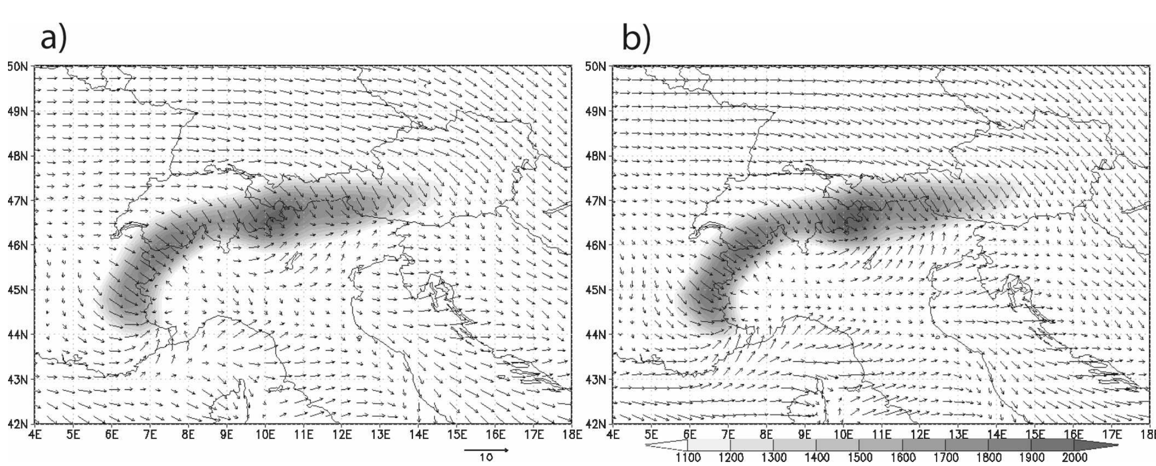

FIG. 4. Ten-meter wind (m s^{-1}) for 1200 UTC mean during June 2001. (a) Small downscaling run over Europe and (b) NH downscaling run. Shading indicates surface elevation (m).

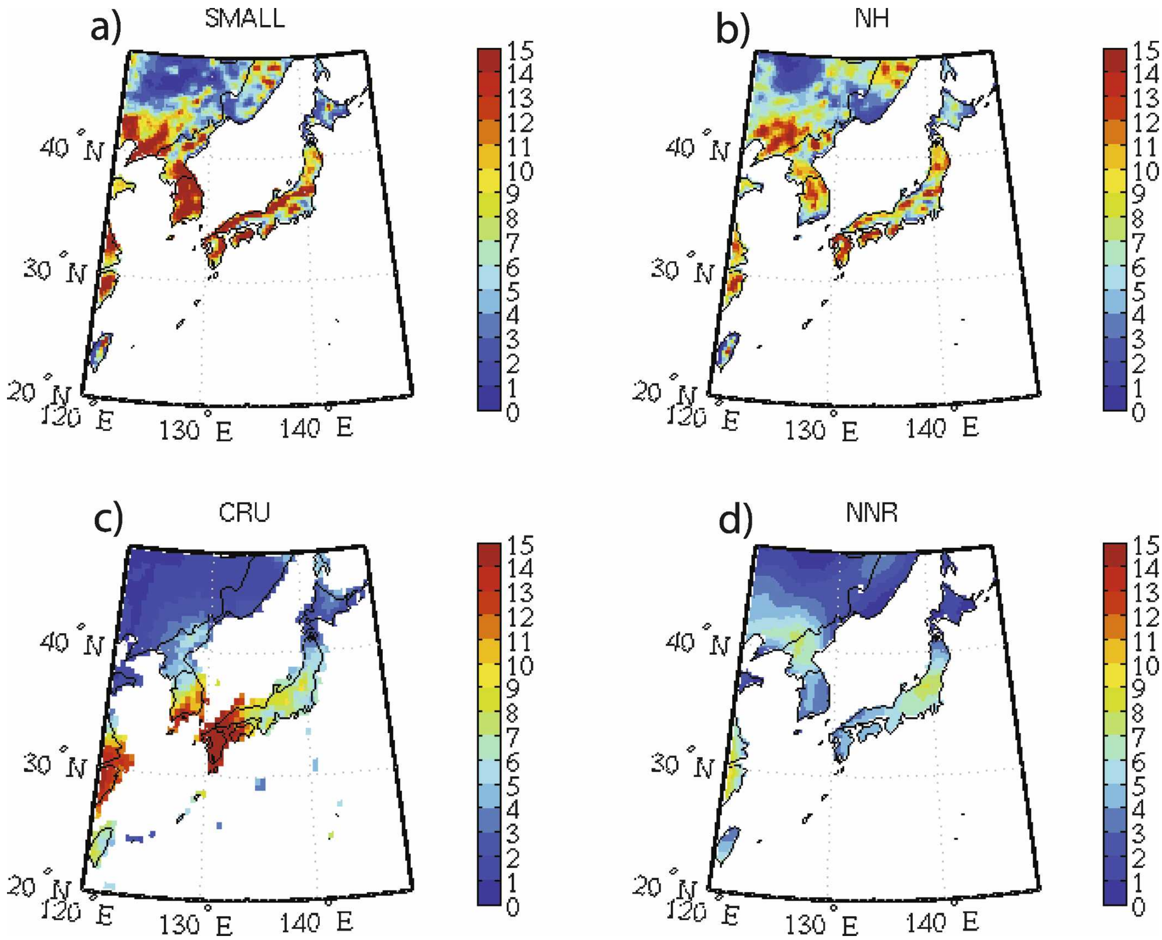

FIG. 5. Precipitation (mm day^{-1}) in June 2001. (a) SMALL: downscaling run over Japan, (b) downscaling run over the NH, (c) gridded observation from CRU, and (d) NNR.

perature and precipitation agree better with CRU gridded data than the NNR does. No degradation of quality in downscaled climate analysis is found by expanding the domain from a regional scale to a hemispheric scale. The NH run and the smaller regional runs produce similar analyses of near-surface temperature and precipitation.

In addition to the one-month summer runs (June 2001) discussed in section 4, 12-day winter runs (3–14 January 2001) were performed for the NH and the Europe region (Fig. 6). The differences of near-surface temperature and precipitation are of similar magnitude to those of summer (Figs. 3a,c). The dynamical downscaling system works just as well in winter when the large-scale circulation is stronger and the regional climate is more susceptible to large-scale forcing.

It is encouraging for the regional modeling community that climate dynamical downscaling can produce reasonable fine-resolution analysis at the hemispheric scale. Further validation of the downscaled analysis is warranted although this is difficult because of the lack of high-resolution reanalysis.

In a common practice for the dynamical downscaling of climate analysis and simulation, a regional model is continuously run with periodic forcing at lateral boundaries from reanalysis or GCM outputs. This continuous integration approach is based on the premise that the dynamics of the regional model and surface forcing (such as topography, vegetation, and surface characteristics) provide regional-scale details that are consistent with large-scale analysis. In this approach, however, the large-scale fields in the regional domain may drift away from those of the driving coarse-resolution analysis over the course of the downscaling integration. The problem is more apparent in the case of downscaling over a very large area, such as an entire hemisphere with lateral boundaries positioned in the tropics.

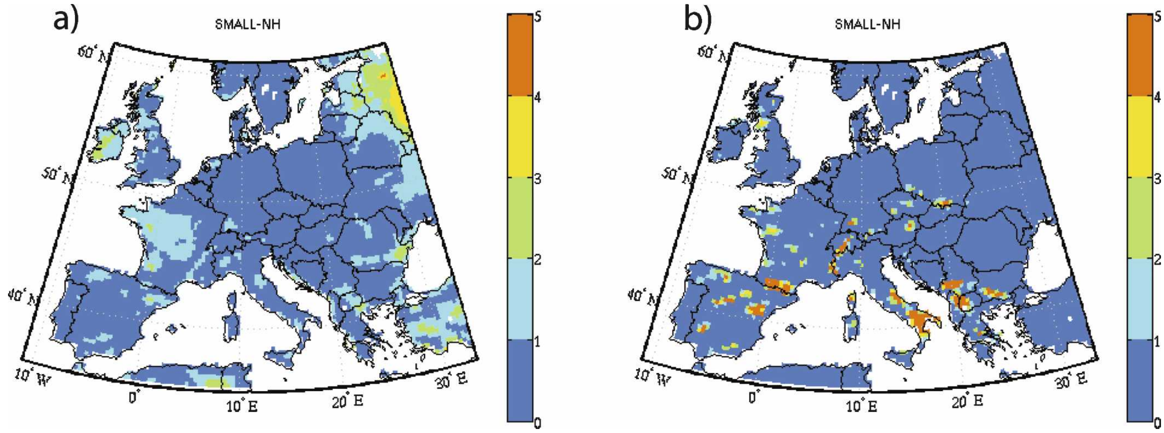

FIG. 6. Twelve-day mean downscaling runs for 3–14 Jan 2001: (a) difference of near-surface temperature (°C) between the Europe run and the NH run (absolute values); (b) difference of precipitation (absolute values, mm day^{-1}).

One approach to counteracting this problem is reconsidering dynamical climate downscaling as an initial value problem. In this approach, the downscaling is performed by making consecutive short forecasts from a coarse-resolution initial analysis with a high-resolution regional model (Pan et al. 1999; Qian et al. 2003). It is based on an assumption that small-scale details can be produced from coarse-resolution initial analysis with a fine-resolution regional model, and that those details stay consistent with the evolution of the large scale given at the initial time during the short forecast period. The reinitialization is also expected to minimize the accumulation of large-scale errors in the continuous integration method. The regional model is still driven by the lateral boundary forcing but the weight on the initial condition is much greater in the regional solution. One serious problem of this approach is that the simulation suffers from spinup because of inconsistencies between the coarse-resolution analysis and the regional model solution after each reinitialization. To minimize the spinup effects the integration may need to be extended by a few days or more. But in this case, there is a possibility that this extension could cause large-scale forecast errors to develop when the regional domain is large, thereby degrading the downscaling.

The SSBC is able to incorporate the benefit of the reinitialization approach into the continuous integration approach. In addition to the lateral boundary forcing, the technique nudges the large-scale field of coarse-resolution analysis *within* the regional domain. In an extreme application of the technique where the large-scale fields within the regional domain are replaced by those of coarse-resolution analysis ("initial condition" in the reinitialization approach), the SSBC should have the same effect as reinitialization of the model, but without the spinup problem, since the small-scale features are always in a balanced state with the initial condition in the regional model.

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