NOTES AND CORRESPONDENCE

One-Way Nested Regional Climate Simulations and Domain Size

S. VANNITSEM AND F. CHOMÉ

Institut Royal Météorologique de Belgique, Brussels, Belgium

(Manuscript received 16 March 2004, in final form 24 June 2004)

ABSTRACT

The impact of domain size on regional climate simulations is explored in the context of a state-of-the-art regional model centered over western Europe. It is found that the quality of the climate simulations is highly dependent on the domain size. Moreover, the choice of an optimal version is more complex than usually thought, the less appropriate domain having an intermediate size (about 3000 km × 3000 km), and the best versions nearly cover a quarter of the Northern Hemisphere. The use of periodically reinitialized trajectories does improve the climate of suboptimal models but leads to unrealistic dynamical behaviors. The implications for regional climate simulations are briefly discussed.

1. Introduction

Regional climate models (RCMs) have been developed in order to increase the resolution of climate predictions in specific regions of the globe. One approach currently adopted is to integrate the atmospheric model equations on a particular domain with a high resolution after defining the boundary conditions from a global circulation model. These models are known as one-way nested RCMs. Earlier studies of the role of domain size and boundary locations on regional climate predictions have indicated the importance of their impact on the regional climate variability (e.g., Jones et al. 1995; Seth and Giorgi 1998, and references therein). These early studies have been the origin of many investigations of climate sensitivity and downscaling (e.g., Denis et al. 2002; Seth and Rojas 2003). However, the difficulty in simulating the natural variability is still present although the physics of the models have been considerably improved. This has led Qian et al. (2003) to propose transient simulation strategies in order to compensate for these deficiencies.

Chomé et al. (1999, 2002) have shown, in the context of a one-dimensional convection model and in an operational regional weather prediction model, the decisive and complex role played by the domain size on the quality of the solution. One spectacular result is that depending on the domain size, a regional operational weather prediction model can generate qualitatively different solutions (periodic, chaotic, etc.) once the boundaries are fixed during the whole integration to prescribed values coming from one particular Aviation Model (Avn) analysis. The domain size therefore plays the role of a *bifurcation parameter* that affects the ability of such models to provide predictions.

The above experiments reveal that one-way nesting is at the origin of unavoidable errors whose impact should be minimized through an optimization of the domain size. In this note, we investigate the impact of the domain choice on the climate of a state-of-the-art regional model, briefly described in section 2, and we show that the choice of an optimum is more complex than usually thought (section 3). The conclusions are given in section 4.

2. The model and the experimental strategy

The Eta Model is routinely used at the National Centers for Environmental Prediction (NCEP) to produce daily high-resolution weather forecasts. A workstation version of the model is currently used at the Royal Meteorological Institute of Belgium for experimental and operational runs. A detailed description of this model can be found in Rogers et al. (1996) and Mesinger (2000). We have integrated this model on seven different domain sizes, which are detailed in Table 1. Their respective latitude–longitude output grids are shown in Fig. 1. The surface properties (sea surface temperature and snow cover) are kept equal to

Corresponding author address: Dr. S. Vannitsem, Institut Royal Météorologique de Belgique, Avenue Circulaire, 3, 1180 Brussels, Belgium.
E-mail: svn@oma.be

TABLE 1. The different experimental regional Eta Model domains used in this study.

Acronym	Approximate Eta rotated grid extension (lat × lon)	Center of the model domain (lat × lon)	No. of mass grid points in the west–east direction × No. of rows
D1	(21° × 21°)	(46°, 5°)	33 × 67
D2	(30° × 30°)	(46°, 5°)	45 × 91
D3	(43° × 43°)	(46°, 5°)	67 × 133
D4	(51° × 51°)	(46°, 5°)	80 × 159
D5	(64° × 64°)	(46°, 5°)	100 × 199
D6	(60° × 90°)	(46°, 5°)	140 × 185
D7	(66° × 102°)	(35°, 5°)	160 × 205

the values obtained at one particular date of the period for which the integration is performed.

To reduce the errors coming from the lateral boundary conditions (LBCs), we adopt the experimental design of Seth and Rojas (2003) and Qian et al. (2003). The LBCs are fed every 6 h by the analyses of the global model used operationally at NCEP (Avn). Note that, even though the integrations are performed using different domain sizes, the statistics will be evaluated over a *target area* as defined by the output grid of D1 (see Fig. 1). The different model versions are run for 40 days starting from four different dates: 1 April 2001, 10 May 2001, 1 July 2001, and 1 September 2001 at 0000 UTC, allowing for several distinct scenarios. These will be referred to hereafter as A–M, M–J, J–A, and S–O scenarios, respectively.

The spatial resolution is fixed to 0.32° on the rotated grid of the model and the time step is chosen according to the numerical stability (no explosion of the solutions) of the different model domains. Its value is fixed to 120 s for small domains and 90 s for large ones. Note

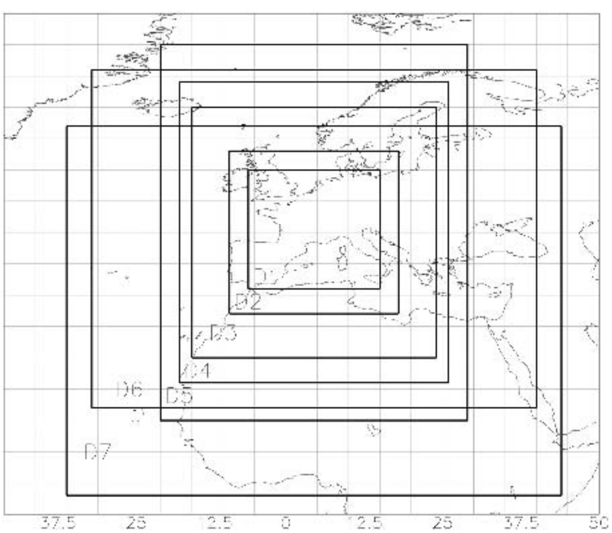

FIG. 1. Latitude–longitude output grids of the various domains considered in the present paper; D1 is the target area over which the statistics are computed.

that a smaller time step (60 s) was tested for different domain sizes and initial dates without substantially modifying the statistics presented in the next section (a few percent for the spatiotemporal average over the target area).

The impact of two simulation strategies on model quality are also explored for the two 1 July 2001 runs: 1) a continuous run during which the model is developing its own asymptotic solution, and 2) a run for which the model is periodically reinitialized on a 10-day basis as in Qian et al. (2003).

3. Results

The results for the J–A scenario are first described in detail. The impact of the change of boundary scenarios is discussed in the second part of this section.

a. J–A scenario

At low levels, the averaged temperature is positively biased as compared to the Avn analyses during the whole integration on the smallest domains D1 and D2 (see Fig. 2a). Domains D3, D4, and D5 generate a solution that slightly underestimates this quantity during the second half of the integration. Model versions D6 and D7, however, display a variability that is closer to the analyses. At 2 M, this bias is also present but less pronounced for D3, D6, and D7 (not shown). As indicated in Fig. 2b, precipitation is largely overestimated for model versions D1 and D2 as compared to the 5-day-averaged field coming from the merged analyses of the National Oceanic and Atmospheric Administration (NOAA)/NCEP/Climate Prediction Center (CPC) (Xie and Arkin 1997; more information available online at http://iridl.ldeo.columbia.edu/SOURCES). For this key observable, the model version that displays the best agreement is D3.

The results are summarized in Fig. 3, in which the averaged fields over the target area and over the 20 last days of the integration are shown. These quantities have been divided by the corresponding value obtained with the analyses. This picture allows us to readily identify (values close to 1) the most promising model domains for regional climate predictions at that period, namely, D3, D6, and D7. For D3, the averaged precipitations are closer to reality, while the other observations display a better agreement for D6 and D7. Notice, however, that in view of the strong slope of the precipitation curve as a function of domain size around D3, a slight change of the size of the domain could have a strong impact on the quality of the output.

At this stage, one could argue that the results presented in the figure are not general since they depend on the particular initial conditions, surface fields, and domain location. To check this, we have first performed additional experiments by slightly changing the initial conditions and the surface fields. For the small domains

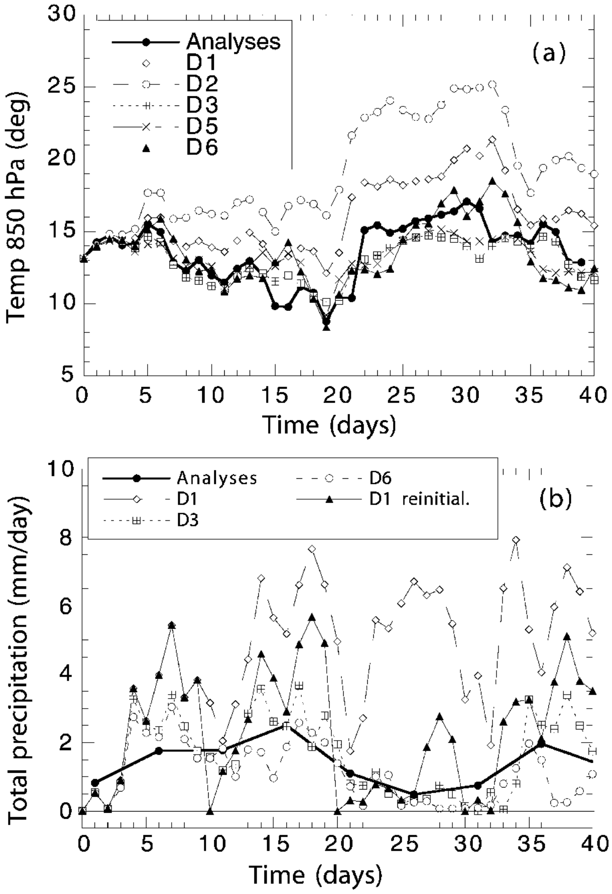

FIG. 2. Temporal evolution of (a) the temperature at 850 hPa and (b) precipitation, averaged over the regular latitude–longitude output grid of domain D1 (see Fig. 1) for the different model sizes presented in Table 1. The initial date is 1 Jul 2001 at 0000 UTC, and the surface fields used for the runs are those of 15 Jul 2001. The reference line in (b) (continuous thick line) is the precipitation data averaged over the target area for 5-day periods and comes from the merged analyses of NOAA/NCEP/CPC (see Xie and Arkin 1997).

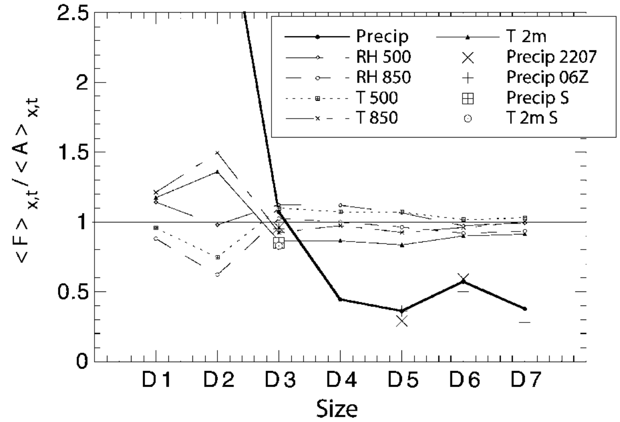

FIG. 3. Ratio between the average of selected fields [temperature at 850 (T 850) and 500 hPa (T 500), T 2m, Precip, and relative humidity at 850 (RH 850) and 500 hPa (RH 500)] and the average of the corresponding analyses. The average is performed over the target area for the last 20 days of the integrations. Here, F and A stand for forecast and analysis, and $< \cdot >$ denotes an average. The extensions 06Z, 2207, and S refer to results obtained with a new initial condition (analysis at 0600 UTC), different surface fields (22 Jul 2001), and the use of a shifted domain, respectively.

(D1 and D2), the solution is not very different than the original run, suggesting that the variability around the attractor of the solution for prescribed (time-evolving) LBCs is very small. This behavior is reminiscent of the stable nature of the internal dynamics of the small-domain regional models as shown in Chomé et al. (2002) for autonomous LBCs. For larger domains, a small change in the surface fields or the initial conditions leads to quite distinct trajectories, reflecting a larger variability of the solutions. However, in all of these runs, the modification is not as substantial as the one that could be introduced by choosing a new set of boundary conditions, suggesting that the picture presented in Fig. 3 is robust.

In regional modeling, a central recommendation is to put the boundaries as far as possible from the target area. In the present runs, this area corresponds to the central part of all the domains. In order to check the role of the domain location (and the role of the distance from the boundaries), additional runs were performed, one for the J–A scenario and several for the other ones (see section 3b). For the J–A scenario, domain D3 is displaced by 5° westward. The target area is now closer to the right boundary. A new run is performed whose results are displayed in Fig. 3 [2-m temperature with a shifted domain (T 2m S) and precipitation with a shifted domain (Precip S)]. Clearly, the results are close to the original ones, further suggesting the robustness of the findings and invalidating the key role of the distance from the boundaries for regional climate simulations.

All of these findings suggest that there is not a simple relation between the quality of the model and the size of the domain for the period considered. This point is taken up further in section 3b by considering several boundary condition scenarios.

When adopting the second strategy by reinitializing model D1 every 10 days, the quality of the solution (thin continuous line in Fig. 2b) is improved. However, this system is still much less efficient than the best model versions and leads to an unrealistic evolution of the precipitation as revealed by the negative bias during the first days after reinitialization and the positive one later.

b. Impact of other boundary scenarios

For the three other scenarios, the results are summarized in Fig. 4. Two conclusions already found for 1 July are still valid here: 1) domains D1 and D2 do not provide adequate averages, D2 being even worse than D1 for the majority of the fields; and 2) in general, the best

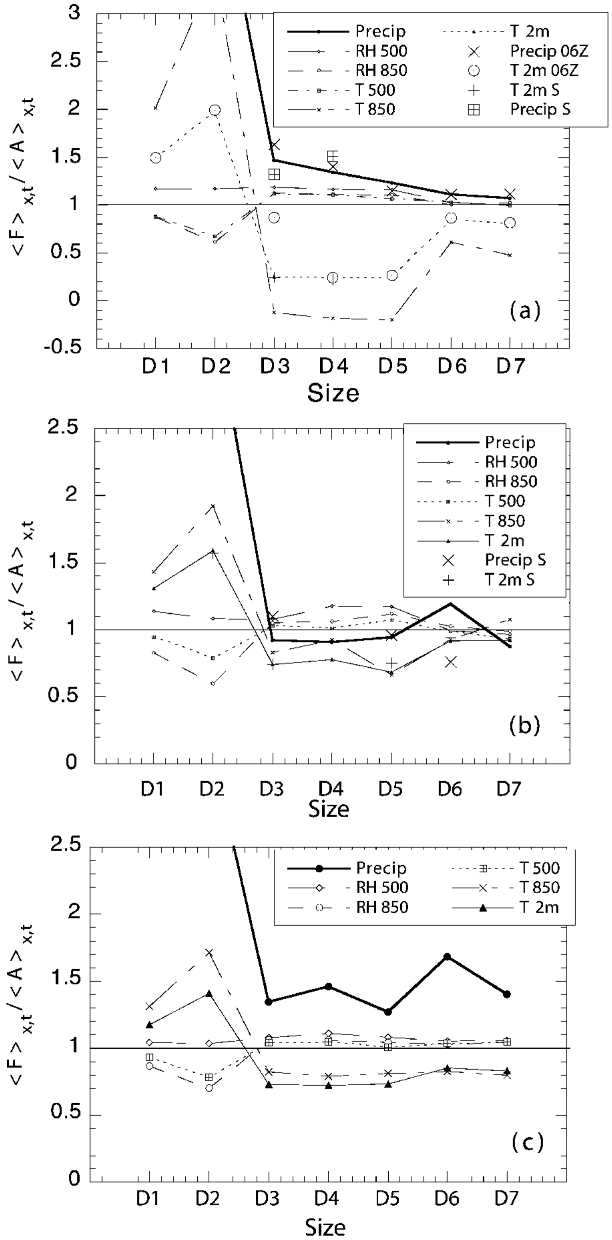

FIG. 4. As in Fig. 3, but for initial dates of (a) 1 Apr 2001, (b) 10 May 2001, and (c) 1 Sep 2001 at 0000 UTC. The surface fields are those of 15 Apr, 30 May, and 16 Sep 2001, respectively.

model domains are D6 and D7. In addition to these general properties, three aspects have to be emphasized:

1) D3 is now less efficient in predicting the average precipitation, particularly in the A–M scenario (Fig. 4a).
2) Domains D3, D4, and D5 considerably underestimate the temperature at low levels in the A–M scenario (Fig. 4a).
3) Precipitation averages stabilize around a value similar for domains D3 up to D7, which changes as a function of the boundary scenario. The distance of this "asymptotic" value from reality is indicative of the amplitude of the error in modeling the precipitation process in the regional model. Notice that this amplitude seems to display a strong seasonal dependence.

The impact of initial conditions, surface fields, and domain location is also tested for scenarios A–M and M–J. For precipitation, a substantial variability is present around the asymptotic value already mentioned above. For the other fields, the results are remarkably robust, except for domain D3 in the A–M scenario. For the latter, the choice of another initial condition leads to a strong improvement of the quality of the temporal evolution and of the statistics at low levels (see the large circle in Fig. 4a for temperature at 2 m). Note, however, that a displacement of this domain does not substantially affect the statistics of the fields compared to the original run. It reveals the existence of two drastically different trajectories of the spatially averaged fields for this domain at that particular period. Since domains D6 and D7 do not display such a qualitative change in the evolution as a function of the initial conditions, surface fields, and domain location, and are close to the actual trajectory, one can expect that the multiplicity of states of D3 is an artifact associated with the specific domain choice.

Finally, notice that the modification of the domain location (T 2m S and Precip S in Figs. 4a and 4b) does not substantially degrade or improve the quality of the solutions inside the target region D1 (Fig. 1), further supporting the notion that the key parameter is not the distance of the target area from the boundaries but the size of the domain itself.

4. Conclusions

The one-way nesting procedure in regional models introduces a new parameter, the size of the domain, which governs in a decisive way the possible solutions that can be generated by this system. Underestimating this important aspect could lead to overemphasizing the role of the physical parameterization in the development of an incorrect variability. In fact, both the physical equations and the particular domain size should be optimized in order to provide an "optimal" RCM.

For the region considered here, a high sensitivity of the model quality as a function of domain size is found (see Figs. 3 and 4) that should be related to the specific dynamics that can be effectively realized in the regional domain. Obviously, for small domains, the dynamics are far from the real chaotic flow, inducing large climate forecast errors. For larger domains, although most of the fields display an improvement as a function of the domain size, dramatic behaviors can be found, such as that for the A–M scenario for which domains D3, D4, and D5 provide trajectories that are as far from reality as D1. The very large domains, D6 and D7, seem to display the best results (except for precipitation in the J–A scenario). The traditional view that the larger domain is better should therefore be reassessed in the light of our findings.

Note that as indicated in Rojas and Seth (2003), the specific domain choice should also be motivated by the quality of the coarser resolution global model providing the LBCs, since a large RCM is able to partly compensate for its deficiencies. Conversely, if the quality of the external fields is good, then a smaller domain such as D3 should be more economic, but one should be cautious in its use.

The use of transient evolutions instead of a long-term climate run is questionable since, by definition, they constitute trajectories that cannot in principle be realized by the real climate system. The success in using transient trajectories reflects the large discrepancy between the real and model climates.

Additional scenarios for other years and for winter should be useful for deriving a "climatological" picture of the quality of the model as a function of domain size. Moreover, in other regions of the globe, these sizes might not be optimal, especially over the Tropics. The present analysis should therefore be repeated region by region.

Acknowledgments. We are grateful to C. Nicolis for enlightening discussions and to Dr. Anji Seth and the second reviewer for their constructive comments. We thank S. Lord, Director of the NCEP/EMC, for allowing the use of an experimental version of NCEP's Eta Model and M. Pyle, who provided considerable help during its implementation at the RMI.

REFERENCES

Chomé, F., S. Vannitsem, and C. Nicolis, 1999: Dynamics, statistics and predictability of a simple limited-area model. *Tellus,* **51A,** 222–232.

——, ——, and ——, 2002: Intrinsic dynamics of the regional Eta Model: Role of the domain size. *Meteor. Z.,* **11,** 403–408.

Denis, B., R. Laprise, D. Caya, and J. Coté, 2002: Downscaling ability of one-way nested regional climate models: The big-brother experiment. *Climate Dyn.,* **18,** 627–646.

Jones, R. G., J. M. Murphy, and M. Noguer, 1995: Simulation of climate change over Europe using a nested regional-climate model. I: Assessment of control climate, including sensitivity to location of the lateral boundaries. *Quart. J. Roy. Meteor. Soc.,* **121,** 1413–1449.

Mesinger, F., 2000: Numerical methods: The Arakawa approach, horizontal grid, global, and limited-area modeling. *General Circulation Model Development,* D. A. Randall, Ed., Academic Press, 373–419.

Qian, J.-H., A. Seth, and S. Zebiak, 2003: Reinitialized versus continuous simulations for regional climate downscaling. *Mon. Wea. Rev.,* **131,** 2857–2874.

Rogers, E., T. L. Black, D. G. Deaven, G. J. DiMego, Q. Zhao, M. Baldwin, N. W. Junker, and Y. Lin, 1996: Changes to the operational "early" eta analysis/forecast system at the National Centers for Environmental Prediction. *Wea. Forecasting,* **11,** 391–413.

Rojas, M., and A. Seth, 2003: Simulation and sensitivity in a nested modeling system for South America. Part II: GCM boundary forcing. *J. Climate,* **16,** 2454–2471.

Seth, A., and F. Giorgi, 1998: The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate model. *J. Climate,* **11,** 2698–2712.

——, and M. Rojas, 2003: Simulation and sensitivity in a nested modeling system for South America. Part I: Reanalyses boundary forcing. *J. Climate,* **16,** 2437–2453.

Xie, P., and P. A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.,* **78,** 2539–2558.