Predictability of a Nested Limited-Area Model

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ABSTRACT

This note investigates the nature of the extended predictability commonly attributed to high-resolution limited-area models (LAM) nested with low-resolution data at their lateral boundaries. LAM simulations are performed with two different sets of initial, nesting, and verification data: one is a set of regional objective analyses and the other is a synthetic high-resolution model-generated dataset. The simulation differences (equivalent to forecast errors in an operational framework) are studied in terms of their horizontal scale distribution normalized by the natural variability in each scale, as a measure of predictability, which constitutes an original contribution of this note. The results suggest that the extended predictability in LAM is confined to those scales that are present both in the initial condition and lateral boundary conditions (LBCs). No evidence is found for extended predictability of scales that are not forced through the LBCs. Instead, these smaller scales exhibit predictive timescales in direct relation to their spatial scales, similar to the behavior in autonomous global models.

1. Introduction

Since the pioneering work of Lorenz (1969) on atmospheric predictability, it is understood that small errors in the initial state of a nonlinear system will grow with time and will render a forecast useless after some time; this is true even in the absence of model errors, which in practice degrade the quality of a forecast even faster than the estimate based on a perfect model. The forward-in-time integration of an atmospheric forecast model from slightly different initial conditions produces solutions that diverge with time from one another; the difference eventually becomes as large as that between two randomly chosen states. The rate of divergence depends on the nature of the initial differences and on the initial state. By repeating this experiment for many different cases and using mean square error (E) as a measure of the difference, it is observed that the ensemble average value of E grows in time and asymptotes to a

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value equal to twice the variance (S) due to natural variability, implying that by then the states are on average uncorrelated (e.g., Leith and Kraichnan 1972). With this measure a forecast is normally considered useful as long as $E < S$, since a forecast consisting of the climatological average would give $E = S$.

Atmospheric analysis errors occur predominantly at small spatial scales due to inadequate observational coverage and to the analysis methods. These small-scale errors in the initial state of a forecast model grow in time and, through nonlinear interactions, eventually contaminate larger scales. This upscale propagation of error was clearly shown in the study of Boer (1984) by performing a spectral decomposition of a global model forecast error. Hence in practice there is no unique time range that can be attributed for atmospheric predictability because each spatial scale has a different validity time range, larger scales having longer predictability limits than shorter scales. This is consistent with the interpretation of atmospheric circulation as a turbulent process with turnover times a function of the spatial scales.

In the seminal work of Anthes (Anthes et al. 1985, 1989) and following studies (e.g., Errico and Baumhefner 1987; Vukicevic and Errico 1990; Paegle et al. 1997), it has been demonstrated that the predictability limit of nested, limited-area models (LAMs) is very distinct from that of global forecast models. Based upon an ensemble of integrations of a LAM nested with analyses at the lateral boundaries, it was shown that the value of E, unlike the case for global models, asymptotes to a value much smaller than S, thus implying that LAMs have predictive skill at all time ranges. This ‘‘extended predictability’’ stems from imposing valuable information from *analyses* as lateral boundary conditions (LBCs) of a LAM through the nesting technique. When a LAM is used as an operational forecast model in numerical weather prediction centers however, it is initialized with high-resolution objective analyses but it is nested within a low-resolution global *forecast* model. Thus, the contamination at the lateral boundaries of the LAM by the forecast errors of the global model limits the operational usefulness of the LAM beyond some forecast time range. Despite some documented difficulties with the nested approach (e.g., Warner et al. 1997), LAMs offer a computationally attractive alternative for achieving high resolution over a region of interest.

Following the steps of Giorgi and colleagues (e.g., Giorgi and Bates 1989), LAMs have increasingly been used to downscale coarse-resolution global climate models (GCMs) and a number of groups are now actively applying the LAM technique to climate investigations, developing, and exploiting regional climate models [RCM; see the review by McGregor (1997) on current RCM research activities]. In the case of a RCM, a LAM is initialized and nested with low-resolution GCM-simulated data, and it is integrated for very long periods (ranging from a few months to many decades) in order to establish a statistically significant climate estimate at regional scale, similar to what is done with GCMs at global scales. The premise underlying the RCM strategy is that, when nested with the large-scale flow from a low-resolution GCM, a high-resolution RCM simulation will develop small-scale features that are dynamically consistent with the large scales provided at its lateral boundaries and with the small-scale forcings at its lower boundary, thus downscaling the GCM simulation. It is by now well documented that RCMs develop rapidly (in the course of a few days) small-scale details despite the fact that they are both initialized and nested by coarse-resolution data (e.g., Miyakoda and Rosati 1977; Anthes 1983). The small-scale features may result from small-scale surface forcings (such as land surface inhomogeneities or orography), but also from hydrodynamic instabilities or from nonlinear interactions (such as frontogenesis due to stretching by large-scale flow variations) that induce the development of finescale structures even in the absence of localized surface forcings.

In this note we investigate the nature (and challenge the concept) of extended predictability of LAM by performing an analysis of the scale distribution of forecast (or rather simulation) errors of a LAM initialized and nested with two sets of data: a high-resolution objective analyses dataset and a LAM-ganerated synthetic dataset.

2. Numerical experiments

The LAM used for this study is the Canadian RCM (CRCM; Caya and Laprise 1999; Laprise et al. 1998). The dynamical core of this model, based on the fully elastic nonhydrostatic equations and solved by semi-implicit and semi-Lagrangian marching schemes, was developed by scientists at the Cooperative Centre for Research in Mesometeorology (Laprise et al. 1997). The horizontal domain consists of a polar-stereographic projection on an Arakawa C grid and the vertical coordinate is a terrain-following Gal-Chen scaled height. The physical parameterization package of the CRCM is taken from the second-generation Canadian GCM (McFarlane et al. 1992), and dissipation consists of a weak biharmonic lateral diffusion applied to the dependent variables. The nesting in this model is achieved through the application of a 10-point sponge layer around the perimeter of the computational domain; in this sponge the RCM-dependent variables are gradually restored to the nesting field values.

a. Simulation using high-resolution objective analyses

For the first experiment, the model horizontal resolution is 35 km (nominal value at 60°N) and 19 levels are used in the vertical with a computational lid near 33 km. The horizontal domain consists of 118 by 118 grid points, corresponding to a $(4130 \text{ km})^2$ domain centered over Montréal, Québec, Canada. The 4-day period selected for this case study starts at 0000 UTC on 8 November 1996. For these experiments the CRCM is initialized and nested with, as well as verified against, a set of high-resolution 6-hourly objective analyses. These regional analyses were produced by the Canadian Meteorological Centre (CMC; Chouinard et al. 1994). They were obtained by data assimilation with the quasi-hemispheric, variable-resolution Canadian Regional Finite Element model on a polar-stereographic grid covering the whole of Canada and adjacent regions at 35-km resolution. In the regional analysis cycle, a coarser-resolution global analysis is also used to update the larger scales at 12-h intervals. This regional data were also initialized by a nonlinear normal modes scheme.

The CRCM's root-mean-square simulation error ($E^{1/2}$) averaged over a 98 × 98 subdomain, excluding the lateral sponge zone, is shown in Fig. 1a for the *x* component of the horizontal wind (i.e., the component parallel to the abscissa of the polar-stereographic computational grid) at midtropospheric levels. The well-known results obtained under similar conditions (Anthes et al. 1985, 1989; Errico and Baumhefner 1987) are reproduced here, but with a larger computational domain and a finer resolution: the initial error grows but then rapidly levels to values much smaller than the natural variability, as can be seen with the relative error curve displayed in Fig. 1b. It is this kind of behavior that has lead to the notion of ''extended predictability'' of LAMs when nested with observed high-resolution LBCs.

In order to better understand the origin of this predictability, the forecast errors are decomposed into different horizontal scales by performing Fourier analyses following the technique developed by Errico (1985) for limited-area domains. Figure 2 shows the vertically integrated relative error in kinetic energy as a function of time and scale. It can be seen in Fig. 2b that scales smaller than about 300 km have lost all predictability by 12 h and, similarly, for scales of 500 km by 24 h; only scales greater than 1000 km retain skill for the whole simulation period. The small relative rms errors shown in Fig. 1 reflect mostly the skill of larger scales because the bulk of the variance is contained in the larger scales, which are well simulated in LAMs when the LBCs are adequately prescribed by the nesting technique.

Qualitatively similar results were obtained with CRCM by Ravi Varma (1998) for another cases, so we are confident that these results are not solely an artifact of this particular case. Our result suggests that the long-range predictability of LAMs is confined to the very large scales, which are not those for which LAMs are expected to contribute added value to the nesting analyses.

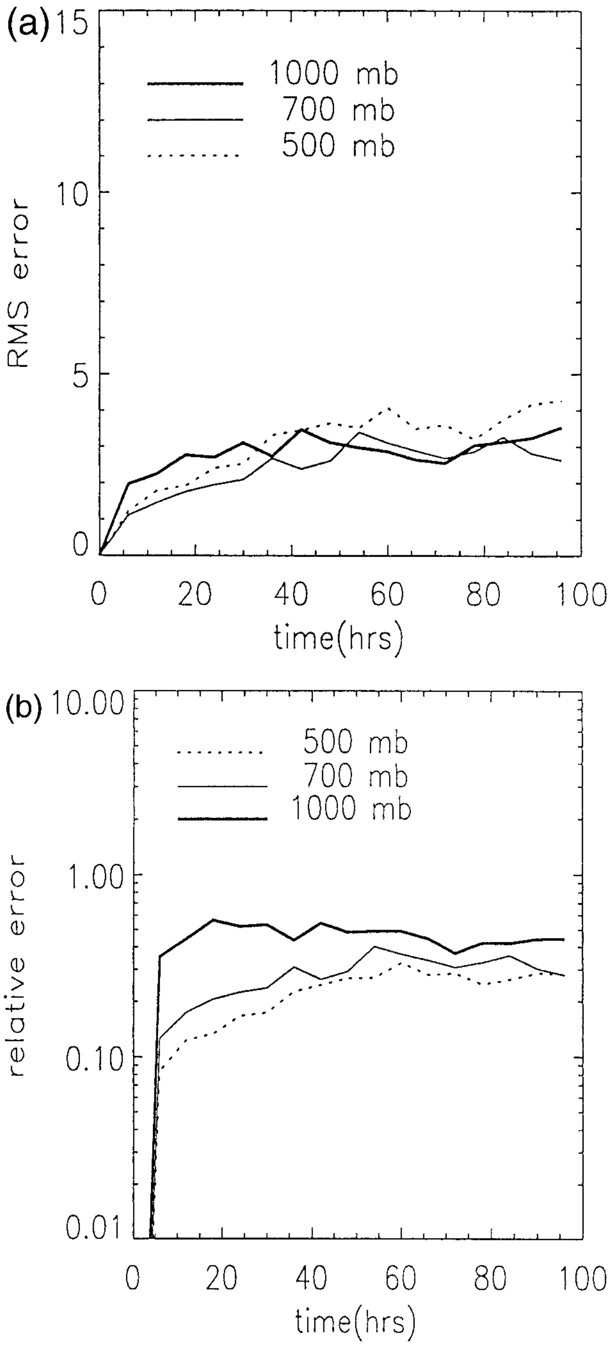

FIG. 1. Temporal evolution over 4 days of root-mean-square difference ($E^{1/2}$) between the RCM simulation and the CMC analyses used to initialize and nest the RCM, calculated for the *x* component of wind at 1000, 700, and 500 hPa. (a) The value of $E^{1/2}$ in m s^{-1}, while (b) the relative mean-square difference (E/S), after normalizing by the variance S of the verification field.

b. Simulation using synthetic, LAM-generated dataset

Two factors may explain this poor performance in simulating the fine scales. The CRCM might simply be a poor forecast model; after all its physical parameterization package is based on a fairly old formulation that was developed for use at much coarser resolution in climate mode. Alternatively the CMC regional analyses may be poor, containing little valuable information at

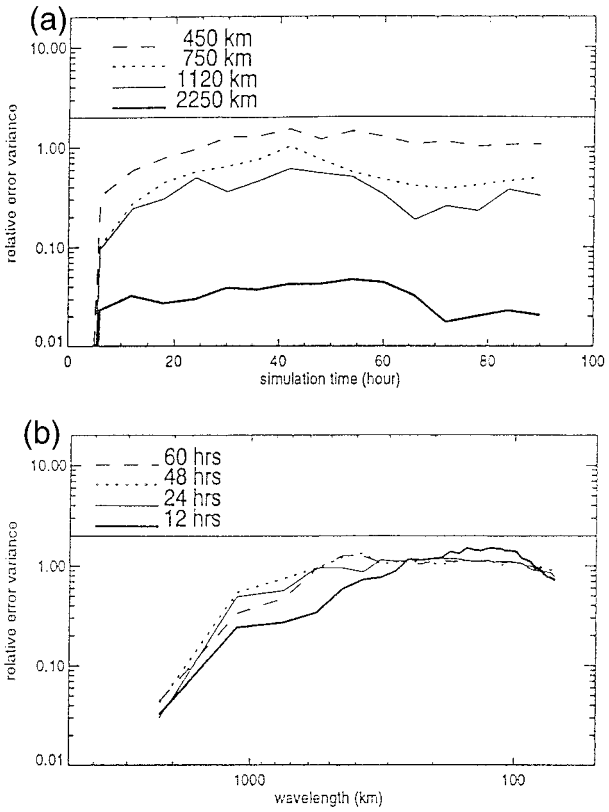

FIG. 2. Scale decomposition of the simulation shown in Fig. 1 but for the kinetic energy of the difference this time. (a) The time evolution of the relative mean-square difference (E/S) is shown for four spatial scales: 450, 750, 1120, and 2250 km. (b) The spatial scale spectrum of the difference field is shown at four different times: 12, 24, 48, and 96 h.

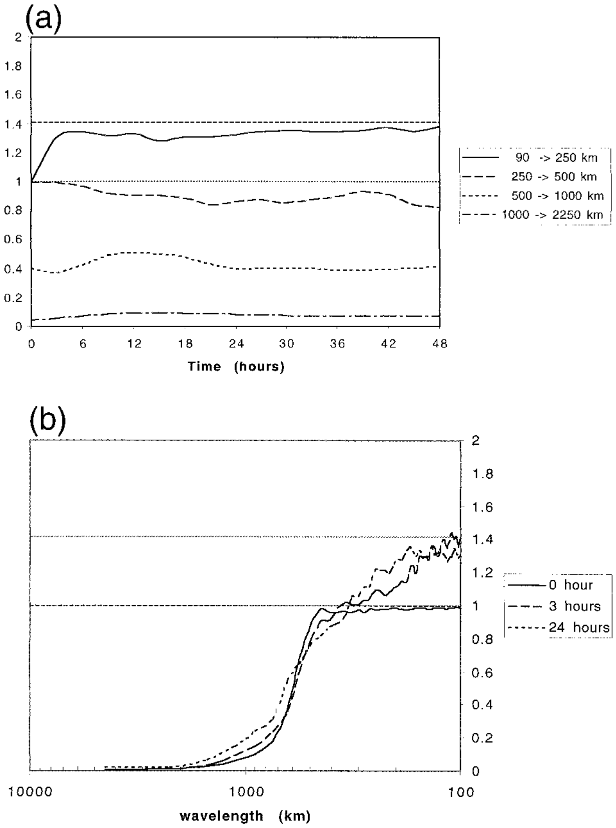

FIG. 3. Temporal evolution over 2 days of relative root-mean vertically integrated kinetic energy of the difference $(E/S)^{1/2}$ between the small-domain RCM simulation and the large-domain synthetic dataset whose filtered version is used to initialize and nest the small-domain RCM. (a) The relative error is plotted as a function of time in four scales bands: 90–250, 250–500, 500–1000, and 1000–2250 km. (b) The same information is displayed as a function of length scales at three different times: 0, 3, and 24 h.

fine scales (below 500 km) because of the paucity of observations and/or of the analysis technique. To eliminate the contamination from these possible causes, another simulation was performed in a ‘‘perfect model’’ mode using a synthetic dataset.

This synthetic dataset was created by running CRCM over a large 196 × 196 domain, with a horizontal resolution of 45 km and 36 levels in the vertical (25 of which are below 150 hPa), using a truncated T32-resolution version of National Centers for Environmental Prediction reanalyses as LBCs. The horizontal domain is centered over Cape Cod and a 7-day period selected for this case study corresponds to 27 January–3 February 1996. This high-resolution simulated dataset should be consistent with the virtual reality behavior of CRCM. The resolution of this synthetic reference dataset is then degraded by filtering short scales. The gradual filter is built to eliminate completely all scales shorter than 500 km and retain intact scales larger than 1000 km (these scales are commensurate with the resolution of upper air soundings or GCMs). The resulting low-resolution dataset is then used as the initial condition (IC) and LBC for the integration of CRCM on a 100 × 100 domain for the 2-day period 1–3 February, thus allowing for a 5-day spinup period for the high-resolution reference dataset against which the experiment is verified. Note that the verification is made only over a 64 × 64 subdomain, in order to exclude the sponge and the adjacent adjustment zone.

The root-mean kinetic energy simulation relative error for this experiment is displayed in Fig. 3a for four scales bands. In this case the initial errors in length scales smaller than 1000 km are not small, because the LAM was initialized with the low-resolution dataset but verified against the high-resolution dataset. In fact the error shows little time tendency in all bands but the shortest (90–250 km), which grow to saturation within less than 6 h. (We do not judge significant the small error decrease in the 250–500-km band.) Figure 3b shows the same information, but this time presenting the scale distribution of the relative error at different times. It is seen that the short scales (shorter than 500 km) that are removed from the IC and LBC become unpredictable in less than 6 h. Only scales that are present both in the IC and LBC (larger than 1000 km) appear to remain predictable. Similar results prevail for other variables (not shown).

Another case was studied by Ravi Varma (1998) with CRCM, reaching qualitatively similar conclusions. Hence despite the fact that model errors are eliminated through the use of LAM-generated dataset, this experiment suggests that a LAM cannot predict finescale structures correctly (i.e., deterministically) if these are not present both in the IC and in the LBC. Some elements of this interpretation could have been anticipated from the investigations of van Tuyl and Errico (1989) and Vukicevic and Errico (1990), although their particular choice of error measure did not lend itself easily to an interpretation in terms of predictability.

3. Discussion and conclusions

Two numerical sensitivity experiments were carried with a nested limited-area model, the Canadian Regional Climate Model, for a single winter case over eastern North America. A Fourier decomposition was applied on the simulation errors with the aim of shedding some light upon the nature of the apparent ‘‘extended predictability’’ commonly attributed to LAMs because of the specification of valuable information through the lateral boundary conditions. While it is well known that Fourier decomposition of aperiodic data is not without problems, the technique developed by Errico (1985) allows for obtaining what appears to be a reliable estimate of the distribution of variance with scales.

The results of this limited study with a LAM nonetheless suggest the following conclusions.

1) The predictability of small spatial scales is shorter than that of larger scales.
2) In the absence of strong surface forcing, specification of large-scale flow at the lateral boundary is incapable of correcting for small-scale errors in the IC or for the lack of small-scale information in the LBC.
3) Larger scales that are present both in the initial and in the lateral boundary conditions may remain predictable for extended period of time [although there are circumstances when they do not, e.g., Waldron et al. (1996), Biner et al. (2000), and von Storch et al. (2000)].

Conclusions 1 and 2 obtained with a LAM are consistent with the understanding of atmospheric predictability and with the behavior of global models. Hence the extended predictability with a LAM (conclusion 3) appears to be confined to the scales that are adequately forced through the LBC. This finding casts serious doubts upon some enticing perspectives for using LAMs as ‘‘intelligent interpolators’’ to regionalize or downscale large-scale analyses, except possibly under circumstances of strong localized surface forcings. Furthermore when LBCs are provided not from analyses but from a forecast model, the large scales will not be perfect; some numerical experimentation results (not shown) indicate an even more limited forecast skill for short scales under such circumstances. We must point out however that these results and the conclusions we derived from them are preliminary.

This note cannot end without an important caveat. All the above interpretation rests upon one measure of skill, the rms difference (albeit a scale-dependent one, calculated over a subset of the computational domain). There is no universal agreement about what constitutes a useful forecast. A displacement of an otherwise perfectly simulated feature may result in an rms score that is worse than a flat forecast field. For this reason a number of groups have attempted alternative measures of forecast skill, for example, Hoffman et al. (1995), to cite only one.

The assessment of the RCM’s skill for climate application will have to proceed differently than that of LAMs for simulations or forecasts, which was the topic of this note. For forecasting, a model is considered skillful if it reproduces weather events deterministically, that is, respecting their specific intensity, location, and chronology. For climate applications, on the other hand, a climate model is skillful if it reproduces the statistical characteristic of the real world over some periods. Hence there is no contradiction between the loss of predictability of NWP models after several days and the GCM’s skill over multidecade timescales. The fact that simulations or forecasts produced by LAMs exhibit no extended predictability at fine scales does not bear consequences on the skill and usefulness of RCM for climate applications; only the former was addressed in this paper.

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