Intrinsic Dynamics of the Eta regional model: role of the domain size

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Abstract

This note investigates the dynamical properties of the Eta model, a state-of-the-art nested limited-area model, following the approach previously developed by the present authors. It is shown that the intrinsic dynamics of the model depends crucially on the size of the domain, with a non-chaotic behavior for small domains, supporting earlier findings on the absence of sensitivity to the initial conditions in these models. For such domains, the role of the boundary conditions is predominant in reproducing the natural variability of the atmosphere. For large domains, an intrinsic unstable dynamics is recovered that is only slightly modulated by the boundary conditions. The impact of these properties on the skill of the model is briefly discussed.

1 Introduction

High resolution predictions of regional weather configurations are nowadays performed operationally in a large number of weather forecasting centers and constitute an important source of information. They are based on the short-term integration of an atmospheric model in a limited region of the globe with a higher spatial resolution than the one used for the global atmospheric models.

A large variety of regional models are currently available which belong to three main classes: nested Limited-Area Models (LAM), variable mesh models and perturbation spectral models, the most common ones being the nested limited area models. The main philosophy of this last approach is to construct a fine-mesh model on the region of interest and to impose boundary conditions provided from a coarse resolution model integration on a larger domain containing the region of interest. The system providing the boundary conditions is usually chosen to be a global atmospheric model.

Recently, the problematic of regional modeling has been considered from the theoretical point of view by the present authors (Chomé and Nicolis, 1999; Chomé et al., 1999; Chomé, 2001). The ideas put forward were illustrated on a simple one-dimensional model displaying chaotic dynamics, one of the main characteristics limiting atmospheric predictability, whose intrinsic simplicity allowed one to adopt a probabilistic viewpoint and to analyze the quality of the LAM prediction using a large number of realizations. In this idealized setting, the authors showed that the boundary conditions influence in a decisive way the predictability of nested regional limited-area models, thereby confirming the important role of the nesting procedure in regional modeling. Moreover, they were able to identify an optimal size for the limited-area domain based on the statistical properties of the LAM models.

A number of studies have addressed the problem of the predictability of operational nested regional models with special emphasis on the role of the initial and boundary conditions (see i.e. Warner et al, 1997, and references therein). One of their major findings is the lack of sensitivity to initial conditions. Vukicevic and Errico (1990) have pointed out the importance of the nesting procedure on this property that imposes an upper wavelength to the solution that can be described by the regional model. A more recent study confirms this aspect and indicates that the unstable subspace of the nested model is small as compared to the one of global models (Ehrendorfer and Errico, 1995).

The goal of the present note is to analyze the variability and predictability properties of an operational limited-area model, following the dynamical system approach adopted previously by the present authors. The system considered is the Eta model developed at the NCEP (National Centers for Environmental Prediction).

Several model versions differing only by the regional domain size are considered and summarized in Section 2. Section 3 is devoted to the nature of the dynamics generated by the LAM. As well known, the atmosphere displays a complex dynamics whose most ubiquitous signature is the sensitivity to initial conditions. Our analysis shows that the dynamics of the principal fields in the small LAM domains as revealed by subjecting the limited area to fixed boundary conditions are, in fact, far from unstable, a conclusion consistent with previous predictability studies of LAM. Our interpretation of this seemingly paradoxical result is that the erratic character of the atmosphere is accounted for solely by the global model playing the role of a forcing through the boundary conditions. On the other hand, for sufficiently large domains, the natural erratic dynamics of the atmosphere is recovered. The repercussions of these characteristics on the best choice of the LAM model are briefly discussed in Section 4.

2 The model and the experimental setting

The Eta model is routinely used since 1993 at the NCEP to produce daily high resolution weather forecasts. It is recognized to be one of the best state-of-the-art regional models since it allowed considerable improvements in the skill of the precipitation forecasts over the United States (Mesinger, 2000). A description of this model and some of its more recent modifications can be found in Rogers et al. (1996, 2002).

A workstation hydrostatic version of this model is currently used operationally at the Royal Meteorological Institute of Belgium four times a day. It includes 45 vertical levels with a horizontal resolution of 23 km. In this version, the initial condition is provided by the interpolation of the analysis of the global spectral T170 Avn model used operationally at the NCEP. This analysis represents the best estimate of the state of the atmosphere at the time of prediction. The boundary conditions are provided by the global predictions of the same model. In various uses of the Eta model reported in the literature these conditions are updated every 3 or 6 hours. In the present version of the model a 6 hour updating is adopted.

We have built 5 experimental versions of the model comprising 45 vertical levels with different limited-area domain sizes, integrated with a time step of 120 seconds. The horizontal resolution is of 0.32 degrees on the semi-staggered rotated E grid over which the model is integrated, i.e. 0.32 degrees between the rows along the latitudes and 0.32 degrees between mass and velocity grid points of the semi-staggered grid along the longitude. These experimental models are detailed in Table 1. The largest computational domain covers a region on the rotated grid of about 64°x 64° (longitude x latitude) while the smallest domain is a region of 21°x 21°.

The intrinsic variability of the signals are compared to the Avn analyses over an area centered on France (from -6 to 15° longitude and from 36 to 55° latitude).

3 Intrinsic dynamics of the Eta model

The integration of the evolution equations of a spatially extended dynamical system like the LAM necessitates the choice of initial and boundary conditions. In practice, the latter are provided by coupling the LAM to an outer autonomous model of coarser resolution as mentioned in section 2. Figure 1 (thin lines) depicts the type of boundary conditions provided through this coupling to the Eta LAM at one boundary grid point at level 20, for a particular field (here a horizontal component of the wind) and for different calendar dates sampled during summers 2000 and 2001. In view of the complexity of this boundary condition it is legitimate to inquire whether the essential part of the physics comes from such boundary forcings entraining the fine-scale model to remain close to the solution of the coarse one, or, rather, from the dynamical processes taking place within the limited area covered by the fine scale model itself. The answer to this question depends on at least two factors. First, which among the basic physical processes contributing to atmospheric dynamics and accounted for by the coarser model (gravity waves, baroclinic instabilities etc) are also present in their own right within the limited area of interest. And second, what is the characteristic time of response of the subsystem to the boundary forcing and, in particular, is the latter perceived as a sudden or, on the contrary, as an adiabatic perturbation. In the former alternative the system will not be able to reach an attractor in its phase space but will, rather, perform a transient walk in this space. In the latter alternative the system will spend most of its time around an invariant set of phase space, which will merely be modulated by the boundary forcing. Intuitively, one expects that in all the above questions and scenarios the size of limited area considered is bound to play a decisive role.

In order to disentangle the respective roles of boundary forcing and internal dynamics and to assess which of the above two alternatives is likely to be realized we carry out in this section a series of experiments in which the boundary conditions are frozen to a particular value (in the range of values depicted in Fig. 1, thick line). This operation implies that the values of the variables at the boundaries are fixed, but does *not* preclude inflow and outflow from the model domain in, for instance, the form of baroclinic disturbances. On the other hand, the transmission of very large processes like planetary waves is ruled out.

Figure 2 shows the time evolution (every 24 hours) of the mean temperature (a) and humidity (b) at 850 hPa predicted by the model integrated over 3 of the 5 experimental domains (see Table 1) and averaged over the whole output grid (see Section 2) starting from the boundary and initial conditions of July 14, 2000, at 00Z for models $D1$, $D3$ and $D5$. The pluses represent the natural evolution of the successive 24h Avn analyses interpolated and averaged over the same domain. Note that the integrations of models $D2$ and $D4$ are not shown for clarity because their behavior is qualitatively similar to that of $D1$ and $D5$, respectively. From Fig. 2, it is seen that the models, differing only by the size of the computational domain and starting with almost the same initial conditions, display very different behaviors. Specifically, the integration on small domains ($D1$ and $D2$) leads to an evolution characterized by the absence of variability in the model fields (except the diurnal cycle not shown for clarity). Indeed, the time evolution of the averaged fields is extremely flat when compared to the natural variability depicted by the analyses. This asymptotic trend is observed for all model variables for domains $D1$ and $D2$ (Fig. 2, long-dashed line). On the contrary, the integration on larger domains displays a pronounced variability with an apparent erratic behavior on the largest domains explored, $D4$ and $D5$. This result already suggests that, at least qualitatively, the variability of the atmosphere could only be reproduced by regional models of domain sizes beyond some minimal value.

Looking closely at the details of the weather evolution during the 80 days of integration on the larger domains $D4$ and $D5$, we have found a succession of highs and lows developing or entering in the target area whose typical life time was of the order of a few days whereas their space scale was of the order of the size of the target area. This suggests that the larger domains are able to sustain dynamical processes related to the baroclinic eddies known to be at the origin of the midlatitude synoptic systems.

The above conclusion is further supported by the fact that the typical wavelength of these baroclinic waves is of the order of 4000 km (see for instance Holton, 1972). Therefore in order to capture this type of phenomena, the model at hand should at least be integrated on a domain whose horizontal dimension is larger than this typical wavelength. Domain $D1$ whose size is approximately equal to 2200 km x 2200 km is much too small to resolve these scales. This is reflected by the unrealistic asymptotic drift toward a stable attractor found for this domain. Domains $D2$ and $D3$, while closer to the typical baroclinic wavelength, are still not large enough to account adequately for the physics of mid-latitude synoptic systems. Domains $D4$ and $D5$ whose sizes are larger than 6500 km x 6500 km resolve part of the spectrum of baroclinic waves, and this is reflected in the more erratic dynamical behavior of Fig. 2 and therefore should be closer to the dynamics of the real atmosphere.

In order to check the stability of these asymptotic states, one can compute several trajectories starting from slightly different initial conditions. A very simple way to choose such initial conditions is to use time-lagged analyses or forecasts close to the analysis at $00UTC$ of the forecast Day D (Dalcher and Kalnay, 1989). The results are depicted in Figs. 3 a, b, c and d for domains $D1$, $D3$, $D4$ and $D5$, respectively, results for domain $D2$ being qualitatively similar to the ones of domain $D1$. For small domains (Fig. 3a), the trajectories starting from these different initial conditions (for a given model and with the same boundary couplings) evolve toward the same asymptotic state, whose only time dependence is the periodic diurnal signal (not shown). One therefore deals with the unrealistic picture of a dynamical system that reaches for long times an unrepresentative asymptotic stable state.

For large domains ($D4$ and $D5$, Figs. 3c and d), slight changes in the initial conditions lead to substantially different trajectories even if the boundary conditions are kept identical. The distance between them increases (erratically) in time, suggesting that the unstable (chaotic) nature of the atmosphere is, at least qualitatively, recovered. This divergence between the trajectories of a particular model cannot be related, straightforwardly, to the dominant Lyapunov exponent of the system since there is most probably a transient period during which the model is moving toward its own attractor. In order to obtain a first estimate, we have computed the mean amplification rate of a small error between two trajectories differing only by the sea surface temperature boundaries, of model $D5$ starting from an initial condition obtained after a transient period of 40 days (cf. Fig. 2). The mean amplification rate of the error is found to be about $0.15\,\mathrm{day}^{-1}$. The order of magnitude of this quantity is acceptable but quantitatively it is rather small as compared to the estimated amplification rate of initial errors in the atmosphere or in global atmospheric models (see for instance Simmons et al, 1995). Two possible explanations can be advanced: the particular experiments considered belong to stable regions in phase space, or the size of the domains are still too restricted to be able to reproduce a realistic value of the largest Lyapunov exponent. The first possibility has been explored by considering other initial dates (providing the initial and boundary conditions) for which similar amplification rates have been found. One can therefore argue that although the variability of the largest domain models used here is closer to reality, the intrinsic amplification of small perturbations remains quite limited as compared to the one of the global atmosphere. It is expected that larger regional domains (like the ones used currently at the NCEP) should be even closer to the dynamics of Reality.

For the intermediate domain, $D3$, the trajectories issued from different initial conditions seem neither to converge to the same "asymptotic" (after 40 days) situation nor to display very different paths (Fig. 3b). Indeed, the distance between these trajectories grows more slowly in time than the one obtained on larger domains and displays a strong (multi-)periodic component up to 40 days. Although for long times (see Fig. 2) the behavior of the fields on this domain does not seem to display a clearcut periodic or multiperiodic signal (a longer run would be necessary), it is reminiscent of the error dynamics found on periodic or multiperiodic attractors.

These results indicate that in our regional Eta model the domain size plays the role of a bifurcation parameter as in simple spatially distributed systems (Manneville, 1990) leading to a clearcut change of the nature of the dynamics as the system size increases.

We have explored boundary conditions pertaining to other calendar dates as well. In this case although the structure of the coupling files provided by the Avn model are significantly different, the results found are qualitatively similar: the nested models with small domain sizes still evolve smoothly toward a stable asymptotic state (whose value is strongly dependent on the boundary conditions), while a more erratic behavior is found for very large domains.

4 Discussion

We have shown that one of the main characteristics of the Eta regional model integrated on small domain sizes is the existence of a stable dynamics once the boundary conditions are fixed. The unique source of intrinsic variability is thus, in this case, provided by the global model through the boundary conditions. For very large domains, a non-trivial dynamics, probably chaotic, is recovered which is expected to be closer to reality. This property can be related to the fact that these model versions resolve part of the synoptic scales at which large-scale baroclinic instabilities act. Moreover, the results indicate that a lower bound in the domain size exists such that certain important features (here the baroclinic eddies) of the flow can be incorporated and lead to a clearcut improvement of the intrinsic variability of the model (see also Chomé et al., 1999; Chomé and Nicolis, 1999; Chomé, 2001).

This qualitative change of the nature of the intrinsic dynamics should have a strong impact on the type of solution that can be produced by the regional model once the boundary forcings are updated. Obviously, for small domains, the intrinsic solution is far from reality and the dynamics of regional solution is slaved to the sudden changes at the boundaries. For intermediate domain sizes, the intrinsic variability is more pronounced but the boundaries are strongly affecting the nature of the solution. Finally, for very large domains, the boundaries are acting much more like adiabatic perturbations that modulate the internal chaotic solution.

Several domain sizes have been explored in the present work. It is clear that both smaller and larger domains can be considered as well. For smaller domains, we suspect that the internal dynamics should be the same as for $D1$ since the spatiotemporal dynamics depends generically on the number of unstable modes which in turn depends on the size of the domain of the system (Manneville, 1990). For the same reason, one can suspect that the model integrated on even larger domain sizes could display a dynamics even closer to the large-scale dynamics of the atmosphere. However, these very large domains (keeping the resolution unchanged) imply a huge computer time demand and under these circumstances, one may wonder whether the integration of the global model at a higher resolution with an improved physical package will be more appropriate.

An additional question that could be raised at this stage is the role of the intrinsic variability on the skill of the system. As a preliminary analysis of the impact of the domain size on the forecast quality, we have performed a predictability experiment using forecasts from 15 dates sampled during the summers 2000 and 2001. For that purpose, the boundary conditions have been updated every 6 hours with the Avn predictions and the mean square error between the Eta forecasts and the Avn analyses over the region of interest (see Section 2) averaged over the 15 dates has been computed. Figure 4 summarizes the results where the averaged root mean square error at 48 hour lead time for 850 hPa geopotential height (dashed line) are displayed as a function of the domain size. The skill of the forecast decreases with the increase of the domain size up to domain $D3$. For the larger sizes the tendency is reversed and the skill increases with the domain size leading to a considerable improvement of the forecast quality for domain $D5$ (though not as substantial as the one on the smallest domain). At 500 hPa, a similar trend is found, except that the model version $D4$ is now the one possessing the poorest skill (Fig. 4, solid line), indicating that intermediate size models, for which boundary perturbations and intrinsic dynamics are strongly competing, lead to the poorest prediction systems. The above preliminary results suggest a complex dependence of predictability of large scale flows on the domain size.

Throughout this work we focused on large scale variability of LAM. On the other hand, even when such models account poorly for this type of variability (as is the case in models $D1$ and $D2$ in the present study) they may still be useful in predicting such small scale features as precipitation patterns and boundary layer related phenomena. A unified analysis incorporating both short and large scales would certainly be worth addressing in the future.

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Figure captions

Figure 1: Evolution of the x-wind component (m/s) at 1 boundary point at level 20 of the smallest Eta regional model version for different calendar dates selected during summers 2000 and 2001 (thin lines). The boundary conditions are fed with the predictions of the T170 Avn model every 6 hours. The thick line indicates the boundary condition chosen in the frozen boundary experiment.

Figure 2: Time evolution (sampled every 24 hours) of temperature, degree Celsius, (a); and relative humidity, %, (b) at the 850 hPa level obtained through the integration of the Eta model on domains $D1$, $D3$ and $D5$ (see Table 1) and averaged over the target area centered on France (from -6 to $15°$ longitude and from 36 to $55°$ latitude). The boundary conditions are frozen to their initial configuration (14 July 2000 at 00Z). For reference, the trajectory of the Avn analyses averaged over the same area is shown (crosses).

Figure 3: Time evolution (sampled every 24 hours) of the mean temperature, degree Celsius, at the 850 hPa level, averaged over the target area (see Section 2), as obtained from integration of the model on domains $D1$ (a), $D3$ (b), $D4$ (c) and $D5$ (d) listed in Table 1. The boundary conditions are frozen to the configuration of July 14, 2000 at 00Z. For each of these domains, three trajectories have been computed starting from slightly different initial conditions.

Figure 4: The root mean square error averaged over the 15 dates selected during summers 2000 and 2001 at 48 hour lead time for the geopotential height (m) at 850 hPa (dashed line) and at 500 hPa (solid line) as a function of the domain size.

Table 1: The different experimental Eta models used in this study.

Acronym	Approximate Eta rotated grid extension (lon x lat)	center of the model domain (lon x lat)	nb. of mass gridpoints in the west-east direction x nb. of rows
D1	$(21^o \times 21^o)$	$5^o, 46^o$	33 x 67
D2	$(43^o \times 43^o)$	$5^o, 46^o$	67 x 133
D3	$(51^o \times 51^o)$	$6^o, 46^o$	80 x 159
D4	$(61^o \times 61^o)$	$0^o, 46^o$	95 x 189
D5	$(64^o \times 64^o)$	$-11^o, 48^o$	100 x 199

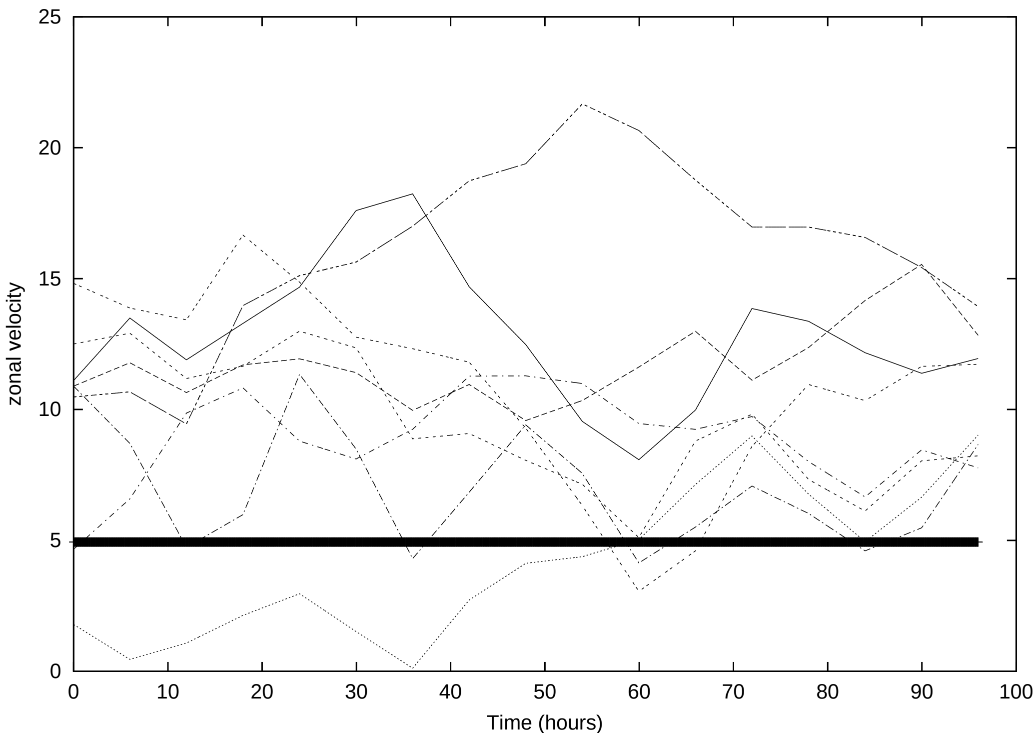
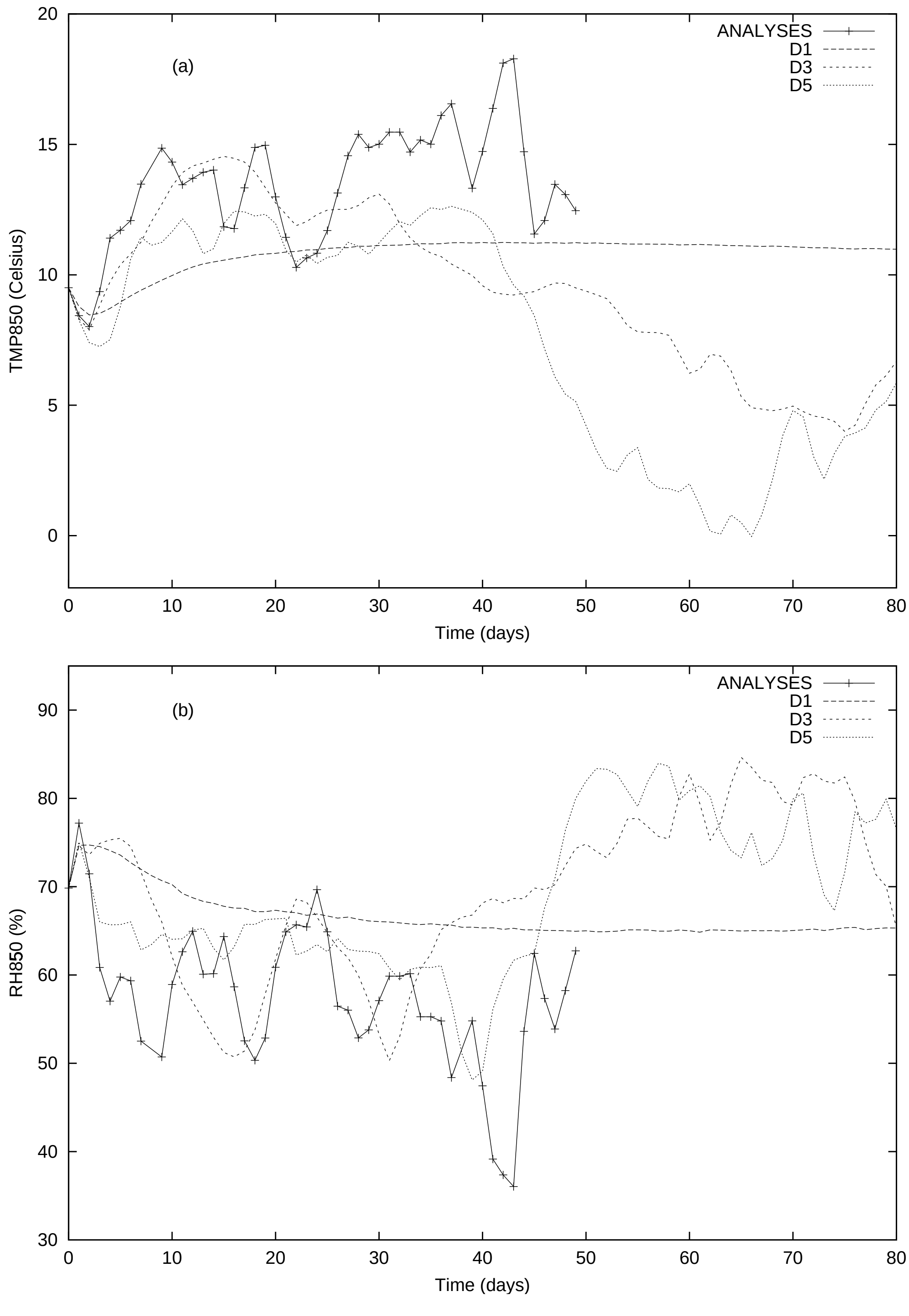
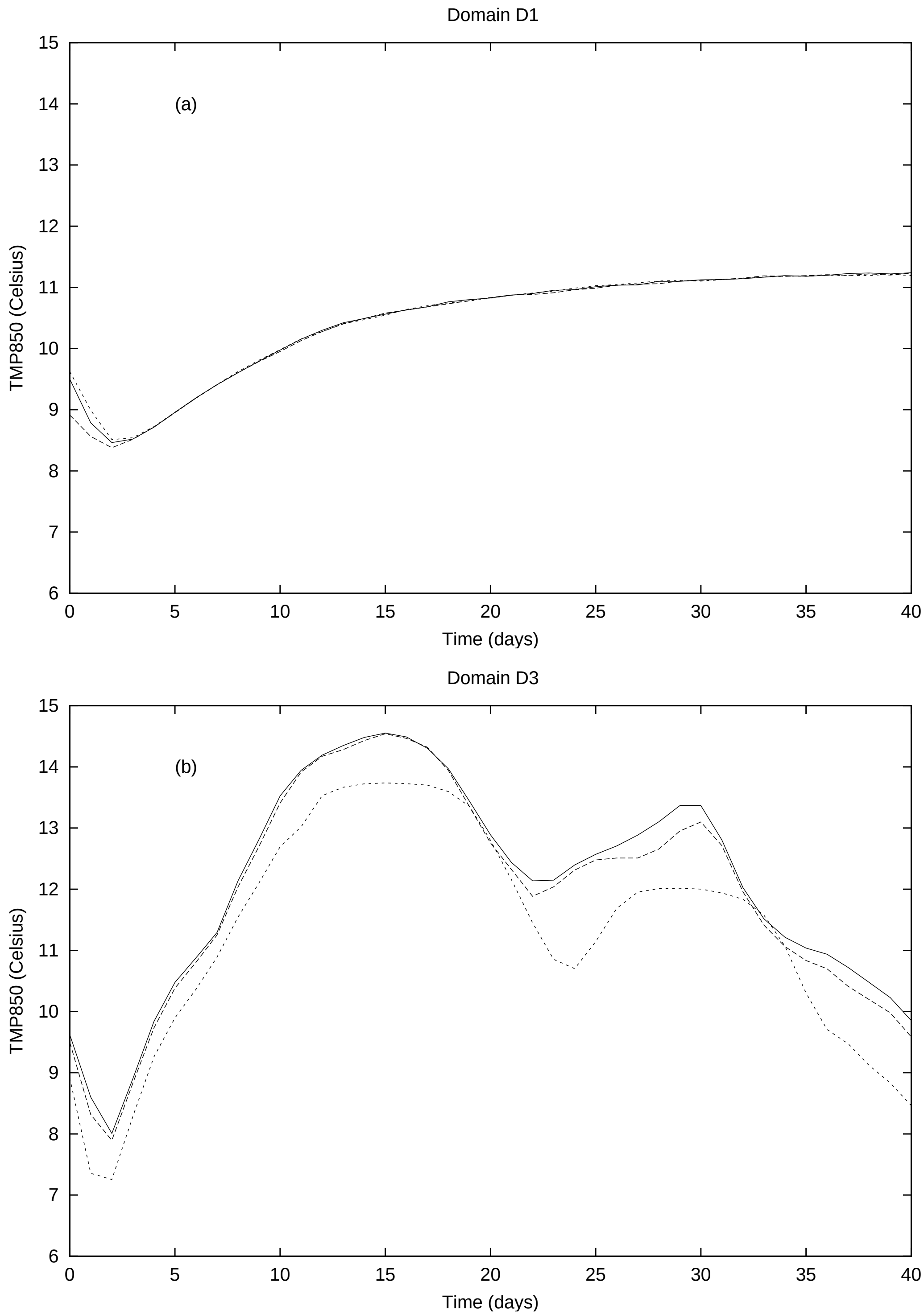


Figure 1



(a)
ANALYSES
D1
D3
D5
TMP850 (Celsius)
Time (days)
(b)
ANALYSES
D1
D3
D5
RH850 (%)
Time (days)

Figure 2



Domain D1
(a)
TMP850 (Celsius)
Time (days)
Domain D3
(b)
TMP850 (Celsius)
Time (days)

Figure 3

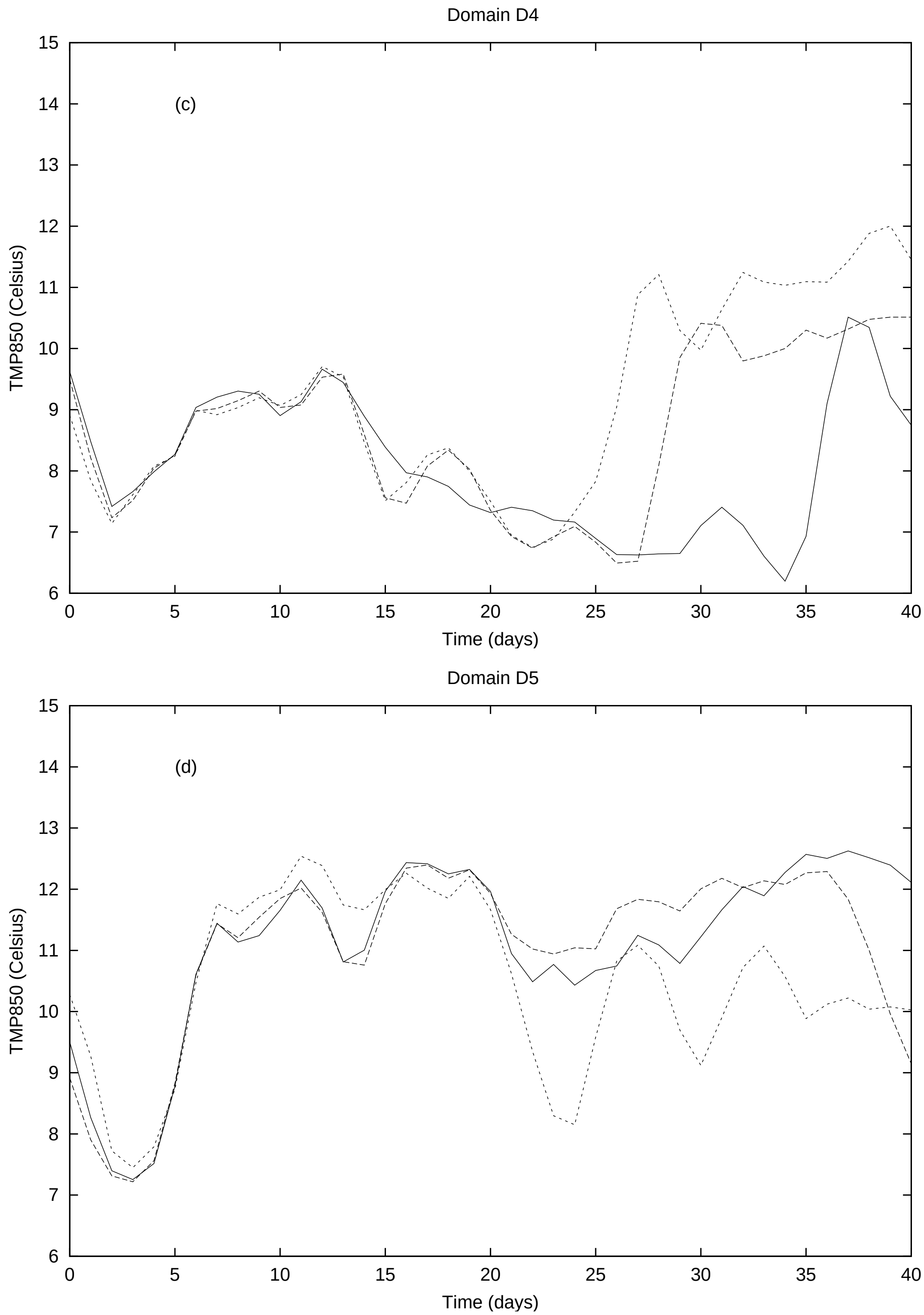


Figure 3, continued

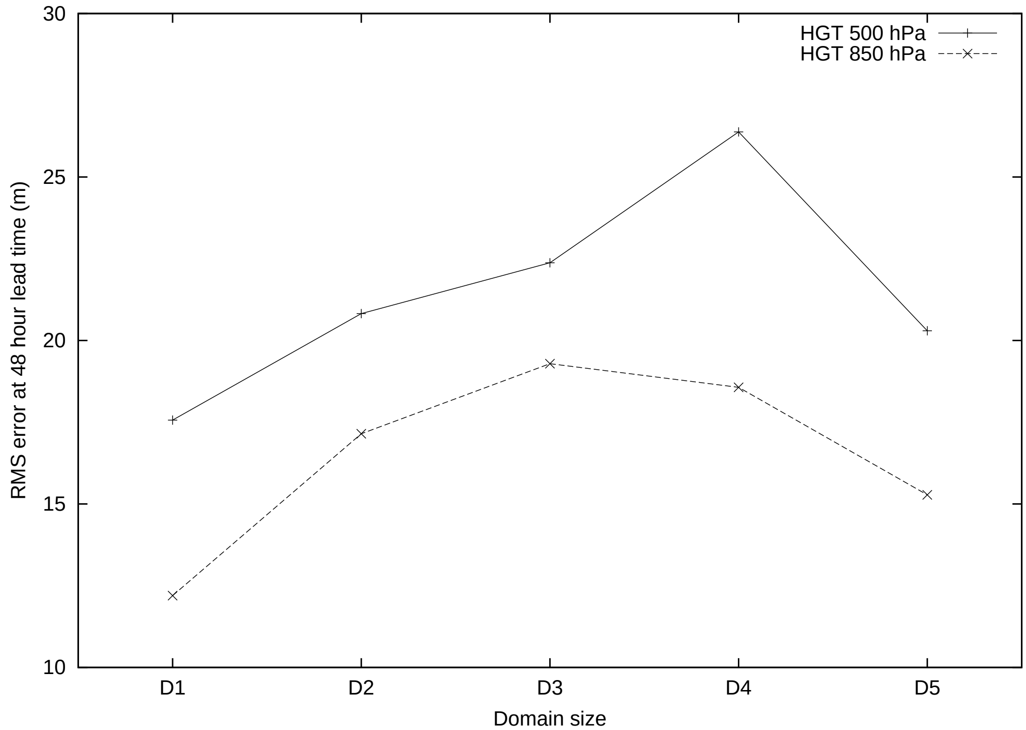

30
25
20
15
10
RMS error at 48 hour lead time (m)
HGT 500 hPa
HGT 850 hPa
D1
D2
D3
D4
D5
Domain size

Figure 4