ATMOSPHERIC PREDICTABILITY AT SYNOPTIC VERSUS CLOUD-RESOLVING SCALES

by Cathy Hohenegger and Christoph Schar

A quantitative comparison of predictability at the two scales raises questions about the applicability of typical synoptic NWP strategies to short-range, cloud-resolving forecasts.

The atmosphere is a chaotic dynamical system, and this implies intrinsic predictability limitations (e.g., Lorenz 1963; Ehrendorfer 1997; Palmer 2000). Small-scale uncertainties, which are inevitably present in numerical weather prediction (NWP) models, amplify with time, lead to a divergence of initially nearby phase-space trajectories, and disrupt the skill of the forecast. The resulting predictability limitations set an upper bound on potential forecast capabilities and amenable lead times, and, as such, constitute a fundamental aspect of NWP.

On synoptic scales, the chaotic nature of the atmospheric dynamics has been addressed by the development of ensemble prediction systems (EPS) (see, e.g., Kalnay 2003). EPS in effect sample the possible evolution of the atmosphere by integrating a set of simulations generated by perturbing their initial conditions. In general, the ensemble mean exhibits a better skill than a single (deterministic) integration. Moreover, the ensemble spread can serve as an indicator for...
the predictability of the simulated weather event (see, e.g., the simulated precipitation rates in Fig. 1).

EPS have initially been applied to medium-range synoptic-scale weather forecasts, and many studies have documented their usefulness (e.g., Molteni et al. 1996; Toth and Kalnay 1997; Houtekamer et al. 1996; Zhu et al. 2002). The latest developments include the consideration of model errors (e.g., Buizza et al. 1999; Mylne et al. 2002), the diagnosis of sensitive regions requiring supplementary measurements [adaptive or targeted observations, see, e.g., Bishop and Toth (1999)], and their implementation to either seasonal predictions (e.g., Palmer and Anderson 1994) or limited-area models (e.g., Hamill and Colucci 1998; Du et al. 1997; Stensrud et al. 1999; Marsigli et al. 2001; Grimit and Mass 2002; Eckel and Mass 2005).

In recent years, interest has grown in the application of EPS to next-generation NWP models (Fritsch and Carbone 2004; Kong et al. 2006) that explicitly resolve moist convective processes [grid spacing O(1 km)]. The development of these cloud-resolving models is well underway [e.g., the Weather Research and Forecasting model in the United States or the Lokal-Modell (LM) Kürzestfrist in Europe] because a higher horizontal resolution is hoped to improve the forecast skill (Mass et al. 2002). As illustrated in Fig. 1, cloud-resolving simulations face qualitatively similar difficulties as synoptic-scale integrations. In particular, numerical experimentations conducted within the Mesoscale Alpine Programme (MAP; see Bougeault et al. 2001; Benoit et al. 2002) have demonstrated that predictability limitations occurring at such scales are highly relevant for quantitative precipitation forecasting (e.g., Richard et al. 2003; Walser et al. 2004; Hohenegger et al. 2006) and flood forecasting (e.g., Bacchi and Ranzi 2003; Benoit et al. 2003; Walser and Schär 2004), even when assuming a perfect model and a perfectly predictable synoptic-scale situation.

Despite promising prospects, the application of traditional ensemble methods to cloud-resolving models raises the following series of fundamental questions: Do standard synoptic-scale EPS strategies still remain appropriate? What are the relevant growth mechanisms and associated doubling times? What is the role of nonlinearity? It is the goal of this article to address these issues.

Our approach will employ a comparison between medium-range synoptic-scale and short-range cloud-resolving simulations. This comparison will make use of three distinctive time scales. The first is the lead time, which derives from meteorological practice (or plans for future practice). We assume characteristic lead times of 10 days and 1 day for synoptic-scale and cloud-resolving NWP integrations, respectively. The second time scale is the asymptotic doubling time of perturbation growth. It is intrinsic to the simulations considered and depends upon the underlying instabilities. The third time scale is the tangent-linear time scale, designating the integration period during which linear theory qualitatively applies.

Because many NWP procedures explicitly or implicitly adopt the tangent-linear approximation (see, e.g., Kalnay 2003), our study may serve to assess the applicability of such methods to short-range cloud-resolving simulations. This especially concerns singular-vector and breeding-mode methodologies to generate optimal perturbations, traditional techniques for adaptive observations, and four-dimensional variational data assimilation (4DVAR). Even beyond linear techniques, nonlinearity plays a central role in forecasting. In particular, as soon as an NWP integration enters the full nonlinear regime, the question of using a particular ensemble, targeting, or data assimilation method is a moot point, because a regular one-to-one mapping between initial and evolved perturbations no longer exists. This may be critical if the latter transition occurs well within the anticipated forecasting period.

From past experiments, it is expected that an increase in horizontal resolution yields a corresponding decrease in error-doubling times (increase in growth rates) and enhanced nonlinearities. Such results have been obtained for barotropic flows (Tanguay et al. 1995), for global NWP models at varying mesh sizes (e.g., Hartmann et al. 1995; Buizza et al. 1997; Simmons and Hollingsworth 2002; Gilmour et al. 2001), for limited-area integrations (e.g., Ancell and Mass 2006; Errico and Raeder 1999; Zhang et al. 2003), for idealized simulations of moist convection with cloud-resolving models (e.g., Park 1999; Park and Droegemeier 2000; Sun 2005), and from
turbulence theory (e.g., Lorenz 1969; Leith 1971). The expected degradation of the tangent-linear approximation implies that the usefulness of adjoint-based methods may decrease with increasing resolution. These ideas will be further investigated herein and systematically quantified for real-case global and cloud-resolving simulations.

The remainder of this article is structured as follows: in “Experimental setup” we document the numerical models and their setups. Respectively, “Error growth mechanisms and doubling times” and “Nonlinear effects and the tangent-linear assumption” are devoted to the derivation of the doubling times and tangent-linear time scales. The study is concluded in the final section.

EXPERIMENTAL SETUP. To conduct our comparison, we use as examples of medium-range synoptic-scale and short-range cloud-resolving NWP the operational European Centre for Medium-Range Weather Forecasts (ECMWF) EPS (see, e.g., Buizza et al. 2005) and simulations performed with the LM (Steppeler et al. 2003; Hohenegger et al. 2006), respectively. We believe that our conclusions qualitatively hold for any modeling systems with the respective resolutions, provided the high-resolution model is compressible such as to support sound modes, which is a property that has been shown to affect error propagation in cloud-resolving models (Hohenegger and Schar 2007).

The technical specifications of the two systems are listed below: The ECMWF EPS is a global system with a horizontal spectral resolution of T255 (80 km). More recently (February 2006), it has been upgraded to T399 (50 km). The ensemble contains 50 members generated by using singular vectors. Singular vectors aim to identify initial perturbations that grow fastest over a finite time interval, in a linear sense, and with respect to a chosen norm (see, e.g., Mureau et al. 1993). For the current study, we consider one single ensemble forecast from the year 2005. We believe that this is likely sufficient, because in a global ensemble a wide range of differing flow situations is accounted for by design (see also the “Summary and discussion”).

The LM integrations have a horizontal resolution of 0.02° (2.2 km) and are integrated in a computational domain covering 882 km × 662 km (see, e.g., Fig. 2) for three cases characterized by weak-to-strong convective activity. The different initial conditions are obtained, unless stated otherwise, by shifting the initialization time of each simulation by 1 h [see Hohenegger et al. (2006) for further details]. The construction of initial perturbations for cloud-resolving integrations is still an unresolved issue and allows for many subjective choices. The shifting initialization

![Fig. 1. Examples of precipitation forecast obtained with (a), (b) a medium-range synoptic-scale EPS [ECMWF, mm (6 h)⁻¹] and (c), (d) a short-range cloud-resolving prototype EPS (LM, mm h⁻¹). Time (h) 0 corresponds to (a) 1200 UTC 3 Oct 2005, (b) 1200 UTC 20 Apr 2006, (c) 2100 UTC 16 Sep 1999, and (d) 2100 UTC 19 Sep 1999. The ensemble members are shown in gray and the control run in black. Results are for area-mean precipitation amounts in a box of 5 × 5 grid points. The 50 ECMWF members use singular vectors as initial perturbations, while the 20 LM integrations are generated by shifting the initialization time or by introducing initial random perturbations. Further details on the technical specifications of the two ensembles can be found in “Experimental setup.” Note how both systems show unpredictable [e.g., (a) 0–240 h; (c) 0–12 h and 26–34 h] and predictable [(b) 0–36 h; and (d) 9–21 h] episodes of precipitation.](image-url)
technique in effect generates small-scale perturbations that are regime dependent. They have a demonstrated tendency to grow within the forecasting system, although they are less optimal than singular vectors in triggering fast error growth (e.g., Kalnay 2003). The boundary conditions of the 2.2-km LM integrations are downscaled from the ECMWF analysis with an intermediate-resolution 7-km (0.0625°) LM simulation. They are identical in all members (thus assuming perfect synoptic-scale predictability). This procedure serves to separate the two predictability problems—one associated with the synoptic scale (represented by the ECMWF EPS) and one with the cloud scale (represented by the LM).

ERROR GROWTH MECHANISMS AND DOUBLING TIMES. Figure 2 shows differences obtained between two ECMWF and LM members, respectively. In both cases, the imposed initial perturbations amplify, but there are striking differences. In the ECMWF, large finite-amplitude perturbations can be found in the displayed 500-hPa geopotential height and 2-m temperature fields. Associated peak values are of the order of ±125 m and ±5 K, respectively, after 30 h of integration (see Figs. 2a,b). For the 4 October 2005 case, the ECMWF control simulation yields a cyclonic development over Ireland, while the first member simulates an anticyclone. Error growth is primarily embedded in baroclinic activity (Buizza and Palmer 1995; Molteni and Palmer 1993).

In the LM (Figs. 2c,d), in opposition, the perturbations are negligible at the 500-hPa geopotential height (order of some few meters), while they still significantly affect temperature with values peaking around ±2.5 K. As implied by the use of identical lateral boundary conditions, the synoptic situation

![Figure 2](https://example.com/figure2.png)

**Fig. 2.** Examples of difference map for (a), (b) synoptic-scale (ECMWF) and (c), (d) cloud-resolving (LM) ensemble members, 30 h after initialization, in terms of (a), (c) 500-hPa geopotential height (m) and (b), (d) 2-m temperature (K). The selected ECMWF EPS member is based on the first singular vector, while the initial perturbation for the LM is generated by shifting the initialization time by 1 h. Control simulations start at 1200 UTC 3 Oct 2005 and 2100 UTC 16 Sep 1999 for the ECMWF and LM, respectively. The LM computational domain is indicated in green on the top maps.
is fixed for all the ensemble members. Error growth is thus restricted to mesoscale processes, which especially impact temperature and precipitation. For the case under consideration, both perturbed and control simulations predict the development of a squall line over the Alpine region, but both the timing and amount of precipitation vary (see, e.g., Fig. 1c). Mesoscale error growth can be particularly strong in regions of convective instability (Zhang et al. 2003; Hohenegger et al. 2006), where it is able to significantly disrupt the predictability of the simulated flow and the skill of a short-range weather forecast, even at scales exceeding 100 km [and despite identical lateral boundary conditions; see Walser et al. (2004)].

Figure 3 serves to estimate the associated doubling times, growth rates, and saturation time scales. For simplicity, we calculate exponential growth rates from domain-mean rms differences between two selected ensemble members. The computations use the 500-hPa geopotential height and the temperature in the lowest model layer for the ECMWF and LM, respectively, because the chosen variables need to be primarily sensitive to the underlying baroclinic and convective instability (see also the “Summary and discussion” section). Because the estimates depend upon the imposed initial perturbations, we further choose for the LM temperature perturbations with a ratio between the initial and saturation amplitude that is comparable to the one obtained in the ECMWF EPS.

In the ECMWF EPS (Figs. 3a–c), saturation of perturbation growth takes place between 6 and more than 10 days, and in the LM (Figs. 3d–f) the saturation takes between 12 and 28 h. Although the computed values vary both among ensemble members and among simulated synoptic- and mesoscale situations, error saturation tends to occur ~10 times earlier in the LM as compared to ECMWF. Similarly, the estimated doubling times (a few days for ECMWF and a few hours for the LM) are typically one order of magnitude smaller in the LM. The derived doubling

---

**Fig. 3.** Time series of the rms difference between perturbed and control simulations for (a), (b), (c) the 500-hPa geopotential height (m) in the ECMWF EPS averaged over the northern extratropics and (d), (e), (f) the temperature (in the lowest model layer, K) in the LM averaged over its whole computational domain. Regression lines and slopes are indicated in red, doubling times are in green; time is in hours. Three typical examples are shown for each EPS. For the ECMWF, we show the members starting from the (a) 1st, (b) 9th, and (c) 29th singular vector, initialized at 1200 UTC 3 Oct 2005. For the LM, we use a Gaussian temperature perturbation introduced at (d) 2100 UTC 16 Sep 1999, (e) 2100 UTC 19 Sep 1999, and (f) 2100 UTC 24 Sep 1999.
times are consistent with typical growth rates of baroclinic instability (e.g., Snyder and Joly 1998) and convective instability (e.g., Fuhrer and Schär 2005), respectively.

Closer inspection of Fig. 3 reveals some additional interesting features that result from the choice of the initial perturbations. In the case of the ECMWF operational EPS, singular vectors induce transient (nonmodal) growth during the first 2 days (see Figs. 3a–c), which may be much faster than the mean exponential (Lyapunov type) growth. This confirms the efficacy of the singular-vector methodology in selectively triggering the fastest-growing perturbations. In contrast, the initial growth rates in the LM (see Figs. 3d–f) are substantially smaller (or even negative) than the derived exponential rates. The LM Gaussian temperature perturbations are by no means optimal, and only their projection upon rapidly growing modes will amplify.

In order to derive a representative value for the doubling time of perturbation growth $T_d$ characterizing each system, we compute the median of the analysis (shown in Fig. 3) for all ensemble members. This yields 40 and 4 h for ECMWF and LM, respectively. The values scale like the respective lead times in both systems ($T_{\text{lead}}/T_d = 6$, as listed in Table 1). In terms of intrinsic growth rates, a 10-day synoptic-scale forecast thus corresponds to a 1-day cloud-resolving simulation. From this point of view, the prospects for 1-day cloud-resolving weather forecasts appear promising, in the sense that the successful synoptic-scale NWP strategies (EPS, data assimilation, and targeting techniques) may be equivalently applied to short-range cloud-resolving integrations. This argument, however, ignores the role of nonlinearity, as discussed below.

**NONLINEAR EFFECTS AND THE TANGENT-LINEAR ASSUMPTION.** Figure 4 shows the temporal evolution of linearity indicators for ECMWF and LM ensemble members starting from initially anticorrelated perturbations. This technique has been used in several previous studies (e.g., Gilmour et al. 2001; Reynolds and Rosmond 2003) to assess the degree of linearity characterizing NWP integrations. The selected indicators are the spatial correlation $r$ and the relative linearity $\theta$, defined as (see Gilmour et al. 2001)

$$r = \frac{\text{Cov}(\delta^+, \delta^-)}{\sqrt{\text{Var}(\delta^+) \text{Var}(\delta^-)}}$$

$$\theta = 2 \frac{||\delta^+ + \delta^-||}{||\delta^+|| + ||\delta^-||},$$

with $\delta^+$ ($\delta^-$) denoting positive (negative) initially anticorrelated perturbations, and Cov (Var) their covariance (variance). The norm $|| \cdot ||$ is defined by the inner product $\langle \cdot, \cdot \rangle$. In the case of a perfectly linear system, the correlation coefficient and relative linearity would stay at their initial values of $r = -1$ and $\theta = 0$, respectively. For random realizations, they amount to $r = 0.5$ and $\theta = \sqrt{3}$ (see Hohenegger and Schär 2007).

Both ECMWF and LM integrations drift away from the linear regime and finally resemble random realizations (see Fig. 4). This transition occurs much earlier and well within the forecasting period with the LM (for the cases and perturbations tested) compared to the ECMWF EPS. More specifically, we adopt intermediate values of $r = -0.25$ and $\theta = \sqrt{3}/2$ to signal the breakdown of the tangent-linear assumption. The tangent-linear approximation loses its validity between 42 and 144 h for the ECMWF EPS and between 1 and 5 h for the LM. Because the correlation coefficient may be biased (Gilmour et al. 2001), we take as a reference for the tangent-linear time scale $T_{\text{lin}}$ the median time of the simulation pairs of Fig. 4 at which they reach $\theta = \sqrt{3}/2$. This yields 54 and 1.5 h for the ECMWF and LM, respectively, as listed in Table 1.

The shorter validity of the tangent-linear approximation in cloud-resolving simulations is in line with the higher growth rates. However, building either the ratio $T_{\text{lead}}/T_{\text{lin}}$ or $T_{\text{lin}}/T_d$ (see Table 1) indicates that the two systems do not scale accordingly. In terms of nonlinearity, a 10-day synoptic-scale forecast only compares to a 7-h cloud-resolving integration. This

<table>
<thead>
<tr>
<th>Table 1. Typical time scales associated with medium-range synoptic-scale (ECMWF) and short-range cloud-resolving (LM) simulations.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>ECMWF</td>
</tr>
<tr>
<td>LM</td>
</tr>
</tbody>
</table>
is much shorter than the anticipated lead time of 1 day. Because synoptic-scale and cloud-resolving simulations do seem to live in different linear regimes (at least for the investigated cases), the prospects for the direct application of certain synoptic-scale analysis and EPS methodologies to cloud-resolving scales appear less promising.

To further illustrate the meaning of the obtained differences in tangent-linear time scales between the two systems, we briefly consider the Lorenz model. The Lorenz system of equations shows chaotic behavior for suitably chosen parameters and has thus widely been employed as a simplified dynamical system to study the nature of atmospheric predictability (see especially Palmer 1993). Figure 5 shows the

**Fig. 4.** Time series of the (a), (c) correlation coefficient and (b), (d) relative linearity between twin positive-negative perturbation pairs for (a), (b) the ECMWF and (c), (d) the LM. The computations use the 500-hPa geopotential height for the ECMWF (northern extratropics; simulations start at 1200 UTC 3 Oct 2005) and the temperature in the lowest model layer for the LM (whole LM domain; simulations start at 2100 UTC 16, 19, and 24 Sep 1999), respectively. The green and red lines indicate the theoretical values for linear and random dynamical systems, respectively. The blue lines denote the adopted thresholds for the breakdown of the tangent-linear approximation at $r = -0.25$ and at $\theta = \sqrt{3}/2$. Time is in hours.

**Fig. 5.** (a) Projection of the Lorenz attractor on the $x$-$z$ plane and (b)–(f) sensitivity to its initial conditions expressed as $X = f(X_0, t)$, where $X = (X, Y, Z)$ denotes the end point (forecast) of the trajectory at time $t$, which started at $X_0$ (initial condition). The color shading signifies the end point $X = X(X_0, Y_0, Z_0, t)$ for the indicated lead time $t$, while the position on a map provides the initial conditions ($X_0, Z_0$).
Lorenz attractor and the related sensitivity to its initial conditions in terms of $X = f(X_o, t)$. The two regimes of the attractor (i.e., the left and right wings) are colored blue and red, respectively. Elongated regions with strong color gradients (e.g., near $X_o = 10$, $Z_o = 35$ for $t = 1$) represent bifurcation points; here, initially neighboring trajectories end up far away from each other. These regions in phase space mark initial conditions where the evolution of the flow is hardly predictable.

Using the scaling associated with the tangent-linear time scale, the integration of the ECMWF to 5 days and the LM to 12 h (half of the respective lead times) gives 2.2 and 8 nondimensional time units, respectively. The comparison of the corresponding panels of Fig. 5 reveals the more advanced fragmentation of the phase space characterizing a 12-h LM forecast (see Fig. 5f) as compared to a 5-day ECMWF integration (see Fig. 5d). This itself implies a weaker relationship between initial and future states, which would in principle reduce the optimal performance of certain NWP analysis methodologies at cloud-resolving scales for the assumed lead time.

**SUMMARY AND DISCUSSION.** Some fundamental properties characterizing cloud-resolving short-range simulations have been investigated and contrasted to the well-known behavior of synoptic-scale medium-range weather forecasts. The main findings can be summarized as follows:

- Error growth rates are about 10 times larger on cloud-resolving scales, where perturbation growth primarily relies upon convective (instead of baroclinic) instabilities. Because the anticipated lead time is also 10 times shorter, the two systems may be seen as equivalent; that is, a 10-day synoptic-scale integration corresponds to a 1-day cloud-resolving forecast in terms of perturbation growth.

- However, at cloud-resolving scales the tangent-linear approximation fails after short integration periods of $O(1.5 \text{ h})$. In terms of nonlinearity, a 10-day synoptic-scale forecast equates to a cloud-resolving simulation with a lead time of merely $\sim 7 \text{ h}$. This is because, integrating a cloud-resolving forecast for 1 day is a fundamentally different task than performing a 10-day synoptic-scale simulation. The earlier loss of a linear relationship between initial and future states on cloud-resolving scales similarly follows when scaling with the intrinsic time scale of the system (error-doubling time).

- While the prospects for the application of synoptic-scale EPS and analysis methodologies to cloud-resolving scales appear promising considering the respective error growth rates, computation of the tangent-linear time scale raises questions about this view. The higher degree of nonlinearity associated with cloud-resolving simulations, even in a nondimensional sense, may deteriorate the optimal performance of techniques relying on the tangent-linear approximation. To take these effects into account, some adaptations in the design of cloud-resolving EPS may be needed. The higher degree of nonlinearity also implies that a simulation tends to “forget” about its initial small-amplitude perturbations within the anticipated forecasting period. This alone would reduce the possible positive impacts of assimilated or targeted observations on successive forecasts.

The main arguments of our study have exploited differences in perturbation-doubling times and in tangent-linear time scales. Further differences exist between synoptic and cloud-resolving integrations, which are likely to be of importance for the design of their related EPS and analysis methodologies. For instance, the convectively active spectral band (below about 20 km) is nearer to the model truncation in cloud-resolving simulations than the baroclinically active band (above 1000 km) in synoptic-scale models. In addition, the high-resolution error field in cloud-resolving integrations may well be saturated by analysis errors already at initial time. Also, convective and baroclinic instabilities live in the $k^{-5/3}$ and $k^{-3}$ spectral regimes, respectively. The predictability associated with these two spectral slopes differs with bounded (for $k^{-5/3}$) and infinite (for $k^{-3}$) predictability in the limit of vanishing initial uncertainty (see, e.g., Lorenz 1969; Lilly 1990). Because cloud-resolving models (and the LM) are able to replicate parts of the $k^{-5/3}$ spectral regime (see, e.g., Skamarock 2004), it may be postulated that a given scale should have an intrinsic predictability horizon rather independent from the initial uncertainty. This itself would question the direct application of synoptic-scale NWP strategies to cloud-resolving scales.

Our study bares several simplifications. First, the derived perturbation-doubling times and tangent-linear time scales depend upon the chosen experimental setup. In particular, the use of random initial perturbations in the LM yields an overconfident estimate of predictability compared to the one derived from the ECMWF EPS. The application of optimal perturbations at cloud-resolving scales would thus likely strengthen our conclusions.
Second, the estimates depend upon the simulated synoptic- and mesoscale situations. Three different cases, characterized by weak-to-strong convective activity, have been investigated for the LM, while the derived ECMWF time scales rely on one single ensemble forecast. Simmons and Hollingsworth (2002) have analyzed error growth in the ECMWF model from integrations started 1 day apart for a wide range of cases (five winter and summer seasons), and found doubling times between 27 and 43 h (see their Table 1). From Fig. 5 of Gilmour et al. (2001), based on 25 winter ECMWF ensemble forecasts, a mean tangent-linear time scale of 60 h can be deduced. The latter values are on the order of the 40 and 54 h listed in our Table 1 for $T_{J}$ and $T_{lin}$, respectively, and corroborate our conclusions. Although the generality of the LM time scales in Table 1 cannot be assessed, we believe that the overall picture will not drastically change, provided the simulated mesoscale situation exhibits some degree of convective instability. Indeed, even by considering the most rapidly growing mode in the ECMWF EPS started at 1200 UTC 3 October 2005, $T_{J}$ only drops to 35 h and $T_{lin}$ to 39 h. The corresponding ratios $T_{lead}/T_{lin}$ and $T_{lin}/T_{J}$ give 6.2 and 1.1, respectively, and hence still do not approach the LM values.

Third, the estimates depend upon the investigated variables. Consideration of the temperature in place of the geopotential for ECMWF yields $T_{J} = 50$ h, $T_{lead}/T_{J} = 4.8$, $T_{lin} = 30$ h, $T_{lead}/T_{lin} = 8$, and $T_{lin}/T_{J} = 0.6$. While $T_{lead}/T_{lin}$ still indicates that a 1-day forecast is too long for the use of certain NWP strategies at cloud-resolving scales, $T_{lin}/T_{J}$ is comparable to the corresponding LM ratio (given the uncertainties in parameter estimation). This partly invalidates our conclusions. The use of geopotential and temperature for synoptic-scale and cloud-resolving simulations, respectively, can nevertheless be justified by noting that the chosen variables need to be primarily sensitive to the relevant instability (baroclinic versus convective). This follows from the different forecasting targets of the two systems (long-lived large-scale versus short-lived small-scale phenomena).

Finally, our analysis has neglected model errors and assumed perfect lateral boundary conditions in the case of the cloud-resolving model. This has been necessary to isolate the two predictability problems associated with both the cloud and synoptic scales. Theoretically, it may be argued that cloud-resolving simulations are especially meant to improve the forecast of those scales that are not contained in the lateral boundary conditions (Laprise et al. 2000). In practice, however, synoptic scale as well as model errors cannot be neglected, and it is likely that scale interactions are important for cloud-resolving ensemble prediction.

**ACKNOWLEDGMENTS.** We are indebted to the German Weather Service (DWD) and MeteoSwiss for providing access to and support for the use of the LM, as well as to the European Centre for Medium-Range Weather Forecasts and MeteoSwiss for providing access to the ECMWF ensemble members. The LM numerical simulations have been conducted on the NEC SX-5 at the Swiss National Supercomputing Centre (CSCS). The authors would also like to thank Daniel Lüthi for technical support, as well as Tim Palmer and Reinhard Schiemann for useful discussions. The comments of the anonymous referees and of the editor are also appreciated.

**REFERENCES**


1792 1 BAF15* NOVEMBER 2007


Northeast Snowstorms offers the most comprehensive treatment on winter storms ever compiled: more than 50 years of professional experience in the form of a two-volume compendium of insights, examples, photographs, over 200 color figures, and a DVD of added material.

Northeast Snowstorms offers the most comprehensive treatment on winter storms ever compiled: more than 50 years of professional experience in the form of a two-volume compendium of insights, examples, photographs, over 200 color figures, and a DVD of added material.

American Meteorological Society; 818 pages, hardbound; AMS code MM54

Price: $100.00 list/$80.00 member/ $60.00 student member

Submit your prepaid orders to AMS, Attn: Order Dept, 45 Beacon St., Boston, MA 02108-3693. Please make checks payable to the American Meteorological Society. If using a credit card (MasterCard, VISA, and American Express accepted), you may place your order by phone to 617-227-2426 x204 or x258 or by email to amsorder@ametsoc.org.