A Note on Atmospheric Predictability

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Abstract

Using the method of Lorenz (1982) we have estimated the predictability of a recent version of the ECMWF model using two different estimates of the initial error corresponding to six and 24 hours forecast errors, respectively. For a six hours forecast error of the extra-tropical 500 hPa geopotential height field a potential increase in forecast skill by more than three days is suggested, indicating a further increase in predictability by another 1.5 days compared to the use of a 24 hours forecast error. This is due to a smaller initial error and to an initial error reduction resulting in a smaller averaged growth rate for the whole seven days forecast. A similar assessment for the tropics using the wind vector fields at 850 and 250 hPa suggest a huge potential improvement with a seven day forecast providing the same skill as a one-day forecast now. A contributing factor to the increase in the estimate of predictability is the apparent slow increase of error during the early part of the forecast.

1 Introduction

The first assessment of atmospheric predictability with realistic models, Smagorinsky (1963), Mintz (1964) and Leith (1965) and summarized by Charney et al. (1966) indicated an error doubling time of around five days. As more refined models were used to estimate the predictability the error doubling time became smaller. Smagorinsky (1969) using a primitive-equation model found a doubling time of three days. These early predictability estimates were undertaken by introducing a perturbation in the initial state of the model integration and then examining the rate at which this new integration deviated from the control.

An alternative approach was undertaken by Lorenz (1982). He proposed that the rate of growth of the forecast differences would provide a suitable upper limit of forecast skill or of its predictability. A convenient measure of predictability could then be found by comparing the one-day forecast with the two-day forecast from the preceding day and the two-day forecast with the three-day forecast from the preceding day and so on. Lorenz illustrated his discussion with results derived from the archived data set of the ECMWF 500 hPa geopotential height analyses and forecasts for the period 1 December 1980 to 10 March 1981. Lorenz found that the error doubling time for small errors was around 2.5 days.

Data sets for assessing predictive skill and predictability along this line have been produced for every subsequent season at ECMWF and used in predictability studies, for example, Simmons et al. (1995). A recent assessment by Simmons and Hollingsworth (2002) indicated a further increase in the early error growth reaching 1.4 days error doubling time for the Northern Hemisphere for day one and day two. As further demonstrated by Simmons and Hollingsworth (2002) the limits of upper and lower predictive skill have over the years been narrowing suggesting that further improvements in forecast skill is limited to a day or two.

The question remains what may constitute a realistic initial error and its likely growth rate in the early phase of a forecast. Lorenz suggested that the growth rate of the early error was determined by an assumed internal growth rate fitted from the growth rate of somewhat larger errors. Simmons et al. (1995) estimated predictability from consecutive twelve hour forecasts for the winter of 1994. They showed that the rate of error growth was practically the same as for the Lorenz curve (Lorenz, 1982) derived from daily data. However, the global observing system continues to evolve and we are now in a position to have access to a comprehensive global coverage of satellite and other non-synoptic information at least at every six hours. Moreover, numerical prediction experiments suggests that the satellite based information dominates over terrestrial based information for the Southern Hemisphere and complements the terrestrial information in the Northern Hemisphere (Bengtsson et al. 2005). It is thus of considerable interest to undertake an experiment to estimate the upper bound of predictive skill (Lorenz, 1981) using a smaller initial error such as the difference between forecasts, which are only six hours apart. We describe here such a predictability experiment.

2 The predictability experiment

This study uses a data set for the winter (DJF) 1990/91 consisting of 360, seven-day global forecasts undertaken from an analysis every six hours. For a description of the experiments used to produce the data see Bengtsson et al. (2005). The control analyses (both for initialisation and validation) were first used, which is ERA40 without humidity observations. As the control system may vary between 00 and 12UTC (with more terrestrial observations) and 06 and 18UTC, we have repeated the experiments in an analagous way using data from a satellite based experiment (Bengtsson et al., 2005), where only observations from satellites and surface pressure data were used, as we anticipate the observational differences between the four observing times to be small. The ERA 40 assimilation system was used to produce the analyses but the forecasts were obtained with a later version of the ECMWF forecast model, IFS version 26R3, (White, 2000). The same resolution, T159L60, as in ERA40 was used

The study is organised as follows. Firstly, we have undertaken independent calculations for the extra-tropics and for the tropics. For the extra-tropics we have selected the 500 hPa geopotential height field as a representative measure of predictability and in the tropics the vector wind at 850 hPa and 250 hPa as the height fields have insufficient variance to be relevant for assessing predictability in the tropics.

Secondly, we have also calculated the growth rate of smaller initial errors by comparing forecasts separated by six hours. For computational reasons the length of the predictions have been limited to seven days. Figure 1 shows the upper and lower bounds for prediction of the 500 hPa geopotential height field for the extra-tropics of the Northern Hemisphere (NH) and the Southern Hemisphere (SH), respectively. Using 50% of the relative error as a measure of skill, the forecasts reach this limit after four days in the average, while the two different predictability estimates based on 24 hours and 6 hours forecast frequency do so at 5.5 days and more than 7 days respectively. An interesting and somewhat unexpected result is the slow error growth in the extra-tropics of the differences between forecasts six hours apart as there is hardly any error growth for the first 24 hours. An inspection of individual maps for the 6 hours ensemble (not shown) gives the impression of a slow and sluggish error growth rate with a few limited areas associated with developing cyclones having a more distinct growth rate. As discussed in Bengtsson et al. (2005) the predictive skill is less for the satellite based system although the difference is small for the SH.

The satellite based experiment is chosen for the SH to provide a more detailed assessment as the observations are more uniformally distributed in time for the four daily observational periods. However, we believe the result to be broadly representative for the NH as well, and also for the experiments using the control analyses. The forecast doubling time of small errors is less than a day for the first 24 hours. It decreases with time and amounts to 2 days between day two and three. The predictability estimate obtained by comparing the differences between forecasts 6 hours apart has a negative growth rate for the first 12 hours, but starts to increase thereafter. At around 48 hours the difference reaches the same value as it had initially. After that the exponential growth rate is almost constant until day seven, corresponding to an error doubling time of 2.4 days. The differences between forecasts 24 hours apart show no initial error reduction but the growth rate for the first day is slightly smaller than for the second and the third day. Between day two and day seven the error doubling time is 3.2 days. Hence, because the forecasts six hours apart had no averaged growth at all in the first 48 hours the mean error amplification until day seven is less than between forecasts 24 hours apart in spite of a more rapid error growth from day two onwards.

The tropical growth rate curves for the wind field, shown in Figure 2, are very similar but with a much slower internal growth than the extra-tropical 500 hPa geopotential height field. In the tropics we used the absolute error of the wind vector field for validation. Here the error growth is about the same for the two ensembles. The forecast error at 850 hPa is slightly less than 4 m s^{-1} at day seven while the two estimates of predictability for 24 hours and 6 hours forecast frequency reaches 2.5 and 2 m s^{-1} respectively. It is interesting to note that the latter predictability estimate at day seven is the same as the actual forecast error at day one indicating the potential for a massive increase in predictive skill in the tropics. The results for the 250 hPa wind field are broadly consistent with the 850 hPa result. Simmons et al., (1995) estimated tropical predictability using the 850 and 200hPa stream function. They noted that there was hardly any growth between day one and day four. Evidently the apparent scope for forecast improvements in the tropics is as large as it was 10 years ago.

3 Discussion

It is not only the smaller error in the 6 hours forecast ensemble which is the cause of the large differences in the assessment of predictive skill compared to the 24 hours ensemble but also the comparatively slower growth rate during the first 30 hours. We find this result rather intriguing, as a general expectation is that smaller errors have faster initial error growth.

What could cause a reduced growth rate in the 6 hours ensemble? This could for example happen if only a minor proportion of the analysis increments are projected onto the faster growing modes. The space based observations, which are more dominant in the 6 hour ensemble, have a more smooth vertical structure (ERA40 uses a three-dimensional variational approach) and are therefore likely to maintain the vertical structure of the first guess and thus perhaps draws less strongly to the individual observations. This means that the analysis increment is less likely to project onto a rapidly growing mode. A detailed inspection of the individual fields suggests this to be the case. This was probably also the case in previous versions of the ECMWF system based on optimum interpolation which according to Simmons et al., 1995, page 1767 “ is poorly suited to elimination of implied erroneous small-scale baroclinic structures present in the background forecasts from the assimilating model”.

Another explanation could be that analyses separated by only six hours could be artificially correlated due to observational biases in the satellite observing systems. In such a case we would consequently overestimate predictability. However, this is probably not likely as we are dealing with several independent non-synoptic observing systems.

An interesting result is the indication of the large potential predictability in the tropics which is likely to be related to the time-scale of the influence of unresolved scales on the synoptic scale wind. Such unresolved scales mainly influence the larger resolvable scales via moist processes. However this requires some time before moist processes may influence the resolvable scales of the wind field not least in areas with low values of the Coriolis force and a correspondingly weaker coupling between the mass and wind fields.. Alternatively the model and the assimilation system may filter out smaller scale organised weather systems via model resolution and structure functions in the assimilation and thus reduce or eliminate the influence from such systems. This is then likely to give an overly high predictability assessment.

Finally, we may wish to explore what would happen if we reduce the assimilation step even further to 3 hours or perhaps to 1 hour, assuming that there are observations to support this? The initial error will naturally be further reduced but will the initial errors also have a smaller growth rate? We suggest this to be related both to the assimilation procedure and the relative weight given to the observations as well as the capability of the model to realistically handle the up-stream cascade of energy by sub-grid scale processes.

4 Concluding remarks

The assessment of predictive skill described in this note indicates a potential for a considerable increase in predictive skill in both the extra-tropics and the tropics. The extension of the time for a skilful forecast (relative error of 50%) from four to more than seven days in the NH and from three to seven days in the SH is indicated. The potential extension of skill in the tropics is even more impressive with the potential of a seven day forecast being as skilful as a one day forecast today. These results are based on the assumption that the six hour forecast errors are plausable and that the estimate of the slow error increase in the early part of the integration is realistic.

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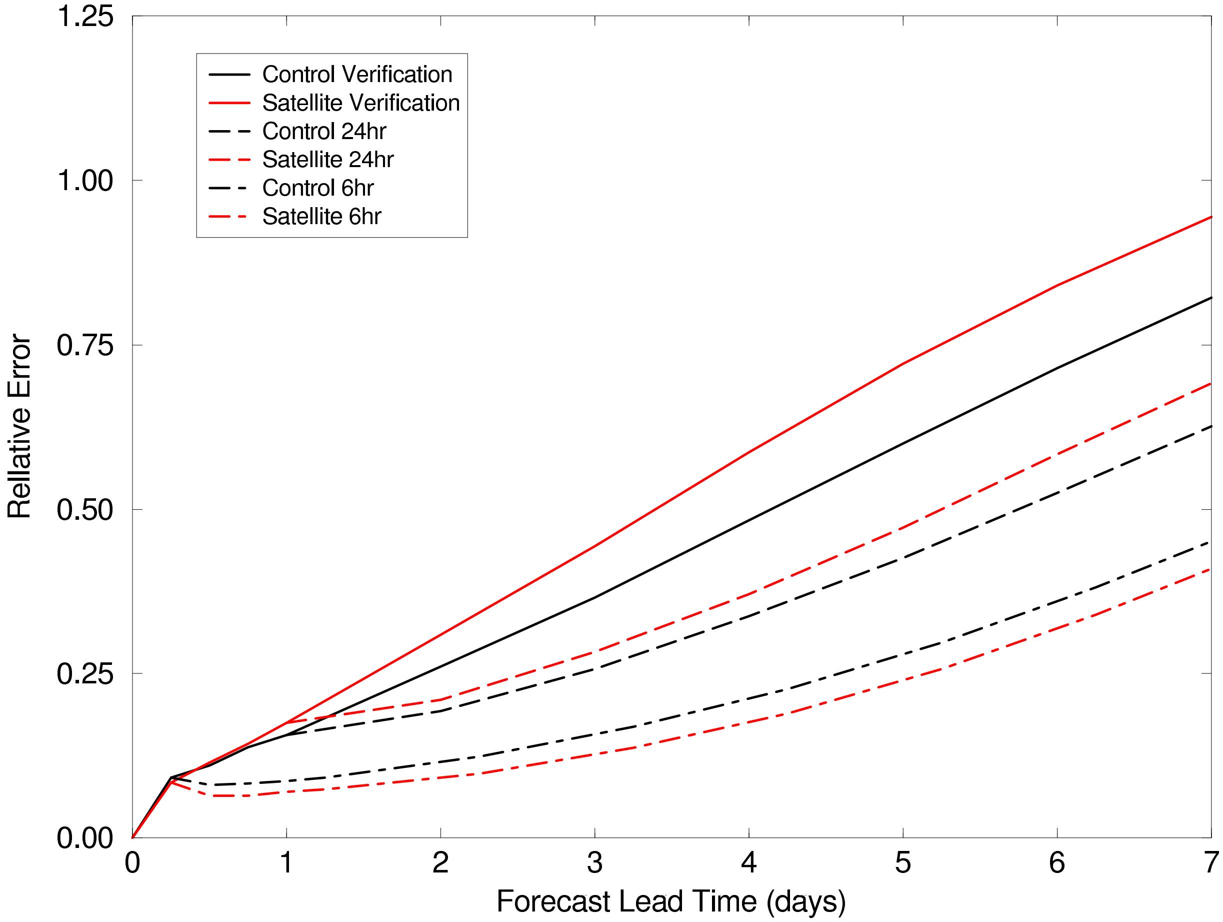
Figure captions

Figure 1 (a) Predictive skill (full line) and two estimates of predictability of the 500 hPa geopotential height field for the NH extra-tropics (20N-90N) during DJF 1990/91 measured as the root mean square difference and normalized by the standard deviation of the control analysis. The long dashed line is the 24 hr. forecast error and the dot-dashed line the 6 hr. forecast error. (b) The same but for the SH extra-tropics (90S-20S). The corresponding results for the skill and predictability for the satellite based system is indicated by the red lines, these are also normalised by the standard deviation of the control analysis.

Figure 2(a) Predictive skill (full line) and two estimates of predictability of the 850 hPa vector wind field for the tropics (20S-20N) during DJF 1990/91 measured as the absolute error ($\langle \sqrt{(\Delta U)^2 + (\Delta V)^2} \rangle$). The short dashed line is a 24 hr. forecast error and the long dashed line the 6 hr. forecast error. (b) The same but for the 250 hPa vector wind field.



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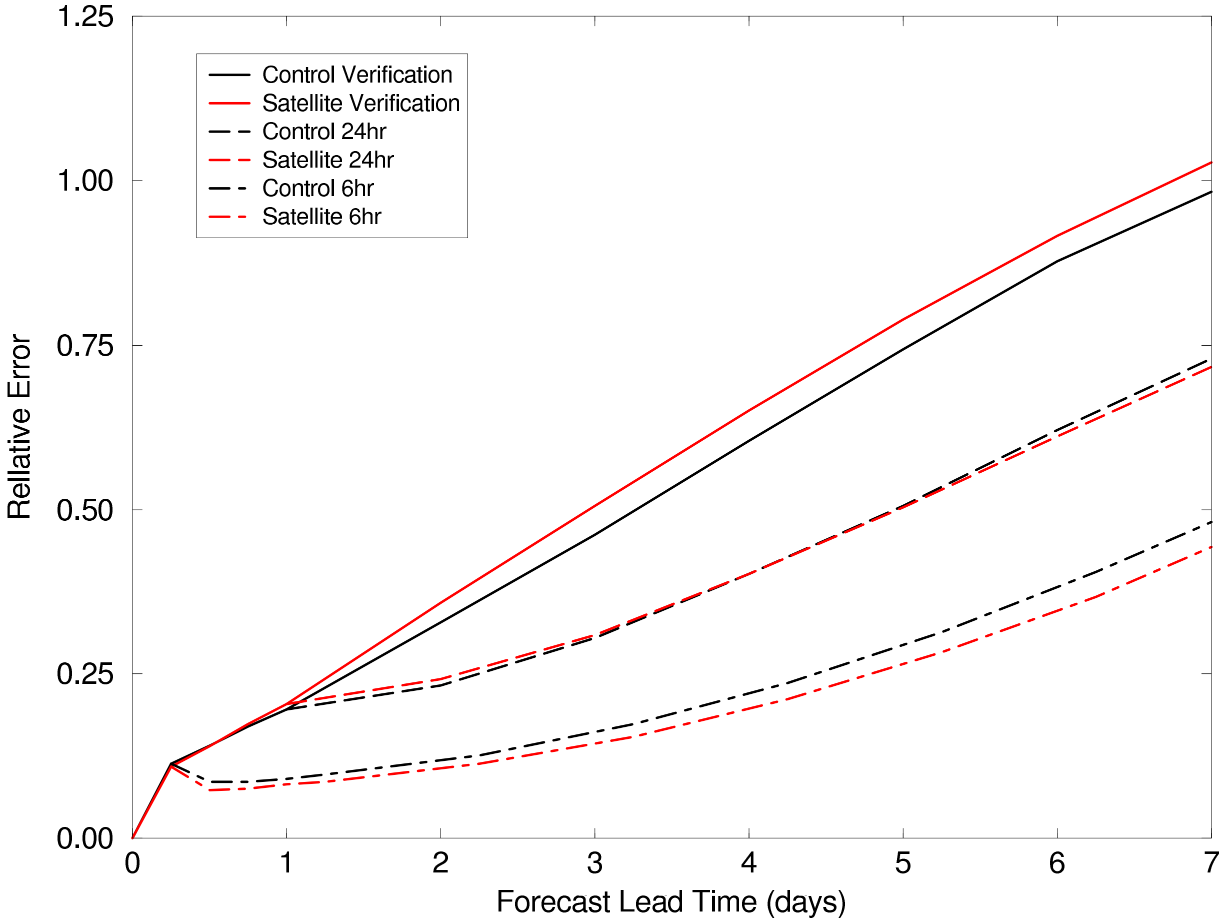
(a)



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Forecast Lead Time (days)
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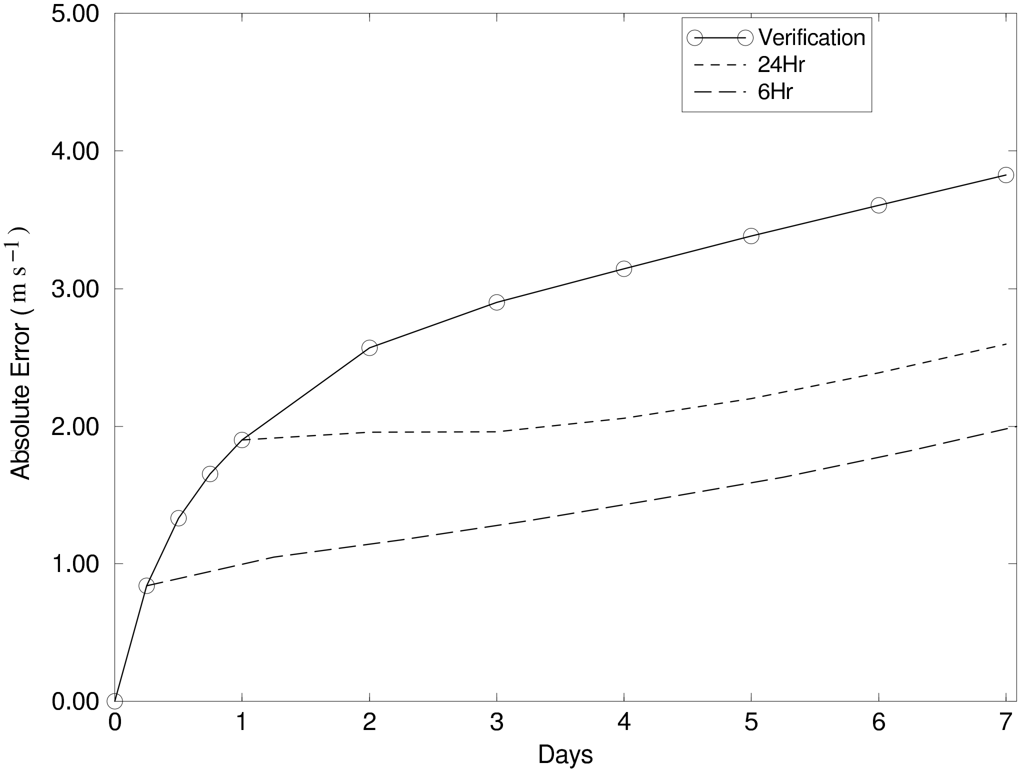
(b)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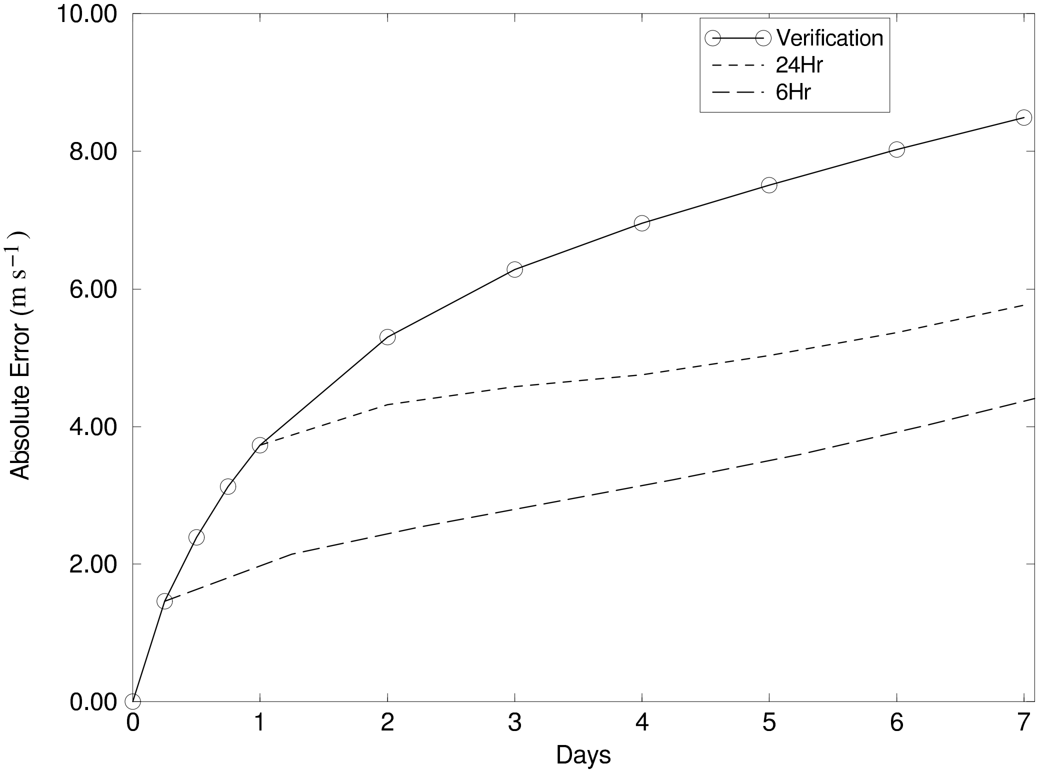
(a)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(b)