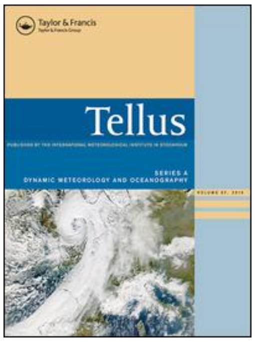

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A note on atmospheric predictability

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ABSTRACT

Using the method of Lorenz (1982), we have estimated the predictability of a recent version of the European Center for Medium-Range Weather Forecasting (ECMWF) model using two different estimates of the initial error corresponding to 6- and 24-hr forecast errors, respectively. For a 6-hr forecast error of the extratropical 500-hPa geopotential height field, a potential increase in forecast skill by more than 3 d is suggested, indicating a further increase in predictability by another 1.5 d compared to the use of a 24-hr 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 7-d forecast. A similar assessment for the tropics using the wind vector fields at 850 and 250 hPa suggests a huge potential improvement with a 7-d forecast providing the same skill as a 1-d 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 5 d. 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 3 d. 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 1-d forecast with the 2-d forecast from the preceding day and the 2-d forecast with the 3-d forecast from the preceding day and so on. Lorenz illustrated his discussion with results derived from the archived data set of the European Center for Medium-Range Weather Forecasting (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 d.

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 rate resulting in an error doubling time of 1.4 d for the Northern Hemisphere (NH) for day 1 and day 2. 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 are 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 12-hr 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 6 hr. Moreover, numerical prediction experiments suggest that the satellite-based information dominates over terrestrial-based information for the Southern Hemisphere (SH) and complements the terrestrial information in the NH (Bengtsson et al., 2005). It is thus of considerable interest to undertake an experiment to estimate the upper bound of predictive skill (Lorenz, 1982) using a smaller initial error, such as the difference between forecasts, which are only 6 hr apart. We describe here such a predictability experiment.

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2. The predictability experiment

This study uses a data set for the Winter [December January February (DJF)] 1990/91 consisting of 360, 7-d global forecasts undertaken from an analysis every 6 hr. For a description of the experiments used to produce the data, see, Bengtsson et al. (2005). The control analyses (both for initialization 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 analogous 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 ERA40 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 organized as follows. Firstly, we have undertaken independent calculations for the extratropics and for the tropics. For the extratropics, we have selected the 500-hPa geopotential height field as a representative measure of predictability and in the tropics the vector wind at 850 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 6 hr. For computational reasons, the length of the predictions has been limited to 7 d. Figure 1 shows the upper and lower bounds for prediction of the 500-hPa geopotential height field for the extratropics of the NH and the SH, respectively. Using 50% of the relative error as a measure of skill, the forecasts reach this limit after 4 d in the average, while the two different predictability estimates based on 24- and 6-hr forecast frequency do so at 5.5 d and more than 7 d respectively. An interesting and somewhat unexpected result is the slow error growth in the extratropics of the differences between forecasts 6 hr apart as there is hardly any error growth for the first 24 hr. An inspection of individual maps for the 6 hr 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 uniformaly 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 hr. It increases with time and amounts to 2 d between day 2 and day 3. The predictability estimate obtained by comparing the differences between forecasts 6 hr apart has a negative growth rate for the first 12 hr, but starts to increase thereafter. At around 48 hr, the difference reaches the same value as it had initially. After that, the exponential growth rate is almost constant until day 7, corresponding to an error doubling time of 2.4 d. The differences between forecasts 24 hr apart show no initial error reduction, but the growth rate for the first day is slightly smaller than that for the second and the third day. Between day 2 and day 7, the error doubling time is 3.2 d. Hence, because the forecasts 6 hr apart had no averaged growth at all in the first

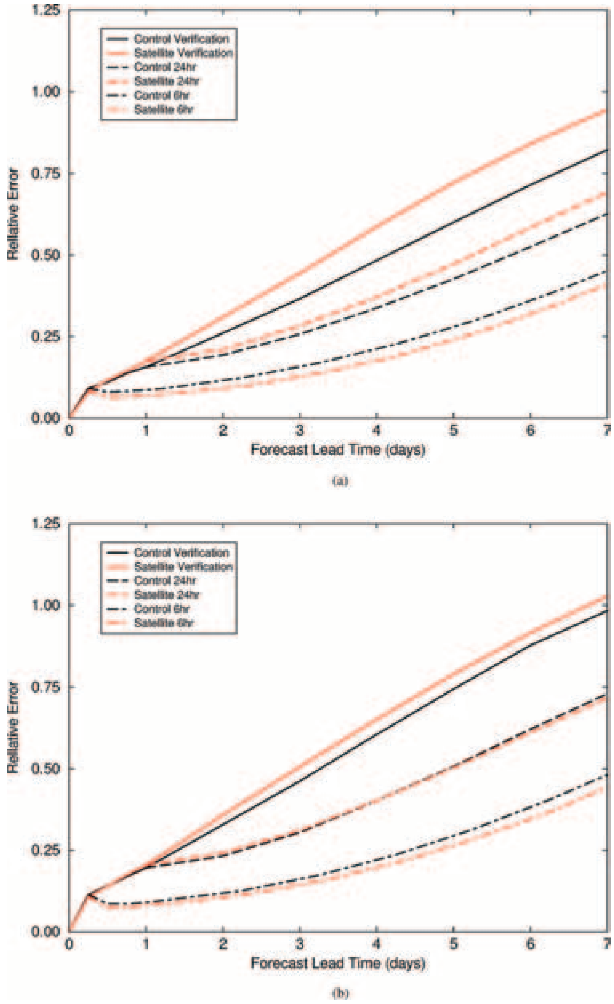

Fig. 1. (a) Predictive skill (full line) and two estimates of predictability of the 500-hPa geopotential height field for the NH extratropics (20N–90N) during DJF 1990/91 measured as the root mean square difference and normalized by the standard deviation of the control analysis. The long dashed line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

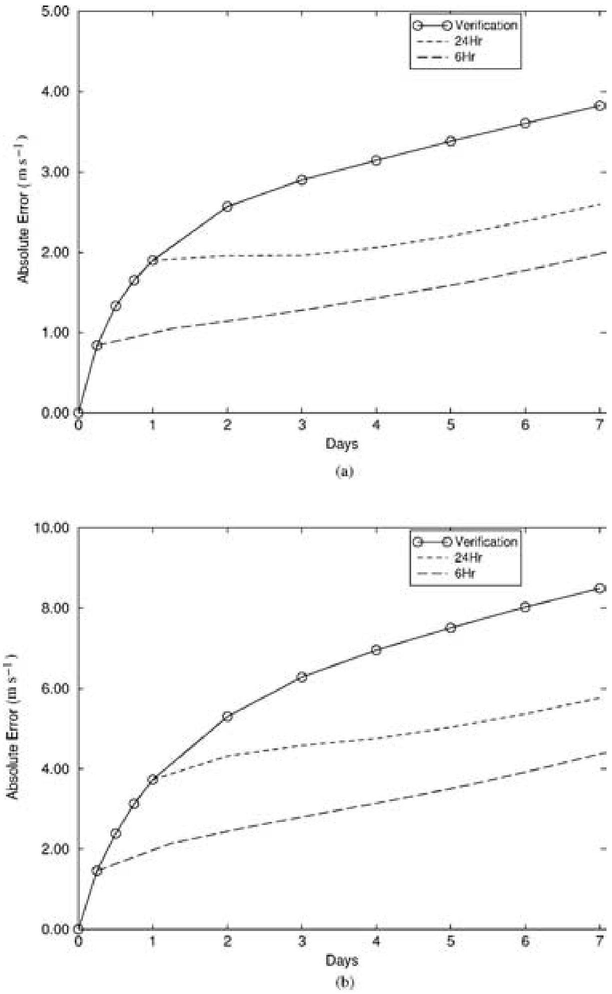

Fig. 2. (a) Predictive skill (full line) and two estimates of predictability of the 850-hPa vector wind field for the tropics (20S–20N) during DJF 1990/91 measured as the absolute error ($\langle\sqrt{(\Delta U)^2 + (\Delta V)^2}\rangle$). The short dashed line is a 24-hr forecast error and the long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

48 hr, the mean error amplification until day 7 is less than between forecasts 24 hr apart in spite of a more rapid error growth from day 2 onwards.

The tropical growth rate curves for the wind field, shown in Fig. 2, are very similar but with a much slower internal growth than the extratropical 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 7, while the two estimates of predictability for 24- and 6-hr forecast frequency reach 2.5 and 2 m s^{-1} respectively. It is interesting to note that the latter predictability estimate at day 7 is the same as the actual forecast error at day 1 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 200-hPa stream function. They noted that there was hardly any growth between day 1 and day 4. Evidently, the apparent scope for forecast improvements in the tropics is as large as it was 10-yr ago.

3. Discussion

It is not only the smaller error in the 6-hr forecast ensemble that is the cause of the large differences in the assessment of predictive skill compared to the 24-hr ensemble, but also the comparatively slower growth rate during the first 30 hr. 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-hr ensemble? This could, for example, happen if only a minor proportion of the analysis increments is projected onto the faster growing modes. The space-based observations, which are more dominant in the 6-hr 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 draw 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 6 hr 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 organized 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 hr or perhaps to

1 hr, 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 upstream cascade of energy by subgrid 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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