Medium-Range Numerical Forecasts of Atmospheric Angular Momentum

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ABSTRACT

Forecasts of zonal wind fields produced by the medium-range forecast (MRF) model of the National Meteorological Center are used to create predictions of the atmosphere's angular momentum at lead times of 1-10 days. Forecasts of this globally integrated quantity are of interest to geodesists and others concerned with monitoring changes in the earth's orientation for navigational purposes. Based on momentum forecasts archived for the period December 1985–November 1986, we find that, on average, the MRF exhibits positive skill relative to persistence-based forecasts at all lead times. Over our entire one-year study period, the improvement over persistence exceeds 20% for 2-6-day forecasts and remains as large as 10% even for 10-day forecasts. On the other hand, skill scores for the MRF momentum predictions vary considerably from month to month, and for a sizeable fraction of our study period the MRF is less skillful than persistence. Thus, although our initial impression of the overall quality of the MRF momentum forecasts is favorable, further improvement is certainly desirable.

1. Introduction

Forecasts of parameters related to the earth's orientation in space are used in precise navigation, both for terrestrial activities and for deep space missions. Thus, organizations such as the U.S. Naval Observatory and the Bureau International de l'Heure routinely issue forecasts of variations in the position of the earth's polar axis and in the rotation rate of the solid earth about that axis. The Jet Propulsion Laboratory (JPL) is interested in such forecasts so that observing time for its Deep Space Network radiotelescopes can be devoted to communicating with spacecraft such as *Voyager 2* during planetary flybys instead of obtaining earth orientation data. Because spacecraft are navigated by observations from the surface of the earth, small errors made in assessing the orientation of the earth can lead to large positioning errors at interplanetary distances. The ability to predict changes in earth rotation accurately over a period of a week or more would, therefore, substantially reduce the burden on Deep Space Network resources during a planetary encounter without causing unacceptably large navigation errors.

Techniques currently used by the geodesy community to forecast earth orientation parameters are statistical in nature, involving the empirical extrapolation of time series of observed values of these parameters. Similar approaches are common in meteorology, of course, especially for monthly and longer time scales. For shorter lead times, however, dynamical approaches have generally supplanted statistical ones in making meteorological forecasts. Our purpose here is to examine the potential for using operationally produced dynamical predictions of the global atmosphere's angular momentum (M) to forecast changes in the earth's rotation rate at lead times of 1-10 days. To do so, we examine the quality of M forecasts produced since December 1985 by the operational medium-range forecast model of the U.S. National Meteorological Center (NMC), thus permitting us an opportunity, as well, to form an opinion about the overall quality of this state-of-the-art model.

Implicit in our approach is the assumption that forecasts of M are relevant for forecasts of changes in the earth's rotation rate. This assumption is based on a number of recent studies (Hide et al., 1980; Rosen and Salstein, 1983, 1985; Eubanks et al., 1985) demonstrating that modern atmospheric and geodetic datasets are able to measure the momentum budget of the earth–atmosphere system to high accuracy and that, on the time scales of interest here, this system appears to be closed so that changes in the momentum of one component are simply balanced by changes in the momentum of the other. Therefore, we expect that forecasts of M can be used to specify changes in the length of day (Δlod, a common measure for changes in the earth's rotation rate) to good approximation. We will not consider this aspect of the problem further here, but will instead concentrate on assessing the quality of the M forecasts themselves.

2. Data and analysis

To extend the range of dynamical weather prediction out to 10 days, NMC introduced a medium-range forecast (MRF) model into its operation in April 1985. Since that time, the model has undergone numerous modifications, an evolutionary process likely to continue. As currently configured, the MRF is an 18-layer spectral model, truncated (rhomboidally) to 40 waves in the horizontal. The model contains an extensive suite of diabatic physical process parameterizations, based on approaches developed at the Geophysical Fluid Dynamics Laboratory (Fels and Schwarzkopf, 1975; Miyakoda and Sirutis, 1977). Further details regarding the MRF are provided by Gerrity (1986).

Beginning in mid-November 1985, forecasts of the zonal wind made at 00 UTC each day for conditions at each successive 12-hour period out to 10 days have been accessed by us for the purpose of creating time series of M forecasts. Approximately 5% of the total possible forecasts since the start of our record are missing, and no attempt to substitute for them was made. We calculated M according to the relationship

$$M = \frac{2\pi a^3}{g} \int_{1000}^{100} \int_{\pi/2}^{-\pi/2} [u] \cos^2\phi d\phi dp,$$

where a is the mean radius of the earth, g acceleration due to gravity, ϕ latitude, p pressure, and $[u]$ zonal-mean zonal wind which is available at every 2½° of latitude and at the ten standard-pressure levels between 1000 and 100 mb. (Values of $[u]$ are also available from the MRF at 70 and 50 mb, but they have not been incorporated into our calculations of M.) In addition to the M forecast series, we have maintained an archive of the $[u]$ forecast fields, but we will not consider these fields here.

Verification of the M forecasts was made using the fields initialized for the MRF (i.e., the "forecasts at lead time = 0"), which after 28 May 1986, when the MRF became incorporated into the NMC global data

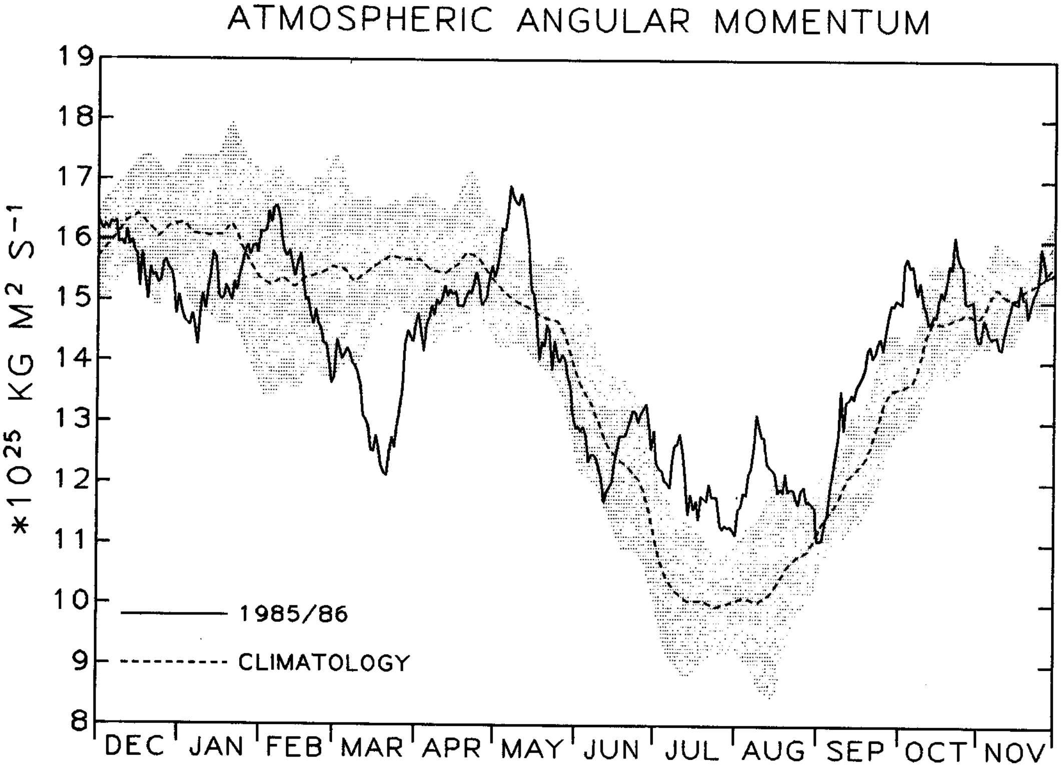

FIG. 1. Time series of the atmosphere's angular momentum, M, derived from daily NMC analyses for 1 December 1985–30 November 1986 (solid line) and from a smoothed 10-year average climatology (dashed line). To form the climatological series, values of M based on NMC analyses for 1976–85 were averaged separately for each calendar date and then subjected to a low-pass digital filter designed to retain periods of about 10 days and longer. The shaded area encompasses values of M that lie within one standard deviation of the climatological mean values. Values of the standard deviation were computed for each calendar date and also low-pass filtered.

assimilation system (GDAS), also became the final analyses produced by the GDAS. Only forecasts verifying at 00 UTC are considered in this study.

Finally, to provide a measure of skill of the MRF forecasts of M, we have computed values of a simple skill score, S, (Murphy and Daan, 1985) for each forecast lead time:

$$S = \frac{\sigma_p - \sigma_{\mathrm{MRF}}}{\sigma_p} \times 100\%,$$

where σ_{MRF} is the root-mean-square error of the MRF forecasts over a given period of time, and σ_p is the root-mean-square error of forecasts based on assuming persistence of the M values during the same time period, i.e., forecasted $M(t_0 + \Delta t)$ = observed $M(t_0)$ for each forecast lead time Δt. Hence, S measures the percentage improvement of the MRF over persistence-based forecasts, so that $-\infty < S < 100\%$. Values of S have been computed for each full calendar month in our record, beginning therefore with December 1985. In creating these monthly values, we have chosen to congregate the forecasts by the calendar month in which they verify rather than the calendar month in which they were made. Values of S for each forecast lead time have also been computed for the entire period 1 December 1985–30 November 1986.

Our decision to use persistence as the statistical model against which to judge the success of the dynamical MRF forecasts is based on several considerations. First, of course, improvement over persistence is a commonly employed measure of weather fore-

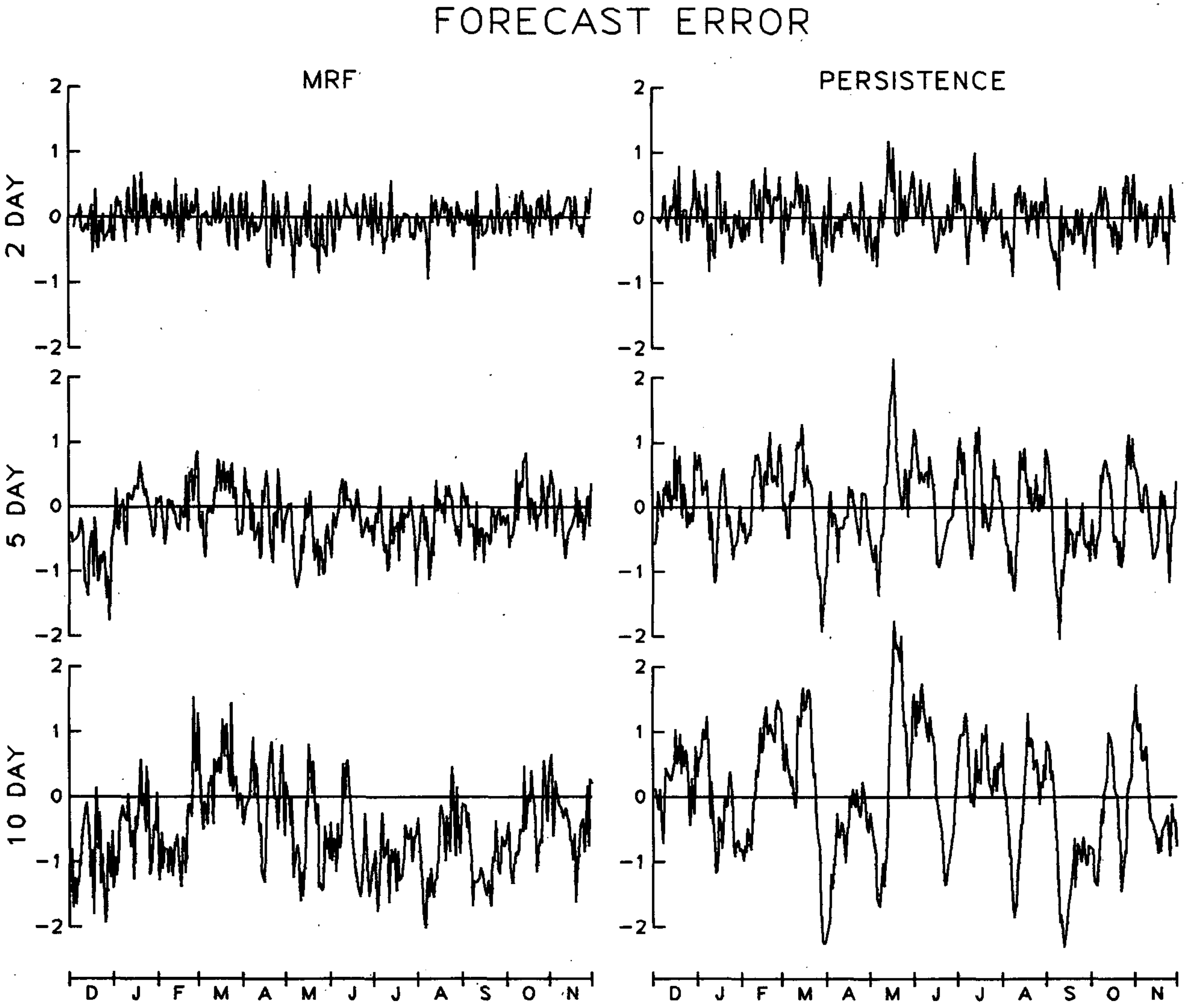

FIG. 2. Daily time series during 1 December 1985–30 November 1986 of the difference, MRF forecasted values minus observed values of M, for forecast lead times of 2, 5 and 10 days (left); and the difference, persistence-based M forecast values minus observed values of M for the same forecast lead times (right). Units are 10^{25} kg m^2 s^{-1}.

casting ability. In addition, there is some evidence that fluctuations in M on the time scales of interest here obey a power law spectrum consistent with a random walk process (Eubanks et al., 1985), in which case persistence would represent the optimal statistical forecast model. As a result, the Kalman filter technique used at JPL to empirically forecast earth orientation parameters reduces, in the case for Δlod, to essentially a persistence forecast. Hence, our choice of persistence here as a "competitor" of the MRF will enable us to measure the quality of the MRF forecasts relative to those from a currently used technique in geodesy.

3. Results

a. *Time series of forecast errors*

Figure 1 displays the time series of M values observed during our study period. Also plotted is a smoothed climatological time series of M based on all the available NMC daily values for January 1976–December 1985. Note the marked difference between the two curves, which accounts for the result (not shown) that climatology-based forecasts during 1986 were less skillful than persistence ones at all lead times up to and including 10 days.

Daily time series of the differences between the observed values of M plotted in Fig. 1 and those forecasted both by the MRF and by persistence are presented in Fig. 2 for forecast lead times of 2, 5 and 10 days. The root-mean-square error between the forecasts and the observed M values computed for the entire study period is plotted in Fig. 3 for all forecast lead times, including the three highlighted in Fig. 2.

As is evident from Figs. 2 and 3, forecast errors, both for the MRF and for persistence, increase as lead time increases, not a surprising result. Significantly, though, σ_{MRF} is smaller than σ_p for all lead times, at least on average, for the whole study period. Interestingly, the difference between the two grows with lead time between 1 and 3 days but remains relatively constant thereafter. Inspection of Fig. 2 does reveal periods when the MRF errors are larger than those for persistence, however, a result that will also be evident when we present monthly skill scores below.

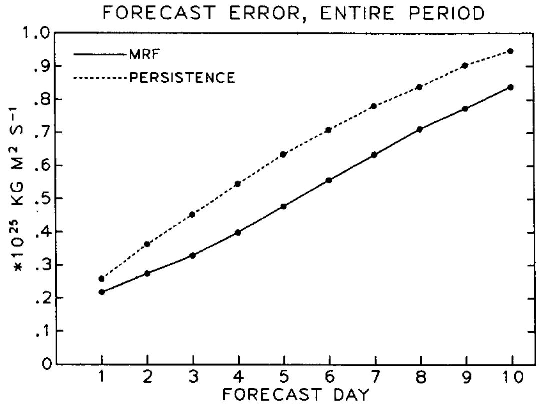

FIG. 3. The root-mean-square difference between observed values of M and those forecasted by the MRF, σ_{MRF}, (solid line) and between observed values of M and those forecasted by persistence, σ_p, (dashed line) as a function of forecast lead time for the entire period 1 December 1985–30 November 1986.

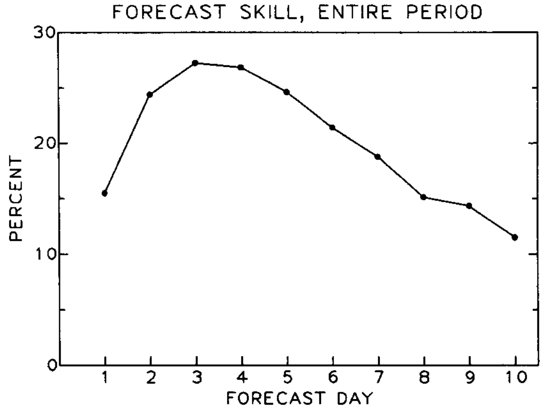

FIG. 4. Skill score, expressed as percentage improvement of the MRF over persistence, as a function of forecast lead time for the entire period 1 December 1985–30 November 1986.

Finally, it is worth noting that the MRF forecast errors contain a low-frequency component in addition to high-frequency noise for the longer lead time forecasts, such as those for 10 days shown in Fig. 2. Were the low-frequency component for the 10-day forecasts to consist simply of a mostly uniform bias, then it could be readily accounted for in an operational forecasting scheme to improve the skill of the forecasts. However, this is clearly not the case. Thus, although the difference between the 10-day MRF forecast and observed M values is generally negative, this was not true, on average, for much of March–April 1986. Nevertheless, it should prove possible in practice to remove errors with periods much longer than the forecast lead time, and consideration of Fig. 2 suggests that doing so could reduce the 10-day MRF forecast error substantially.

b. *Skill scores*

Based on the root-mean-square errors of the MRF and persistence forecasts given in Fig. 3, we have calculated values of S as a function of forecast lead time averaged over our entire study period. The results, presented in Fig. 4, illustrate the point already made in connection with Fig. 3, that the MRF is more accurate than persistence at all lead times. The greatest improvement over persistence (approximately 27%) occurs at the 3-day range, and although the skill scores drop steadily as the lead time increases further, it is somewhat remarkable to discover that the MRF 8- and 9-day forecasts appear to be about as skillful as its 1-

day forecasts. This result, however, is largely a reflection of the much greater difficulty faced in improving upon persistence for 1-day forecasts than for those at 8–9 days.

The simple picture presented in Fig. 4 of the MRF exhibiting positive skill on average is clouded by statistics of skill scores compiled on a monthly basis, as shown in Fig. 5 for 2-, 5- and 10-day forecasts. Although generally positive, monthly skill scores have occasionally been negative for each of these forecast lead times, even dramatically so, as in the case of the 5- and 10-day forecasts for December. As noted earlier, this result is consistent with the impression gained from Fig. 2 that the MRF errors are not always smaller than those for persistence. In the case of the December 5- and 10-day forecasts, however, the especially poor performance of the MRF resulted mainly from the large bias components that month, errors that may be amenable to correction. As for the other instances of negative skills in Fig. 5, inspection of monthly values of σ_{MRF} and σ_p individually (not shown) indicates that all of these instances involved marked decreases in the persistence error rather than significant changes in the MRF error. Nevertheless, differences on the order of a factor of two do exist among the monthly σ_{MRF} values (even discounting the December results), suggesting that the average results in Figs. 3 and 4 cannot be assumed to reflect behavior during all shorter periods.

4. Concluding remarks

Our intent here has been to examine the ability of a state-of-the-art medium-range forecast model to provide meaningful predictions of a globally integrated atmospheric quantity (M) of special interest to geodesists. However, because M is a fundamental physical quantity and is a function of the basic zonal wind field, the ability of the MRF to forecast M ought to be of concern to meteorologists, as well. Overall, we were pleased to discover that the NMC medium-range forecast model has positive skill, on average, out to 10 days relative to persistence forecasts. Moreover, the relatively small component of systematic error in the MRF forecasts out to 5 days or so provides a measure of confidence in the model's formulation. For lead times closer to 10 days, it may be possible to improve upon the skill scores reported here by developing operational approaches that account for the low-frequency error component that does appear to be present in these MRF forecasts. In any case, dynamically based forecasts of earth orientation parameters appear to be a viable alternative to the empirical approaches currently in use.

Our enthusiasm must be tempered somewhat for a number of reasons, however, such as the result that the skill scores for the MRF fluctuate considerably from month to month, particularly for the longer lead time forecasts. In fact, over our entire one-year study period, the MRF 10-day forecasts were more accurate than those of persistence only slightly more than 50% of the time. Although the reliability of the MRF forecasts is higher at other lead times (peaking for 3-day forecasts when the MRF beat persistence 65% of the time), further study is required to determine if this performance is adequate for the applications discussed in the Introduction.

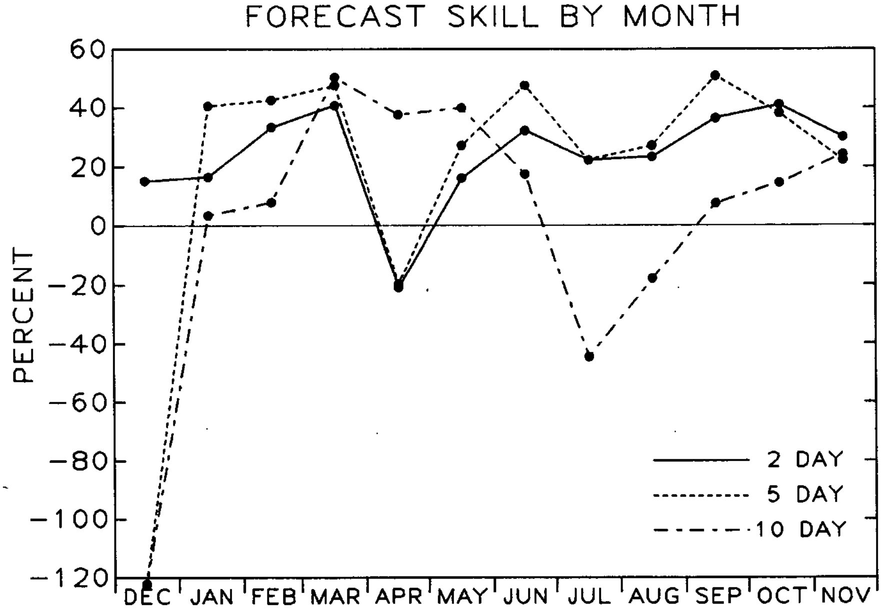

FIG. 5. Skill score, expressed as percentage improvement of the MRF over persistence, as a function of calendar month for forecast lead times of 2, 5 and 10 days.

In this study, we have used a statistical competitor to the NMC MRF, but a different class of competitors, of course, consists of the dynamical forecasts made by other operational meteorological centers. Medium-range forecasts of M from the European Centre for Medium Range Weather Forecasts and the British Meteorological Office are currently being archived (R. Hide, personal communication). Comparisons among these sets of forecasts and analyses of the associated fields of $[u]$ could offer valuable insights into the steps needed to improve the quality of medium-range forecasts.

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