Interaction of Low- and High-Frequency Transients in a Forecast Experiment with a General Circulation Model

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ABSTRACT

Two sets of 15-day numerical forecasts are performed with a general circulation model to examine aspects of the mutual interaction between high-frequency, baroclinic-wave variability and the low-frequency components of the atmospheric flow. A control run based on an initial field, arbitrarily chosen from the history tapes of a previous model integration and a forecast based on a time-filtered version of the same initial state are compared. The results indicate that the high-frequency variability of the flow in the latter forecast returns to normal amplitudes about one week after the initialization time, at which state it is only weakly correlated in space with the high-frequency component of the flow in the control run. The low-frequency components of the flow seems to behave differently depending on their zonal scale: Ultralong waves (wavenumber 1–3) are only weakly affected by the removal of the baroclinic activity from the initial conditions, while long waves (wavenumber 4–6) react to the removal of the baroclinic waves by drifting eastward faster than their counterparts in the control run.

1. Introduction

The mutual interactions between low-frequency planetary-wave variability and higher frequency baroclinic activity are of considerable interest from the point of view of extended and long-range weather prediction. Some investigators (e.g., Green 1977; Gall et al. 1979; Egger and Schilling 1983; MacVean 1985; Illari 1984) have tended to emphasize the role of baroclinic waves in the stochastic forcing of the low-frequency planetary-wave variability. Others (e.g., Hoskins and Karoly 1981; Frederiksen 1983; Simmons et al. 1983; Tung and Rosenthal 1986) have emphasized the deterministic dynamical processes that govern the low-frequency evolution of the planetary waves, which in turn could influence the position of the storm tracks. If the deterministic, low-frequency dynamics were in control, so to speak, the evolution of the state of the atmosphere in a dynamical prediction run would be relatively insensitive to the details of the representation of the baroclinic waves in the initial conditions. In that case one might hope to be able to glean some useful information on the future evolution of the atmosphere, even if baroclinic waves were entirely absent in the initial conditions for the forecast run. In the following pages we examine the consequences of imposing such initial conditions in a numerical forecast, by filtering out the part of the flow with periods shorter than ~10 days.

The experiments were conducted with the perpetual January version of the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM), using as initial conditions selected days from the history tapes drawn from a previous long model run. The “raw” data on these days and their time filtered version (from which the short time-scale synoptic variability was removed) were used as initial states as detailed in section 2. The forecasts based on initial conditions with and without the high frequency transients were compared as will be discussed in sections 3 and 4. We note, at the outset, that these experiments did not provide a definitive answer to the question that we had posed. We, however, believe that the following results are of sufficient interest to warrant this short note.

2. Methodology

Pitcher et al. (1983) have described the numerics and physical parameterizations in the NCAR CCM. In this experiment the model was run with the standard rhomboidal 15 horizontal truncation and 9 levels in the vertical. The solar zenith angle and lower boundary conditions were set to their mean January values as defined in Pitcher et al. The model performance during an extended simulation with perpetual January boundary conditions has been described by Pitcher et al. (1983) and Malone et al. (1984). The essential characteristics of the climatological mean January circulation are well simulated by the model. These features include the location and intensity of the Pacific and Atlantic jet streams and the horizontal distribution
of geopotential height in the middle troposphere. The transient variability in the simulation resembles the observations except for some minor shifts in the location of the centers of action of the low-frequency 500 mb geopotential height variability and the absence of a pronounced maximum over the northern part of the Soviet Union. Blackmon et al. (1986) examined the climatology of blocking in the model simulation and found it quite realistic except for the lack of activity over the northern part of the Soviet Union. As in the observations, the centers of action of the simulated high-frequency variability (storm tracks) are elongated in the east–west direction and appear downstream and slightly poleward of the jet streams.

The CCM has also been used for predictability experiments in which the model was repeatedly initialized with two sets of initial conditions based on observations, one of which was a slightly perturbed version of the other (e.g., Baumhefner 1984). The experiments conducted in the present study are analogous to such predictability experiments in that we compare the evolution of two numerical forecasts based on two different versions of the same initial state, one being a perturbed version of the other. However, the unperturbed state was randomly drawn from the history tape of a perpetual January integration of the model, to represent an arbitrary state of the atmosphere to the level of detail resolved by the model. The forecast based on this initial state will be referred to hereafter as the forecast based on unperturbed initial conditions or the control run. In contrast to conventional predictability experiments, the perturbed initial state was a lowpass filtered version of the first one, obtained by calculating a 5-day average of the fields on the history tape centered on the time of the first initial state (as shown schematically in Fig. 1). The second initial state thus contains only the slowly varying part of the atmospheric circulation at the time of the initialization, and its corresponding forecast will be referred to as the forecast based on filtered initial conditions. We recognize that the latter model run is not a true forecast of the data on the history tape, since the initial conditions on which it is based contain information on the low frequency component of the flow out to two days beyond the time of the initial conditions. We will, nevertheless, refer to both runs as “forecasts” for the sake of convenience.

Two sets of 15-day forecasts were performed: experiment A, initialized using history data centered on model day 362, and experiment B, initialized with data centered on model day 782. The fields generated in the two experiments were saved twice daily.

The initialization procedure of the CCM introduces small perturbations into the initial state and therefore the prediction based on the unperturbed initial state does not match the evolution recorded on the history tape. A comparison between the unperturbed forecast and the history is a measure of the growth of the so-called “predictability error,” in the sense referred to in conventional predictability experiments (e.g., Shukla 1985).

3. Evolution of the forecast fields

The effect of removing the high-frequency transients from the initial state upon the subsequent evolution of the flow was determined by examining the global rms 500 mb geopotential height difference between the unfiltered and filtered forecasts at half-daily intervals. The results are represented by the curves labeled F in Figs. 2a (experiment A) and 2b (experiment B). The curves labeled H in these figures show the evolution of the rms difference between the unfiltered forecasts and the corresponding fields on the history tape. In these figures the abscissa is in days, referring to the initialization time as day-0. The evolution of the global rms differences in the two experiments are qualitatively similar. In both curves the difference between the initialized unfiltered field and the corresponding field on the history tapes is on the order of 1 gpm, which is similar to the difference between initial states in conventional predictability studies (e.g., Baumhefner 1984). The evolution of the forecast error (curve H in Figs. 2a, b) is in agreement with Baumhefner’s results: the initial error growth rate is large (doubling time of 1–1.5 days) and becomes smaller after the fourth day of the forecast (doubling time of 2–3 days). The error reaches saturation between the 13th and 15th day of the forecast.
Fig. 2. The temporal evolution of the global rms 500 mb geopotential height difference between the control run and the corresponding date on the history tapes (curve H) and the control run and the forecast time series based on filtered initial conditions (curve F). (a) experiment A; (b) experiment B. Abscissa is in days where day 0 is the initial state.

The initial rms height difference between the control run and the forecast based on the filtered initial conditions is between 30 and 40 gpm (curve F, in Figs. 2a, b). Compared to the rate of growth of the forecast error (curve H), the large difference introduced by removing the high-frequency transients from the initial state grows much more slowly. This is consistent with other predictability experiments which indicate that larger errors grow more slowly than small ones (e.g., Shukla 1985). The difference between the forecasts approaches the saturation rms value on day 9. At that time the forecast error in the control experiment (curve H) has just reached a value comparable to the rms difference between the unfiltered and filtered initial states and is about one-third as large as the saturation value.

The foregoing results indicate that a considerable degradation in the forecast is caused by the removal of the high-frequency transients from its initial state. It remains to be seen whether this degradation is due to changes in the high- or the low-frequency transients in the circulation. To represent the low-frequency component of the various forecasts, we lowpass filtered each of the forecast time series, using a 5-day running mean filter, consistent with the method of constructing the filtered initial conditions. The evolution of the global rms 500 mb geopotential height differences between the lowpassed time series of experiment A is shown in Fig. 3 (results from experiment B are not shown since they are almost identical). As in Fig. 2 the various curves are for the difference between the control run and the forecast based on filtered initial conditions (curve F) and between the control run and the data on the history tape (curve H). The rates of the error growth in the low-frequency component of the forecast 500 mb height fields are comparable to the rate of growth in the unfiltered forecast fields (see Fig. 2a) but the saturation error is smaller due to the removal of the high-frequency transients from the forecast time series. At the beginning of the forecast period the rms height difference between the low-frequency component of the control run and that of the forecast based on filtered initial conditions grows faster than the (larger) difference in the corresponding unfiltered forecast fields (Fig. 2a). This may be a consequence of the averaging of the forecast fields, filtering out the high-frequency error which is close to saturation and thus grows much more slowly. Four days into the forecast the growth rate of the rms difference in the lowpass forecast fields becomes similar to that in the unfiltered test fields. The rms difference between the lowpass forecast fields based on filtered and unfiltered initial conditions reaches saturation on the ninth day of the forecast when the corresponding rms difference in the control experiment (curve H) is still three times smaller.

The behavior of the high-frequency transients in the forecast time series was examined by repeating the above error analysis with time series generated by subtracting the 5-day mean fields of each forecast from the corresponding unfiltered forecast fields. The results of this analysis are shown in Fig. 4. The predictability
error in the high-frequency component of the control experiment (curve $H$) grows initially at the same rate as the errors in the corresponding unfiltered forecast fields and their 5-day means. This result is consistent with the results shown by Baumhefner (1984, Fig. 2), which indicated that the initial growth rate of small errors is independent of the spatial scale of the forecast errors. A relatively low saturation value (the stronger low-frequency fluctuations were removed by the filtering) is reached after about ten days. The initial rms height difference between the high-frequency components of the forecast fields based on unfiltered and filtered initial conditions (curve $F$) is almost at saturation level to begin with and as such its growth rate is much smaller than that of the predictability error. It remains to be seen how this result is related to the evolution of high-frequency transients in the forecast based on the filtered initial conditions.

Two interesting aspects of the high-frequency behavior in the forecast based on filtered initial conditions are the rate at which these transients return to full amplitude and their phase with relation to their counterparts in the control run. Figure 5 shows the half-daily evolution of the global rms 500 mb height fields in the highpass component of the control run (curve $C$) and the forecast based on filtered initial conditions of experiment A (curve $F$). The results indicate that the high-frequency transients reach "normal" amplitude around the sixth day of the forecast. The phase relationship between the high-frequency transients in the control run and those in the forecast based on filtered initial conditions was examined by calculating the global pattern correlation coefficient between the highpass component of the two forecast series. Results for experiment A are shown in Fig. 6. The initial value of the correlation between the residual high-frequency components in the two runs (curve $F$) is weak but not zero. During the first day the correlation increases to a value of $\sim 0.5$, only to fall off on the third and fourth day of the forecast. (In experiment B, not shown, the period of relatively high correlations lasts only into the second day of the forecast.) Once fully developed, the synoptic scale disturbances in the forecast based on the filtered initial conditions are essentially uncorrelated with their counterparts in the control run. The curious increase in the correlation during the first day might be due to the temporary growth of the small residual high-frequency circulation in the filtered initial state. Figure 6 shows, for comparison, the pattern correlation between the 500 mb height field of the control run and that on the history tape (curve $H$). These correlation values remain high well into the forecast, fall off rapidly only after the eighth day, and reach the low values of the $F$ curve only at the end of the period shown.
To examine further the degree of control that the low-frequency circulation has on the evolution of the high-frequency baroclinic eddies, we performed a second experiment based on an initial state in which the polarity of the latter was reversed. This initial state was achieved simply by calculating the difference between twice the value of the filtered initial state and the unfiltered initial state. The pattern correlation between the high-pass part of this experiment and the control run is shown in curve $R$ of Fig. 6. The two initial fields are almost exactly out-of-phase. The forecast fields become uncorrelated only after the first four days of the forecast. Thus the high-frequency transients in the forecast based on the initial state in which their polarity was reversed, are not forced immediately into phase by their environment but approach rather slowly a state which is uncorrelated with the control run, indicating the limited control that the low-frequency circulation has on the phase of the evolving baroclinic eddies.

4. Impact of the transients on the phase of the low-frequency waves

The results of the previous section indicate that the low-frequency transients are strongly impacted by the removal of the high-frequency transients from the initial state. It is interesting to examine whether that effect is due to changes in the low-frequency wave amplitudes or to changes in their phase. To address this question we performed a latitudinal Fourier decomposition of the gridded half-daily fields of the 5-day averaged forecast data, calculating the complex amplitude of the first six zonal harmonics. A complex pattern correlation coefficient $R$ was then calculated between various pairs of fields at half-day intervals, using:

$$ R(a, b) = \sum_{k = K1}^{K2} \frac{C_{ak} C_{bk}^*}{S_a S_b} $$  \hspace{1cm} (1)

where $S$ is the rms value:

$$ S = \sum_{k = K1}^{K2} C_k C_k^* $$ \hspace{1cm} (2)

Here $C$ is the complex Fourier coefficient of the zonal wavenumber $k$ and $K1$ to $K2$ is the wavenumber range considered. The subscript $a$ denotes forecast fields for the control run, $b$ a forecast fields based on filtered initial conditions, and (*) a complex conjugate. If the difference between fields $a$ and $b$ is only in the relative amplitudes of the various harmonics, $R$ will be real. If, however, the different harmonics of field $b$ are phase shifted with respect to those of field $a$, $R$ will have an imaginary part. A positive phase of $R$ indicates that the wave components of field $b$ are located farther east than their counterparts in field $a$. Note also that the real part of $R$ is equal to the real correlation coefficient between the two fields (hereafter referred to simply as the correlation coefficient).

The results of applying the complex correlation analysis to the lowpass component (5-day running means) of the forecasts based on unfiltered and filtered initial conditions of experiment A are shown in Fig. 7. The figure shows the amplitude of $R$ (given by the length of the arrows), its phase (given by the direction of the arrows, increasing counterclockwise), and the magnitude of the correlation coefficient (the real part of $R$—the contour lines) as a function of latitude and time. Figure 7a is for zonal wavenumbers 1–3 and Fig. 7b for wavenumbers 4–6. Over the extratropical Northern Hemisphere, the ultralong waves (wavenumbers 1–3) in the two runs stay highly correlated throughout the period shown. The decorrelation is generally associated with small changes in phase (less than 45 degrees). In the Southern Hemisphere the correlation decreases more rapidly. The differences between the two hemispheres could be a reflection of the stronger zonally asymmetric boundary forcing in the Northern Hemisphere. Similar results were obtained in experiment B (not shown).

In the long waves (wavenumbers 4–6) the value of the correlation coefficient decreases more rapidly with time. Interesting changes in the complex correlation coefficient are observed over the Northern Hemisphere midlatitudes and, to a lesser extent, over the Southern Hemisphere midlatitudes. The phase of the complex correlation coefficient increases with time during the first five days of the forecast while its amplitude remains close to 1. After the initial period the phase begins to decrease with time while the amplitude retains large values up to the ninth day of the forecast and beyond. This implies that in the absence of fully developed high-frequency transients, the low-frequency waves in the experiment based on filtered initial conditions are located increasingly farther eastward with respect to their counterparts in the control experiment. Different and more chaotic behavior is found over the high latitudes and in the tropics. Over these regions, however, the amplitude of the long waves is small. The analysis of experiment B (not shown) exhibits the same type of behavior.

The behavior of the long waves in the present experiment is consistent with a recent diagnostic study of blocking by Mullen (1986). There it was found that synoptic time-scale disturbances oppose the eastward advection of low-frequency blocking ridges. The phase of the ultralong waves does not appear to be as sensitive to the forcing by the high-frequency transients, perhaps because of their dynamical link to the zonal asymmetries in the forcing from the lower boundary.

5. Conclusions

The major results from this study can be summarized as follows:

- In numerical simulations initialized with only the low-frequency component of the circulation, the high-
Fig. 7. Latitude vs time distribution of the complex pattern correlation between the filtered and the unfiltered forecast series of experiment A. (a) Wavenumbers 1–3; (b) wavenumbers 4–6. Scale for vectors is shown at the bottom of the diagrams. The direction of the arrows indicates the relative phase between the wave components in the two experiments, the value increasing in a clockwise direction. The contoured field is of the real part of the complex correlation coefficient; contour interval is 0.2.
frequency transients grow, exponentially at first, and reach their normal energy levels in about a week. The rate of growth is consistent with the rate of energy growth in the nonlinear integrations of Simmons and Hoskins (1978, 1980). The developing high-frequency transients are only weakly correlated spatially with their counterparts in the control run. This weak correlation diminishes long before they reach their full amplitude.

• The removal of the baroclinic waves from the initial conditions has a considerable effect on the evolution of the low-frequency circulation. The long waves (k = 4–6) appear to be more strongly affected than the ultralong waves (k = 1–3). The initial effect in the long waves is a faster eastward drift of the features in the forecast based on the low-frequency initial conditions with respect to their counterparts in the control run. This effect is confined to the regions of active high-frequency wave variability. The ultralong waves are less affected by the removal of the baroclinic eddies, particularly in the extratropical latitudes of the Northern Hemisphere, where the boundary forcing is strong.

It is reasonable to conclude from these results that the high-frequency transients that develop in the forecast based on lowpass filtered initial conditions reflect the changes in the low-frequency long-wave component of the flow, upon which they develop. Hence, we should not be surprised by the relatively weak spatial correlation between the high-frequency transients that develop and their counterparts in the control run. In order to examine how the developing high-frequency transients are organized by the low-frequency circulation pattern, we computed at each gridpoint 5-day running means of the square of the highpass part of the 500 mb geopotential height field (this amounts to calculating the variance of the high-frequency variability during overlapping 5-day periods). Figure 8 shows the square root of the resulting field (i.e., the rms value).
on day-6 of the forecasts, based on an average from
day-4 to day-8, overlaid on the day-6 lowpass 500 mb
height field. We first notice the eastward shift of most
of the long-wave troughs and ridges in the forecast
based on lowpass filtered initial conditions (Fig. 8b)
with respect to their counterparts in the control run
(Fig. 8a). Several changes in the high-frequency tem-
poral rms distribution are noticeable: In the forecast
based on filtered initial conditions, the Atlantic center
of high-frequency activity is narrower, more zonal, and
protrudes farther eastward than in the control run.
There are also changes in the rms height distribution
over eastern Asia and the western Pacific. These
changes in the high-frequency transients show some
similarity with the small differences in the low-
frequency circulation. The flatter, weaker, and eastward
shifted subtropical Atlantic ridge in the forecast field,
and the eastward shift in the region of diffluence over
Europe could, for example, account for the changes in
the high-frequency activity there.

Our results suggest that the interaction between the
low- and high-frequency circulation is important in
determining the short-term evolution of the transients
in both frequency bands. The results also confirm that
the evolution of the low-frequency component of the
forecast is sensitive to the initial specification of the
high-frequency component of the field.

The incisiveness of our experiments is compromised,
to some extent. Some of the results presented here seem
to have been hampered by our choice of separating the
two scales of motion on the basis of time filtering, using
a filter which is known to have a complicated frequency
response (e.g., see Holloway 1957). In retrospect, we
feel that a separation based on the spatial properties of
disturbances with short and long time scales, taking
into account their different types of anisotropy, could
have led to a clearer analysis.

Although the results from the two experiments that
we conducted turned out to be qualitatively similar
with respect to all the conclusions discussed in this
section, we would have more confidence in our con-
clusions if they were based on a larger ensemble of
experiments. This is particularly important in light of
the results of a recent study by Palmer (1988) showing
that error growth in forecast experiments may depend
on the initial atmospheric state. Finally, it should be
borne in mind that our results and conclusions should
apply to the Northern Hemisphere wintertime and
Southern Hemisphere summertime circulation. It
might be interesting to conduct similar experiments
for the Austral winter season (July conditions), in order
to determine whether the weaker asymmetry in its
boundary forcing renders the low-frequency winter
circulation more sensitive to scale interactions than
the Northern Hemisphere wintertime circulation.

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