# On Physical Basis and Feasibility of Monthly and Seasonal Prediction with a Large GCM

by

J. Shukla

Goddard Laboratory for Atmospheric Sciences
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

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## 1. INTRODUCTION

This paper was motivated by the following question:

> Although the detailed structure of instantaneous flow patterns can not be predicted beyond a few days, is it possible that space and time averages can be predicted for monthly and seasonal time scales?

Before we attempt to answer this question let us first review why there is an upper limit to deterministic predictability and what determines the actual limit. The fundamental reason for lack of predictability beyond a few days is the presence of dynamical instabilities and nonlinear interactions (Lorenz, 1965). This is further aggravated by lack of accurate initial conditons and inadequacy of physical models used to predict the subsequent evolution of the initial state. The rate at which an uncertainty (error) in the initial field can grow depends upon the growth rates of hydrodynamic instabilities, the nature of the nonlinear interactions and the structure of the initial error itself. The upper limit of the error is determined by the maximum possible variance of day to day fluctuations. The upper limit of accuracy for NWP is therefore determined by the growth rates associated with the instabilities of the mean flows with respect to synoptic-scale disturbances and factors which determine the equilibration of the amplitudes of the synoptic scale. Since the nature of instabilities and the mechanisms which equilibrate the amplitude of disturbances depend upon latitude, season and circulation regime, so does the limit of predictability. The results of classical predictability studies with large GCMs are briefly summarized (Smagorinsky, 1969; Shukla, 1981).

a) The deterministic predictability limit for synoptic scales (wavenumbers 5-12) is about 2 weeks, and for planetary scales (wavenumbers 0-4) about 4-6 weeks.

b) The predictability limit for synoptic scales is about 2 weeks for midlatitudes but only 3-5 days for tropics. This is mainly because of two factors: the amplitudes of synoptic scale tropical wave disturbances have a small equilibration value, and the growth rates of tropical disturbances are large because of moist-convective instabilities.

c) The predictability limit is shorter during summer compared to winter. Although the growth rates during summer are smaller compared to winter, the variance of day to day changes is much smaller.

d) The predictability limit is shorter for the Southern Hemisphere compared to the Northern Hemisphere. This suggests the possible role of quasi-stationary thermal and orographic forcings on predictability.

e) Predictability depends upon the initial conditons. Some initial conditions are more predictable than the others. Operational NWP models have shown better success in predicting blocking situations compared to rapidly changing flows.

The relevant question for the present paper is: How important are the synoptic scales for monthly and seasonal prediction? The exact location and amplitudes of synoptic scale systems cannot be too important by themselves because the time and space averaging will reduce the effects of errors in short-scale high-frequency fluctuations, but the interaction of these scales with planetary scales will be very crucial in determining the predictability of monthly and seasonal means. The planetary scales become unpredictable due to the combined effects of instabilities at their own scale, and their interactions with rapidly growing synoptic scales. Since the synoptic scales are not predictable beyond 2 weeks, it does not necessarily follow that the space and time averages are also not predictable. Most of the earlier studies of error growth and scale interaction are based on idealized turbulence models.

A fundamental prerequisite to understand the limits of weather predictability is to understand the causes for day to day weather changes. Similarly, we cannot determine the limits of monthly and seasonal predictability unless we understand the mechanisms which determine changes at monthly and seasonal times scales.

## 2. MECHANISMS FOR CHANGES AT MONTHLY AND SEASONAL TIME SCALES

The mechanisms responsible for changes in monthly and seasonal means can be conveniently divided into two groups:

Internal dynamics: Even in the absence of any fluctuations of external forcings, the combined effects of dynamical instabilites, nonlinear interactions, fluctuations of the zonal wind and its interaction with orography and heat sources, interactions among tropical large scale overturnings (Hadley and Walker cells) and extra-tropical circulations, etc. can be considered as the possible internal dynamical mechanisms responsible for producing interannual variability of monthly and seasonal means. Monthly means can be different simply due to sampling of different 30 days. Whether these factors alone are sufficient to explain the observed interannual variability in the atmosphere has been a matter of great interest in recent times. It is now generally believed that the boundary forcings play a very important role in determining the interannual variability of monthly and seasonal means.

However, it should be noted that even if the entire observed interannual variability was caused by the internal dynamics alone, it does not follow that monthly and seasonal means are not predictable as an initial value problem. Whether it can be predicted with a dynamical model or not will depend, as discussed earlier, upon the relative growth rates of errors for different scales and their interactions.

Boundary forcings. Slowly varying boundary forcings due to sea surface temperature, sea ice/snow, and soil moisture etc. can influence the amplitudes and phases of planetary scales which in turn can influence the intensity, paths and frequency of synoptic scale disturbances. Fluctuations in solar or other extra-terrestrial energy sources are not considered here because we do not have any evidence of their importance for monthly and seasonal prediction.

Changes in the boundary forcings directly influence the sources and sinks of heat and moisture which can produce significant changes in the atmospheric circulation. A large number of observational and GCM sensitivity studies have shown that monthly and seasonal anomalies of atmospheric circulation can be produced by the anomalies of boundary forcings.

As an illustration we summarize here the results of two separate investigations, one on the dynamic predictability of monthly means, and the other about the boundary forced predictability. A summary of GCM results on boundary forced predictability is given in Shukla (1982).

## 2.1 DYNAMIC PREDICTABILITY OF MONTHLY MEANS

The GLAS climate model was integrated for 60 days with nine different initial conditions and identical boundary conditions (Shukla, 1981). Three of these initial conditons were the observed atmospheric conditions on 1 January of 1975, 1976 and 1977. The other six initial conditions were obtained by superimposing a random perturbation with root mean square of 3 m/s in u and v components at all the grid points and all the model levels.

Fig. 1 gives the daily values of root mean square error for six pairs of control and perturbation runs averaged for latitude belt 40-60°N for 500 mb geopotential height. The dashed curve shows the persistence error for the three control runs. It is seen that the synoptic scales (wavenumbers 5-12, shown in Fig. 1b) lose complete predictability after two weeks, however the planetary scales (wavenumbers 0-4, shown in Fig. 1a) show some predictability even beyond one month. This suggests that space and time averages, which are mainly determined by the planetary-scale motions, have a potential for predictability at least up to or beyond one month.

In order to investigate this point further we have carried out the analysis of variance (F test) to determine the statistical significance of the differences in the variances among different control runs and among different perturbation runs. We hypothesize that for a given averaging period, if the rms error among the time averages predicted from larely different initial conditions becomes comparable to the rms error among time averages predicted from randomly perturbed initial condtions, the time averages are dynamically unpredictable. It was found that the variances among the first 30 day means, predicted from largely different initial conditions, were significantly different and greater than the variances due to random perturbations in the initial conditions, whereas the variances among 30-day means for days 31-60 are not distinguishable from the variances due to random initial perturbations. The 30-day means for days 16-46 over certain areas are also significantly different from the variances due to random perturbations. It was noteworthy that the lack of predictability for the second month was not because the model simulations relaxed to the same model state (i.e. climate drift was not a serious problem), but because of very large departures in the simulated model states. This suggests that, with improvements in the models (physics, numerics and resolution etc.), there is potential for extending the predictability of time averages even beyond one month.

## 2.2 BOUNDARY FORCED PREDICTABILITY

Shukla and Wallace (1982) conducted a modeling investigation to determine the response of GLAS climate model to an equatorial Pacific sea surface temperature anomaly. A series of 1-2 month integrations were carried out with observed initial conditions. Three pairs of control and anomaly experiments were carried out with climatological SST and a superimposed anomaly of SST (shown in Fig. 2) respectively. The first pair of integrations denoted by $C_1$ and $A_1$ were started from observed initial conditions for January 1, 1975, and the second pair ($C_2$, $A_2$) from January 1, 1977. Both pairs of integrations were run for 60 days. A third integration for 30 days was carried out starting from initial conditions of day 31 of $C_1$. Results were analysed separately for each month of the integrations. The first and second month of a 60 day run is indicated by a second subscript; for example $C_{21}$ refers to the first month of the second control run. The corresponding difference (anomaly-control) would be referred to as $D_{21}$. For the first month of integration, the averages are taken for days 11-30.

Figure 3 shows the difference (anomaly-control) in precipitation for each of the five month of the experiment. The difference pattern is dominated by a dipole configuration which reflects the eastward shift of the heaviest precipitation from near 165°E to near the dateline. It is rather remarkable that the basic dipole structure is more or less retained in all the five individual months. This attests to the important role of boundary forcings in determining the locations and intesity of large scale tropical circulations. The diabatic heating field associated with the precipitation change affects not only the tropical but also the extra-tropical circulation.

Figure 4a shows the difference (anomaly-control) in 300 mb height averaged over the five months of the experiments. The wavetrain across the north Pacific and North America is in close agreement with observations and results of linear models. The results of a student t test are shown in Fig. 4b which show that the differences for the Pacific sector are highly significant while those for other regions may be vieweed as indications of model's natural variability.

The results of this study suggest that the specifications of SST over equatorial Pacific can influence the monthly predictions over North America if a large GCM, such as the GLAS climate mode, was used for integration. The present results over the Pacific sector are such as to suggest that a prediction with anomalous SST (as was the case in January 1977) could be better than that with climatological SST. However, large changes over Eurasia (see Fig. 4a), for which there is no good observational evidence, raise questions about the appropriate strategy for using these models in actual prediction experiments. We have discussed this aspect again in Section 4.

## 3. MONTHLY AND SEASONAL PREDICTION

In this section we shall discuss the following question:

> Is there sufficient physical basis to predict averages for the next 30-90 days by integrating a multilayer, high resolution large GCM with observed initial and boundary conditions; and, is it feasible to do so for large number of cases?

The accompanying question is:

> Is there some reason to believe that these predictions, if made for large number of cases, would be superior to the pure statistical or subjective forecasts?

As excellent discussion of these and related questions was recently presented by Dickinson (1982). We would first present a list of factors which suggest that the answer to the above questions is no.

a) The predictability limit for synoptic scales is only about 2 weeks. It is not clear if there is any useful information in the predicted fields beyond that period. The classical predictability studies consider only a random error in the initial data. The actual errors might be spatially coherent and have larger growth rates compared to the random errors.

b) Boundary forcings may or may not be necessary to produce changes in the monthly and seasonal means. It is either due to the limitations of the models or due to the procedures followed in the idealized sensitivity studies that the model responses are large. In the real world the inital conditions (I.C.) and the boundary conditions (B.C.) develop interactively and therefore predictions with actual I.C. and B.C. may not show any significant improvement.

c) Recent studies of multiple equilibria have shown that several quasi-equilibrium states can occur for the same external forcing. If transitions from one equilibrium to the other are determined by large scale instabilities, the prospects for prediction of monthly and seasonal means will not be any better than that for such instabilites.

d) The present models have systematic errors (climate drift) in simulating the stationary and transient components of the atmospheric circulation. The sensitivity of different physical parameterizations and numerical schemes is not well understood.

We shall now present a discussion of the above factors and comment on their seriousness and their validity.

a) While it is true that the synoptic scales lose complete memory of the I.C. within about 2 weeks, planetary scales remain predictable beyond that period. Some useful information remains at least up to and perhaps beyond 30 days. In the predicted fields for 30 days each day has successively less useful information. The success of a 30-day mean forecast will depend upon our ability to develop suitable averaging techniques to maximize the extraction of the most useful information from each day. Predictability studies give only an estimate of the maximum possible limits of prediction. The actual limits for useful forecasts can be determined by actual forecasts only. Preliminary investigation along this line can be carried out with already available large sample of 10 day forecasts at ECMWF.

b) There is no evidence to suggest that boundary forcings do not influence the atmospheric circulation. There is a very large body of observational and modeling studies which suggest that boundary forcings influence the monthly and seasonal means. Whether the inclusion of these forcings in an initial value prediction scheme will improve the forecast is not clearly understood and cannot be judged without carrying out actual prediction experiments.

c) If synoptic scale instabilities are responsible for transitions of quasi-equilibrium states, it would be indeed difficult to predict the transitions. However, realistic dynamical models should be able to predict the persistence character of the flow. On the other hand, if quasi-equilibrium states and their transitions are related to the boundary forcings, they will, at least in principle, be predictable.

d) Systematic errors in the GCMs are one of the most serious stumbling blocks in the progress of dynamical prediction of monthly and seasonal means. A concerted effort is needed to improve the physical parameterizations and study their sensitivity. Considering the weaknesses of the current generation of GCMs, it is not clear if they can produce useful monthly and seasonal forecasts. However, there is no doubt, at least in this author's mind, that several of the current GCMs have already demonstrated their ability to simulate the stationary and transient components of the atmospheric circulation with an accuracy which justifies their use for systematic study of monthly and seasonal prediction.

In summary, while there is no guarantee that useful monthly and seasonal forecasts can be produced by large GCMs, it is clear that most of the unanswered questions can be resolved only by actual attempts of dynamical prediciton. The advantages of potential success far outweigh the risks of failure. Moreover, unlike the day to day fluctuations, the observed month to month changes do not show correlation and therefore a new method does not need to have too much skill to be better than a persistence forecast.

The factors which support the feasibility of monthly and seasonal predictions using a large GCM, and therefore would suggest the answer of the above question to be yes, are listed below.

a) There is no evidence that synoptic scales are the main determinants of the behaviour of the planetary scales.

b) The planetary scales show some predictability up to 30 days or more.

c) Space-time spectra of the observations show that most of the variance is accounted for by the low-frequency planetary waves (Straus and Shukla, 1981).

d) Most of the observed interannual variability is accounted for by the low-frequency planetary waves (Shukla, 1981).

e) There is some relationship between the storm tracks and the planetary wave configurations.

f) There are large number of observational, theoretical and GCM results which suggest that the boundary forcings due to anomalies of SST, soil moisture, and sea ice/snow etc. influence the atmospheric circulations at monthly and seasonal time scales.

g) Unlike simple models, large GCMs 'calculate' the magnitude and structure of three-dimensional heat sources associated with the anomalies in boundary forcings. However, If it were possible to determine the three dimensional heat sources independently, GCMs could be used to calculate the effects of prescribed heat sources.

h) Unlike the simplified models, the basic state need not be prescribed but evolves interactively.

i) Some case studies have already shown success in dynamical prediction of monthly means using a large GCM (Miyakoda et. al., 1981).

j) Analysis of the observed circulation patterns suggests that large scale circulation anomalies 'hang' there up to a month or more (Namias, personal communication). Lorenz (1973) has shown that the tendency for observed positive or negative anomalies to persist does not completely die out in 15 days.

k) Advances in the computer technology have made it possible to carry out large number of GCM integrations.

l) Advances in the space observing and communications technology can make it possible to produce real time description of global boundary forcings.

## 4. STRATEGY AND NEEDS

Since the current GCMs show systematic errors in simulating the mean climate, and since sometimes they show large spurious variability, it is not yet clear as to what would be the most appropriate strategy for monthly and seasonal prediction using these models. A straight forward extension of the current

NWP techniques may not give the best results. Some attention has be be paid to the problem of climate drift in current GCMs. The presence of climate drift problem does not necessarily render these models useless, because by appropriate design of predictability and sensitivity studies it may be possible to reduce the effects of climate drift problem.

We suggest here two possible approaches for monthly and seasonal prediction with large GCMs. The first approach is based on the methodology of simpler dynamical models where boundary influences are calculated separately, and the second approach is the modification of current NWP practices.

Approach 1 Separate calculation of monthly anomaly due to dynamical evolution of I.C., and due to the influenc of B.C.

i) Calcuate the monthly mean by integrating the I.C. (with climatological B.C.) and several I.C. perturbations (random or systematic) and their suitable average will give a monthly mean forecast. Subtract the model climatoloby (obtained by a multi-year run) from the above forecast and the result will be a predicted anomaly field based on I.C. and climatological B.C.

ii) Use several I.C.s from the multi-year climate run to carry out the so-called sensitivity experiments for the observed global boundary anomalies and determine a mean signal and a measure of noise. The signal can be suitably scaled by the noise level to get a forecast anomaly field for the boundary forcings.

Sum of the two anomaly fields obtained by i) and ii) would be the predicted anomaly field.

The advantage of the above method is that it reduces the adverse effects of the climate drift problems of GCMs; the most serious disadvantage is that it does not include the interaction between the observed I.C. and the observed B.C. It is quite likely that the influence of the boundary forcings could be quite different for the observed initial conditons, and moreover, it is highly desirable that the observed I.C. and B.C. be self consistent otherwise spurious travelling waves may be generated.

Approach 2 The observed I.C. and B.C. should be used together to integrate the model for several versions of I.C. (random or systematic) and a suitable average of such integrated fields would provide a predicted mean state. The model climatology (obtained from a multi-year run with climatological B.C.) should be subtracted from the predicted mean field to obtain the predicted anomaly field. After several years of operational forecasting by this method a more realistic model climatology will be available which will include the effects of several I.C. and B.C.

This approach also reduces the adverse effects of model drift but the main limitation is the inability to determine whether a large computed change over some region of the globe is mostly spurious due to natural variability and if it could have been very different for different initial conditions.

For example earlier studies have shown (Shukla and Wallace, 1982) that equatorial Pacific SST anomalies produced significant changes over North America and North Pacific and these changes were reasonably similar to each other for very different I.C., but the changes over Eurasia were very different from one I.C. to the other. The question is: can random perturbations (and small systematic changes) in I.C. capture the large variability in the model response due to changes in B.C. or do we need large changes in I.C. to determine the signal and noise in boundary forced responses? At this point there are not enough systematic experiments to give a reasonable answer to this question. If it turns out that large systematic changes in I.C. are needed to distinguish the signal and noise in boundary forced responses, a third approach, which will be a suitable combination of the first and the second approach, will be needed.

The needs for dynamical prediction of monthly and seasonal time scales can be briefly summarized as follows:

a) Global Initial Conditions: This need is already met by the requirements of current global NWP models.

b) Global Boundary Forcings: Global distribtion of sea surface temperature, sea ice, snow, and soil moisture, are needed in real time. They might be prescribed for monthly predictions but should be predicted for seasonal predictions. More modeling and sensitivity studies are needed to determine whether these boundary forcings should be predicted interactively with the atmosphere or they should be predicted by simple statistical extrapolations.

c) Improved Models The present knowledge of the scale of boundary forcings and experience with climate models suggests that the models needed for dynamical predictions should have a resolution of about 2° x 2° in horizontal, and about 20 levels in vertical. Physical parameterizations of convection, boudary layer, hydrology, cloud-radiation interaction, and treatment of orography should be realistic enough to correctly simulate the changes at montly and seasonal time scales.

d) Research on suitable strategy for monthly and seasonal prediction. Considering the limitations of the currecnt GCMs, it is not clear if a straightforward extension of the current NWP procedures would give the best results. Several case studies will be needed to determine the best strategy. It would be necessary to understand the relative roles of I.C. and B.C., and how different scales of motion lose their predictability with time. A systematic study of past observations is needed to determine the space and time scales of monthly and seasonal anomalies. This will help determine the most appropriate averaging domains.

e) Computational and Institutional requirements (see Dickinson, 1982)

Large Computer (Class 7 supercomputer)

Large human and financial resources.

## 5. SUMMARY AND CONCLUDING REMARKS

The large body of observational, theoretical, and GCM results collectively support the basis for and feasibility of dynamical prediction of monthly and seasonal averages. It is difficult to speculate on the degree of their success, but the lack of skill of statistical predictions, especially for the extreme events, suggests the potential for useful forecasts. Considering the great socio-economic benefits of a useful long range forecast, the risks of the failure of a comprehensive feasibility study program are worth taking.

## 6. RECOMMENDATIONS

In the earlier section on the strategy and needs, we have briefly summarized the observational and modeling requirements for understanding and execution of the monthly and seasonal prediction problems. It should be reiterated that the efforts should be made to meet those requirements.

Here we offer some recomendations of organizational nature.

a) Diagnostic workshop on monthly and seasonal anomalies: It is recommended that an international workshop should be organized every year to discuss the monthly and seasonal anomalies over the whole globe during the preceding year. The globe would be divided into key regions (which may be overlapping) and each key region assigned to individual research groups for analysis and discussion of monthly and seasonal anomalies. This should include analysis of circulation, rainfall, surface temperature, SST, snow and sea ice, etc.

b) Experimental prediction to test the feasibility of monthly and seasonal statistics: To conduct a large number of prediction experiments with observed, initial and boundary conditions.

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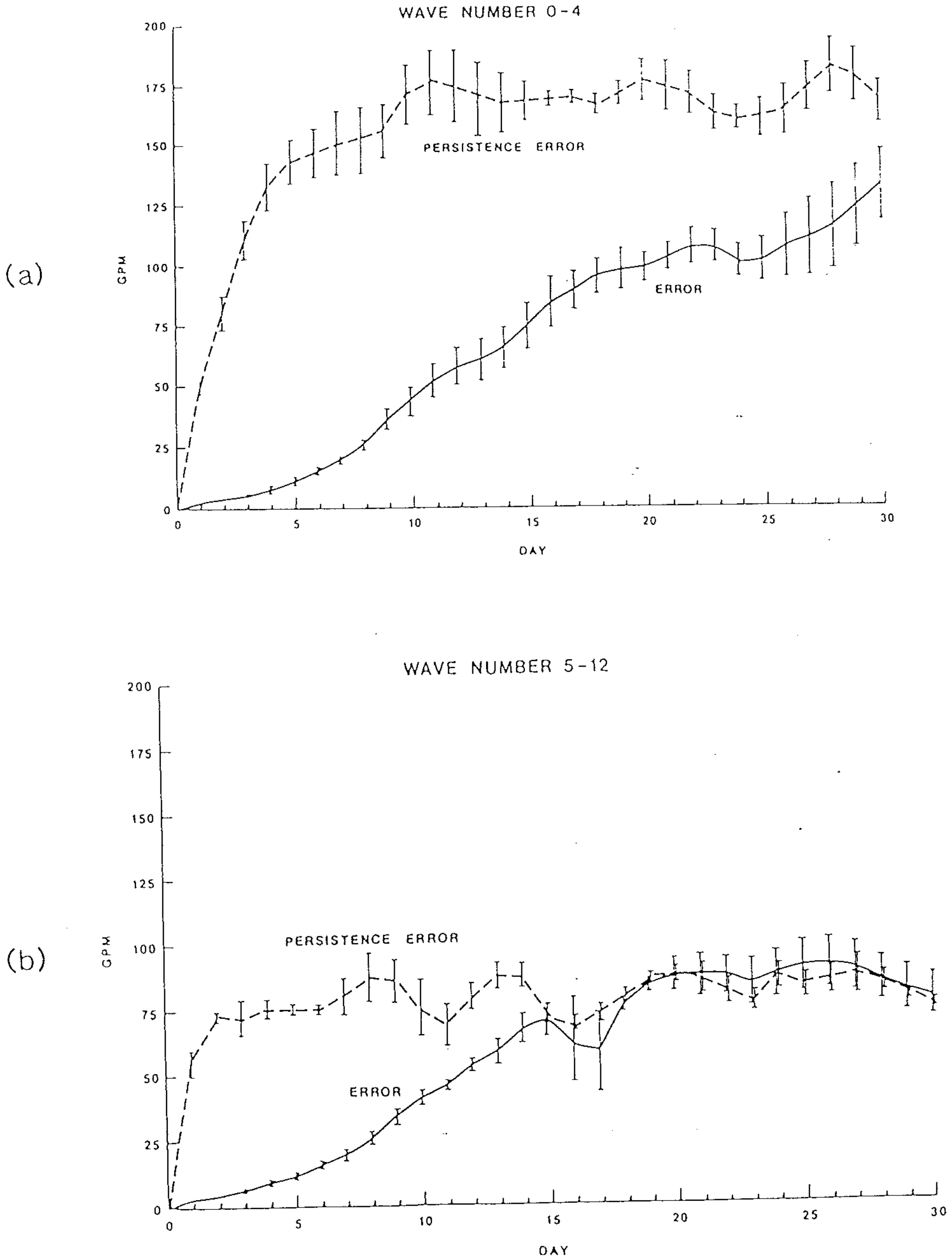
## 7. FIGURE LEGEND

Figure 1 Root mean square error, averaged for six pairs of control and perturbation runs and averaged for latitude belt 40°N-60°N for 500 mb geopotential height (gpm), for (a) wavenumbers 0-4, and (b) wavenumbers 5-12. Dashed line is the persistence error averaged for the three control runs. Vertical bars denote the standard deviation of the error values.

Figure 2 Observed sea surface temperature anomaly for the months of November, December, and January, averaged for the years 1957-58, 1965-66, 1969-70 and 1972-73 (after Rasmusson and Carpenter, 1982).

Figure 3 Precipitation difference between anomaly and control runs for (a) $D_{11}$, (b) $D_{12}$, (c) $D_{21}$, (d) $D_{22}$ and (e) $D_{31}$. Thick solid contour denotes the zero contour, thin solid and dashed line denote positive and negative contours respectively, with logarithmic contour intervals of 2, 4, 8 and 16 mm/day.

Figure 4 (a) Average difference $\overline{D}$ for 300 mb height (m) between anomaly and control runs; contour interval 40 m. (b) Areas with t value significant at levels above 95% (dashed) and above 99% (cross hatched) for 300 mb height differences in the five cases $D_{11}$, $D_{12}$, $D_{21}$, $D_{22}$, $D_{31}$.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(b)
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Figure 1

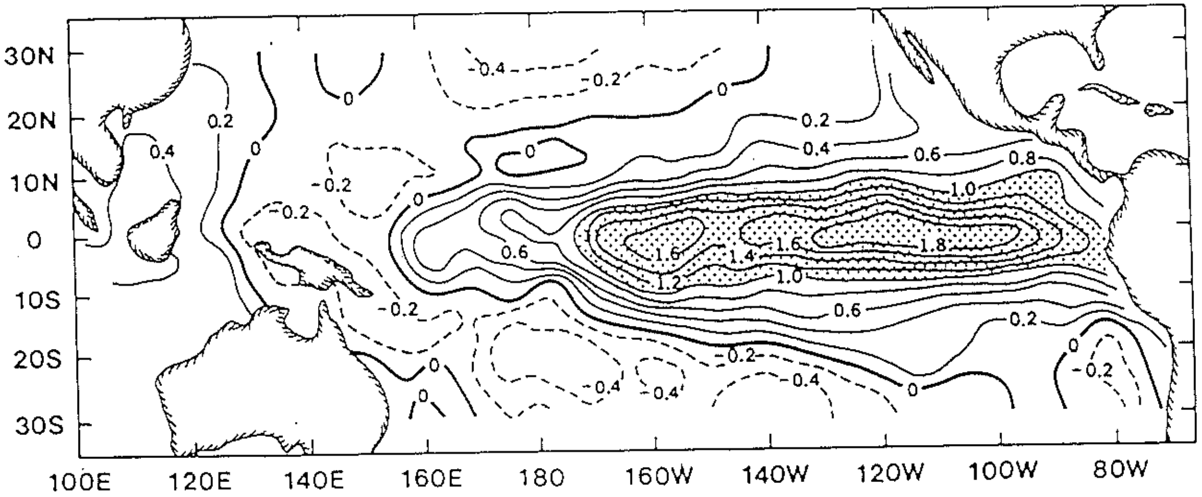
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Figure 2

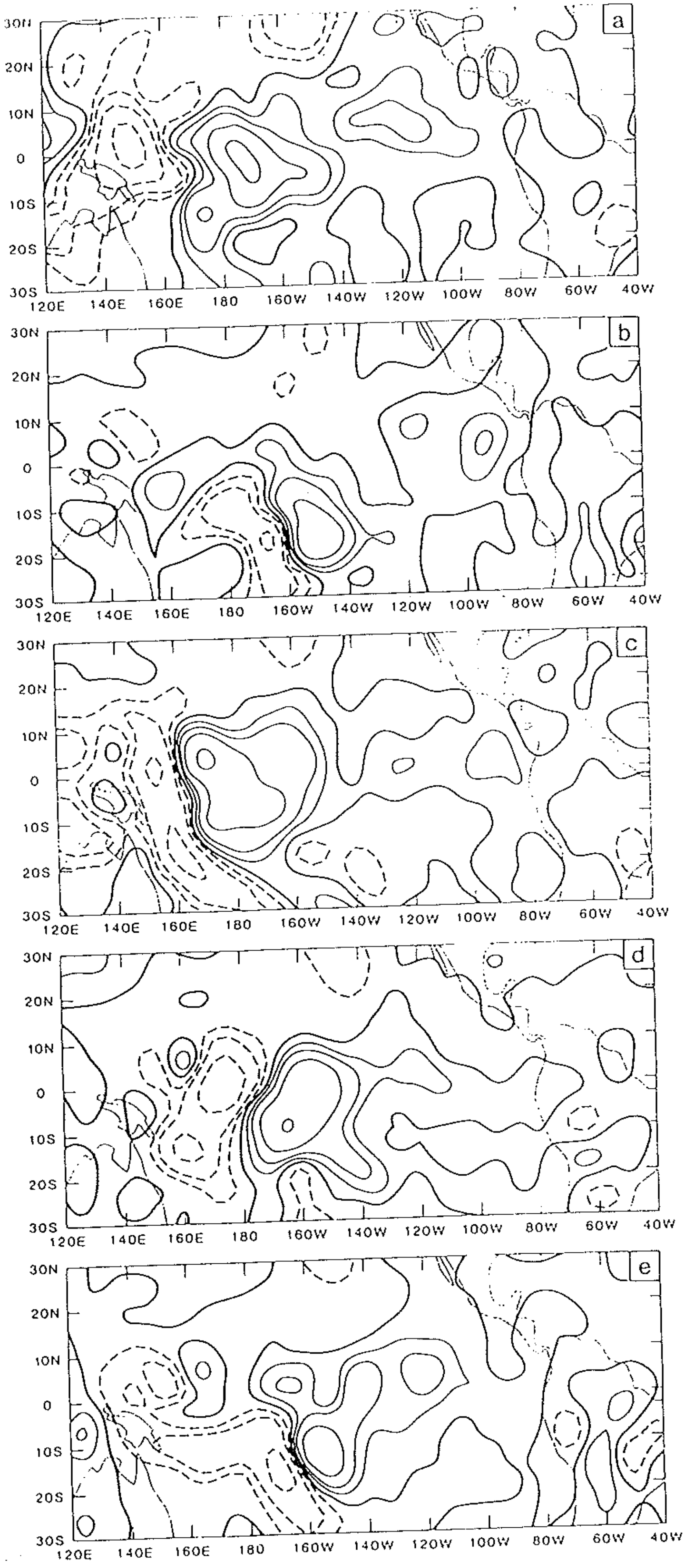
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Figure 3

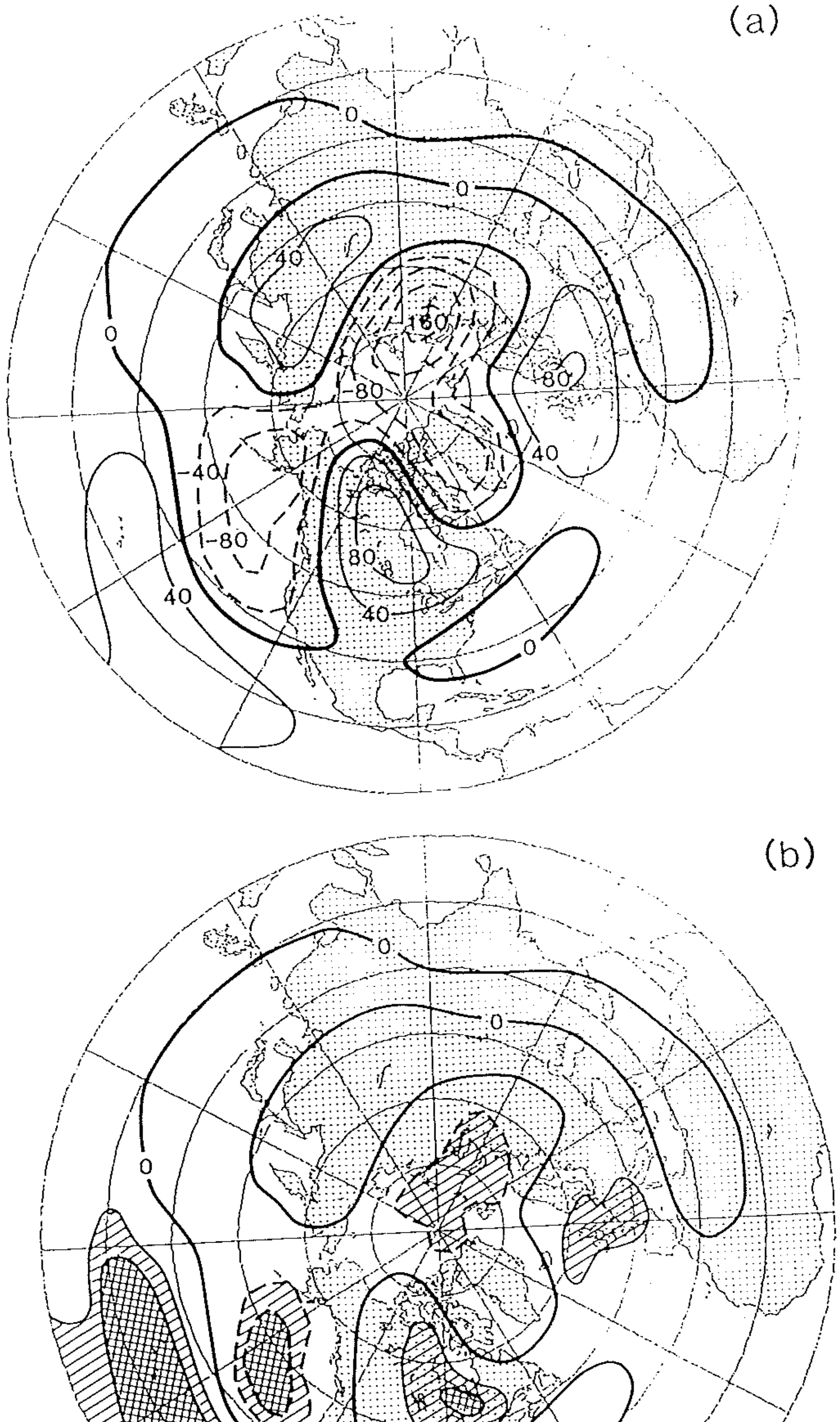

Figure 4