PREDICTABILITY OF SHORT-TERM CLIMATE VARIATIONS

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1. INTRODUCTION

It is well known that day-to-day changes of atmospheric motions are not predictable beyond a few weeks because of nonlinear dynamical interactions which can amplify even small initial errors due to incorrect observations used for defining the initial state of the atmosphere, or imperfect governing equations used for making predictions (Lorenz, 1965). However, is it possible that, despite the lack of predictability of day-to-day weather, monthly and seasonal averages of weather variable can be predicted with sufficient accuracy to be of some value for practical applications? In this paper, we attempt to answer this question by reviewing our current knowledge of observed variability and our understanding of physical processes that determine the interannual variability and predictability of monthly and seasonal averages. We also summarize the recent attempts to predict monthly and seasonal mean atmospheric circulation using dynamical models.

In this paper, the phrase 'short-term' refers to fluctuations with time scales varying from a month (~ 30 days) to a few years (~ 1000 days). Although our main emphasis will be on discussing the predictability of monthly (~ 0-30 day mean) and seasonal (0-90 day mean) variations from a given initial state, we also briefly address the question of predictability of the El Niño-Southern Oscillation (ENSO) phenomenon which has provided a basis for prediction of seasonal averages, several seasons in advance.

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2. MECHANISMS FOR INTERANNUAL VARIABILITY

A convenient conceptual framework to describe and understand the mechanisms for interannual variability of monthly and seasonal average circulation is to consider the role of the internal dynamics and the boundary forcings separately (Shukla, 1981a). It must be recognized, however, that in reality the two are inseparable because the changes in the boundary forcings at the earth's surface (sea surface temperature (SST), soil wetness, snow cover and sea ice) are caused by their interactions with the overlying atmospheric motions.

Consider an idealized situation in which the boundary conditions of SST, soil wetness, snow cover and sea ice at the earth's surface, and the external forcings of the solar radiation are invariant with time, and a global climate model is integrated for several years. The simulated climate will undoubtedly exhibit interannual variability of monthly and seasonal mean circulation. These variations are caused by inherent dynamical instabilities, nonlinear interactions among different space and time scales and interactions of fluctuating zonal winds with orographic and thermal forcings. If observed variations in the real atmosphere were not significantly different from those produced by internal dynamical processes alone, the prospects of predicting the monthly and seasonal averages would not be much better than those for predicting the day-to-day weather fluctuations.

Based on a very large number of observational and modeling studies, it is now well established that changes in the boundary conditions of SST, soil wetness, snow cover and sea ice can produce large and systematic changes in atmospheric circulation. It is, therefore, natural to conclude that the predictability of monthly and seasonal average circulation could be significantly enhanced if the changes in these boundary conditions could also be predicted.

Fortunately, some of these boundary conditions change rather slowly compared to the changes in the atmospheric circulation and therefore, under certain situations, using realistic dynamical models the evolution and persistence of anomalous atmospheric circulation can be predicted with the assumption of persistence of the anomalous boundary conditions.

3. *PREDICTABILITY OF MONTHLY AND SEASONAL MEAN ATMOSPHERIC CIRCULATION*

For prediction of monthly and seasonal average circulation the initial condition of the atmosphere is important; but the boundary conditions at the earth's surface must also be correctly specified. The conceptual framework described here suggests that the predictability of time average atmospheric circulation should be different for the tropical and the extratropical flows (Shukla, 1981b). The tropical circulation consists of the large scale Hadley and Walker circulations whose fluctuations are determined mainly by changes in the boundary conditions at the earth's surface. The day-to-day weather changes in the tropics are associated with synoptic disturbances which, with the exception of tropical cyclones, are generally weaker compared to the large amplitude disturbances in mid-latitudes. The changes in the boundary conditions (viz. El Niño SST anomalies) can produce significant shifts in the locations of the ascending and descending branches of the Hadley and Walker circulations, giving rise to large shifts in seasonal mean rainfall patterns. In fact, the occurrence of seasonal tropical droughts and floods can be generally interpreted as spatial and temporal shifts in the climatological patterns of rainfall. The synoptic scale disturbances in the tropics are of secondary importance in affecting the location and intensity of large scale Hadley and Walker circulations.

The nature of variability in the mid-latitudes is distinctly different. The internal dynamical processes are the dominant mechanism for the day-to-day, as well as, the interannual variability. It is difficult to distinguish between the internal variability and the role of slowly varying boundary conditions. For example, a monthly mean circulation anomaly in the mid-latitudes can be very different depending upon the presence or the absence of a blocking event during that period. Thus, any success in predicting the monthly mean circulation anomaly will largely depend upon predicting the blocking event. Since there is no clear evidence that anomalous boundary conditions are the main forcing for the occurrence of blocking events, there is no guarantee that either a correct specification of the boundary conditions initially or even a correct prediction of the boundary conditions will help predict the blocking event and the corresponding monthly mean circulation.

The role of global boundary conditions in forcing mid-latitude variability remains an open question, in part, because GCM sensitivity experiments to address this question have not been carried out systematically. The available results are inconclusive. There have been several numerical simulations in which an atmospheric GCM is integrated with prescribed climatological SST and the variability is compared with the observed variability. If it is found that the two estimated variabilities are comparable - and they are for the extratropics - it is concluded that the variations of SST are not important because the model was able to simulate the observed variability even without accounting for SST variations. We would like to submit that this argument is flawed because the model simulated variability in the absence of the changes in the boundary conditions can be equal to the observed variability for a variety of other reasons depending upon the nature of global constraints imposed in the particular model.

3.1 Prediction of monthly and seasonal mean tropical circulation

We do not wish to dwell on this topic in any detail here because it has already been established, through a very large number of GCM sensitivity experiments, that the time mean tropical circulation and rainfall are highly predictable if the boundary conditions of SST and soil wetness are correctly specified (Shukla and Fennessy, 1988; Mo and Kalnay, 1991; WCRP, 1988).

The question of predictability of monthly averages about a seasonal average was examined by Fennessy and Shukla (1991) with correctly prescribed SST. It was found that there was little skill in predicting monthly departures from a seasonal mean. This generally has also been the experience for empirical predictions.

3.2 Prediction of monthly mean mid-latitude circulation (winter season)

Following the pioneering work of Miyakoda et al. (1983), large numbers of investigators have carried out hindcasts and forecasts for monthly mean atmospheric circulation using general circulation models (see the paper by Royer in this volume for a comprehensive review). In a study by Baumhefner (1991) in which he carried out an ensemble of forecasts for different initial states, he showed that there is considerable skill in prediction of monthly means. In these hindcast experiments, he used climatological boundary conditions of SST, soil moisture, snow cover and sea ice. It is likely that if he had used the observed boundary conditions, the skill of those hindcasts would have been even higher.

There also have been several classical predictability studies in which the initial state is randomly perturbed and the growth of initial error is examined for the monthly mean circulation. Using the NCAR community climate model with perpetual winter boundary conditions, Tribbia and Baumhefner (1988) found that the root mean square error between the twin model runs was comparable to the model variance for the first 30 day means, suggesting that the prospects for predicting thirty-day averages are not quite good. It is likely that this rather pessimistic result could be at least in part due to the model's deficiency in simulating the low frequency variability. We have further examined (Shukla, 1988) the predictability of monthly means using the two layer model by Schubert and Suarez (1989) and found that in contrast to the results of Tribbia and Baumhefner, for this model, 30-day averages for days 1-30, and even up to days 21-50, are highly predictable. We consider these overly optimistic results also suspect because the low frequency variability for this model was about 150% of the observed values where as it was about 67% for the NCAR model used by Tribbia and Baumhefner.

In an earlier paper (Shukla, 1981a), an analysis of variance was used to compare model integrations with large differences in the initial conditions, and with small random differences in the initial conditions. It was concluded that, even in the absence of suitable models to predict the boundary conditions at the earth's surface the atmospheric monthly means are dynamically predictable.

It is likely that a skillful prediction of monthly mean circulation might require better skill in predicting the 30-60 day oscillations (referred to as Madden-Julian oscillations). Krishnamurti (1991) has shown an example of skillful forecasts of up to a month by using observed SST and suppressing high frequency fluctuations.

Prediction of monthly means is a straightforward extension of numerical weather prediction. It is, however, quite important that, in addition to the usual initialization procedures to have an appropriate divergence field, the initial state must be completely consistent with the boundary conditions at the earth's surface (SST, soil moisture, snow, sea ice, etc.). Predictions beyond short range (0-5 days) should also include a description of different circulation regimes and estimates of ensemble variance.

Based on a large number of investigations made during the past ten years, it is reasonable to conclude that socially useful predictions of monthly mean atmospheric circulation can be produced routinely using dynamical models. However, it should be noted that especially for the extratropical regions, most of the skill in 30-day prediction comes from the first 15 days (e.g., Palmer et al., 1990).

3.3 Prediction of seasonal mean mid-latitude circulation (winter season)

There have only a few systematic investigations of predictability of seasonal mean circulation. If predictability of time averages were defined in terms of the ratio between the observed variances and natural variability (noise), as suggested by Madden (1976), seasonal averages are found to be more predictable than monthly averages (Singh, 1989). Twenty years of daily 500 mb analyses were utilized by Singh (1989) to calculate the ratio of the variance of observed seasonal means and noise in seasonal variance. The ratios were found to be higher than those for monthly means. This enhanced predictability is mainly an indication of the influence of the slowly varying boundary conditions. By taking a seasonal average, intra-monthly variations are filtered out and the effects of the boundary forcings can be detected. The notion of enhanced predictability of seasonal averages is further supported by model calculations of Lau (1985), for which Palmer (1987) showed that the ratio of observed variance to model simulated variance is far higher for the seasonal averages than that for the monthly averages.

Although studies of Shukla and Bangaru (1979), Palmer and Sun (1985), Lau and Nath (1990) and Wallace et al. (1990) show modeling and observational evidence of an association between mid-latitude SST and circulation, the possible influences of tropical and/or extratropical SST variations on the seasonal mean extratropical circulation are not clearly understood. One way, and perhaps the only way, to address this question is to make short term climate predictions with and without global SST variations starting from observed initial states and verify against actual observations. This is necessary because the mid-latitude response to tropical or extratropical SST changes depends on the structure and variability of the mid-latitude flow.

Recently, seasonal predictions (hindcasts) have been carried out by Brankovic et al. (1993) and Shukla and Marx (1993) using the ECMWF and the COLA models, respectively. Both studies have found significant effects of SST anomalies on seasonal predictability. In agreement with a large number of GCM sensitivity studies in the past, the impact of SST anomalies was especially large on the simulations of tropical and subtropical circulation.

3.4 Prediction of seasonal mean mid-latitude circulation (spring and summer season)

Following the conceptual model for the mechanisms for interannual variability, one may formulate the conjecture that, since the day-to-day fluctuations during the spring and summer season are rather weak, it should be possible to detect the influence of the boundary forcings even in the mid-latitudes.

Brankovic et al. (1993) have shown that in the spring season the skill of the ensemble mean seasonal forecast was highest and the spread of the ensemble was smallest among the four seasons.

It has been further shown by Fennessy et al. (1993) that changes in the initial specification of the soil wetness has significant effects on the simulated seasonal mean temperature and rainfall. The GCM simulation of 1988 drought over the U.S. was far more realistic when the initial soil wetness was based on the analysis-forecast cycle of the ECMWF model rather than climatology.

3.5 Prediction of seasonal averages several seasons in advance

The entire discussion in the preceding subsections refers to prediction of monthly (0-30 days) or seasonal (0-90 days) averages starting from a given initial state of the atmosphere and boundary conditions at the earth's surface. There is now a large body of modeling evidence that suggests that the coupled ocean-atmosphere system in the tropical Pacific is predictable up to several seasons (see Latif et al. (1993) for a review). The skill of these forecasts depends upon the initial state of the ocean (forecasts initiated in the summer and fall seasons are more skillful than those initiated in the winter season) suggesting that the initial state of the ocean contains the "memory" which makes it possible to predict the evolution of the coupled system for periods of one to two years. In a classical predictability study by Goswami and Shukla (1990) for the coupled model developed by Cane and Zebiak (1987), it has been shown that the doubling time for small perturbations in the initial state is a few months for the coupled system as compared to a few days for weather prediction models.

The existence of the extended range predictability of the coupled ocean-atmosphere system for the tropical Atlantic and the tropical Indian Oceans is yet to be shown using realistic models and realistic initial states of the ocean. It is likely that it would be more difficult to make skillful forecasts of SST anomalies in the tropical Atlantic and Indian Oceans because the interannual variability of SST is relatively small in these oceans compared to that in the tropical Pacific Ocean.

The prospects for prediction of extratropical SST several seasons in advance are not very good because of the strong dependence of SST on surface heat fluxes which are largely determined by the highly variable and unpredictable mid-latitude atmospheric variability.

4. SUMMARY AND CONCLUSIONS

- Although day-to-day weather fluctuations are not predictable beyond a few days, space-time averages of atmospheric circulation and rainfall are predictable for monthly and seasonal averages.
- Prediction of monthly means (0-30 days) is a straightforward extension of numerical weather prediction with one important difference: The definition of the initial state, in

addition to the usual initialization procedures to have an appropriate divergence field, now must have complete consistency between the atmosphere and the boundary conditions at the earth's surface (sea surface temperature, soil moisture, etc.).

- For prediction of seasonal means (0-90 days), the atmospheric initial condition remains important, but the boundary conditions at the earth's surface must also be predicted. (This has high potential for useful predictions in the tropics because SST changes slowly).
- If predictability of time averages is defined in terms of the ratio between observed variances and natural variability (noise), seasonal averages are more predictable than monthly averages, especially for the tropics.
- For prediction of seasonal means, for lead times of three to five seasons, the ocean initial condition is very important. The "memory" resides in the initial condition of the ocean and the coupling between the atmosphere and the ocean is the source of enhanced predictability of the coupled system.
- If tropical SST variations could be predicted at extended range (a few seasons to a few years), tropical rainfall and circulation could also be predicted with a high degree of confidence.
- The possible influences of tropical and/or extratropical SST variations on the extratropical circulation are not clearly understood.
- There is enough observational (statistical correlations) and modeling (sensitivity experiments) evidence to suggest that experimental prediction of seasonal means should be carried out routinely using the observed initial state of the atmosphere, observed global SST and soil wetness, a "good" GCM, and some scheme for prediction of the global SST.

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