PREDICTABILITY OF FLUID MOTIONS, 1984: American Institute of Physics, Editors: Greg Holloway and Bruce J. West

PREDICTABILITY OF A LARGE ATMOSPHERIC MODEL

J. Shukla
Laboratory for Atmospheric Sciences
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

INTRODUCTION

The future evolution of an observed atmospheric state is not predictable beyond a few days because of the inherent instability of the large scale atmospheric flows and nonlinear interactions among motions of different space and time scales. The theoretical upper limit for deterministic prediction is mainly determined by the growth rates of the most dominant instabilities and the mechanisms for equilibration of their amplitudes. Even a small uncertainty in any one scale grows with the characteristic growth rate for that scale and nonlinear interactions among different scales of motion help spread this unpredictability to all the scales present in the flow. For a simple barotropic fluid without the beta effect and without asymmetric forcing, Lorenz[1] showed that each scale of motion has its own range of predictability which is determined by its interaction with the neighboring scales and the level of energy in that scale. Determination of the limits of predictability for atmospheric motions is of great importance for weather and climate forecasting. Limits on our ability to make accurate weather forecasts at long range can arise either due to incomplete definition of the initial state of the atmosphere or due to incomplete knowledge of the physical laws governing the future evolution of the atmospheric states.

During the last 30 years a variety of models of atmospheric flows have been used to calculate the limits of predictability. One of the standard procedures to conduct such studies is to integrate the model with two nearly identical initial conditions and then to examine the growth of the small initial difference. We would refer to such studies as the *classical predictability studies.* The first such comprehensive study was reported by Lorenz[2] in which he examined the predictability of a 28 variable atmospheric model, and showed that the doubling time for small errors was about four days. Subsequently, several large atmospheric models, generally referred to as the general circulation models (GCMs), were used to calculate the growth characteristics of small initial errors. Charney *et al.*[3] have described the results of such integrations of the then available models of Smagorinsky[4], Mintz[5] and Leith[6]. There were large differences among the estimates of the error doubling time for these three models. In each model a sinusoidal temperature error field was introduced in the initial conditions. The Leith model did not exhibit a consistent exponential growth of the initial error which underwent a transient oscillation for the first week and then levelled off at about seven days. In the Smagorinsky model, the error exhibited quasi-periodic fluctuations for the first two weeks. For very small amplitude of the initial temperature error field, the growth rate was small for the first 30 days after which an exponential growth rate of about 6-7 days was observed. The Mintz-Arakawa model results, which were considered to be more realistic because the pattern of error growth was consistent with the notion of exponential growth of a small 'linear' error field superimposed on the large scale mean flow, exhibited a doubling time of about five days. Since the root mean square difference between randomly chosen fields of Nothern Hemispheric winter temperature fields is about 8°C, a doubling time of five days for an initial perturbation of 1°C would suggest a predictability limit of about two weeks.

These experiments showed a high degree of model dependence of the results of predictability calculations. This was partly because, in the early 60's, model development was still in its infancy. If similar experiments were carried out with the three state-of-the-art GCMs available today, the predictability characteristics would be far more similar for all the models. It has been further noted by Jastrow and Halem[7] and Williamson and Kasahara[8] that even for the same model an increase in the spatial resolution results in a decrease in the error doubling time. These results suggest that a great deal of caution is required in interpreting the results of a particular GCM.

A comprehensive study of the predictability of a nine-level global GCM with orography, moist convection, radiation, and cloudiness was carried out by Smagorinsky.[9] The doubling time of the initial random error of about 0.25°C was about 2.5 days; after the initial error had reached an average value of 0.5°C, the doubling time was about 3.5 days and it took about seven days for the error to double from 1°C to 2°C. These results were far more consistent with the notion of the error growth due to hydrodynamical instabilities than those reported by Charney *et al.*[3] Smagorinsky did not find a clear model resolution dependence for predictability as found by Jastrwo and Halem[7] and Williamson and Kasahara[8]. Smagorinsky also examined predictability as a function of zonal wave number for Northern Hemisphere mid-latitudes and showed that the larger scales are more predictable. However, most of Smagorinsky's analysis concerned the growth of globally averaged error fields.

Since the growth and equilibration of the dominant instabilities are the primary determinants of the limits of predictability, and since the nature of these instabilities strongly depends upon the circulation regime, season, and the presence of quasi-stationary asymmetric forcings, it is considered desirable that the predictability characteristics of a large atmospheric model be examined separately for tropics and mid-latitudes, for winter and summer, for Northern and Southern Hemisphere, and for large and small spatial scales. In this paper, we have briefly summarized the results of such a study.

CLASSICAL PREDICTABILITY STUDIES WITH THE GLAS CLIMATE MODEL

We have carried out numerical integrations of the Goddard Laboratory for Atmospheric Sciences (GLAS) climate model[10] to determine its predictability as a function of the circulation regime (tropics and mid-latitudes of both the hemispheres), season, spatial scale (latitudinal wave number), and meteorological variable.

The two most important quantities which can summarize the results of the classical predictability studies are the error growth rate, and the maximum possible value, to be referred to as the equilibration value of the error. While comparing the predictability of two systems, it is important to note the relative values of both of these quantities. A larger growth rate does not necessarily imply a smaller predictability because larger growth rate may be accompanied with a much larger equilibration value. This is of special relevance in comparing the predictability for the winter and the summer season in the Northern Hemisphere. Based on the values of error growth rate alone, Charney *et al.*[3] had concluded that the summer season is more predictable than the winter. This conclusion is not valid because although the error growth rates are smaller in summer compared to winter, the equilibration values for error are much smaller in summer giving rise to lower predictability in summer.

Most of the earlier studies of classical predictability had examined the growth rate of global or hemisphere mean error fields. It could be argued that the examination of growth of a globally or hemispherically averaged error field is justified because the tropics and the mid-latitudes interact strongly. The drawback of this argument is that the time scale for the growth and saturation of initial observational errors in the tropics is much smaller than the time scale of interaction between the tropics and the mid-latitudes. It is, therefore, not only desirable but necessary that the error growth characteristics be examined separately for the tropics and the mid-latitudes.

The Model

The GLAS Climate Model is a global primitive equation model with a horizontal resolution of 4° latitude x 5° longtitude and in vertical levels in sigma coordinates. The model used for these numerical integrations has been described by Shukla et al.[10] It resolves the orographic features at the earth's surface reasonably well. The seasonally varying values of sea surface temperature, soil moisture, snow and sea ice are prescribed at the model grid points. There is no horizontal mixing in the model, except the one introduced by numerical finite differencing and filtering. There is no explicit parameterization for vertical mixing of momentum in the interior of the atmosphere. Vertical transport of heat and moisture is accomplished by parameterized convection. Short wave and long wave radiation fluxes are calculated every five hours and they are influenced by the model generated space-time variable cloudiness.

The Initial Conditions

Model integrations are started with the observed initial conditions obtained from the operational analysis of the National Meteorological Center (NMC). Fields of horizontal velocity (u,v), temperature (T), moisture mixing ratio (q), and pressure (p) are interpolated from the NMC model grid to the GLAS climate model grid points. The boundary conditions of sea surface temperature, snow, sea ice, and soil moisture are given by their climatological values.

The Initial Error Field

The model is first integrated with the observed initial conditions described earlier. This model integration will be generally referred to as the control run. The initial conditions are then modified by adding a random perturbation field in u and v components at all the grid points at all the levels of the model. This will be referred to as the predictability run. The grid point values of the random perturbation follows a Gaussian distribution with zero mean and standard deviation of 3 m/s in u and v components separately. The magnitude of the random perturbation in either u or v is not allowed to exceed 12 m/s at any grid point. We considered it prudent to perturb the wind field only because the variances of temperature and pressure field differ greatly between the tropics and the mid-latitude. A root mean square error of 1 mb in the pressure field for the initial random error is closer to the observational errors for the mid-latitudes but it is comparable to the observed variance for the tropics. Moreover, several earlier calculations had been done by perturbing the mass field and they did not allow a comparison of error growth for the tropics and the mid-latitudes separately.

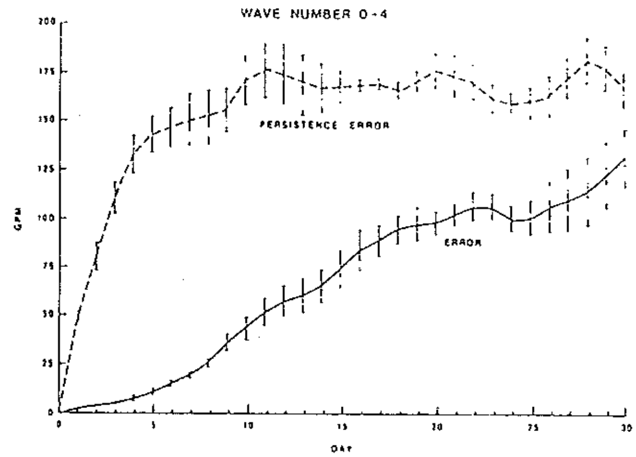
SUMMARY OF THE RESULTS

a) The planetary scales are more predictable than the synoptic scales.

Figure 1 shows the root mean square error, averaged for six pairs of control and perturbation runs and averaged for the latitude belt 40–60°N for the 500 mb geopotential height for planetary scale wavenumbers 0-4 and synoptic scale wavenumbers 5-12. The initial conditions and the boundary conditions are for the Northern Hemisphere winter season. The dashed line is the average persistence error and the vertical bars denote the standard deviation of the error values. Although the growth rate is nearly the same for the planetary scale waves and the synoptic scale waves, the equilibration value is much larger for the planetary waves giving rise to higher predictability (about four weeks) for the planetary waves compared to the synoptic scale waves (about two weeks). The doubling time for very small errors is about 2.5 days and after the error has grown up to 25 meters, the doubling time increases to about three days. Higher predictability of the planetary scales is of special significances for predictability of space and time averages.

b) The theoretical upper limit of deterministic predictability for low latitudes is shorter than that for the middle latitudes.

(a)



(b)

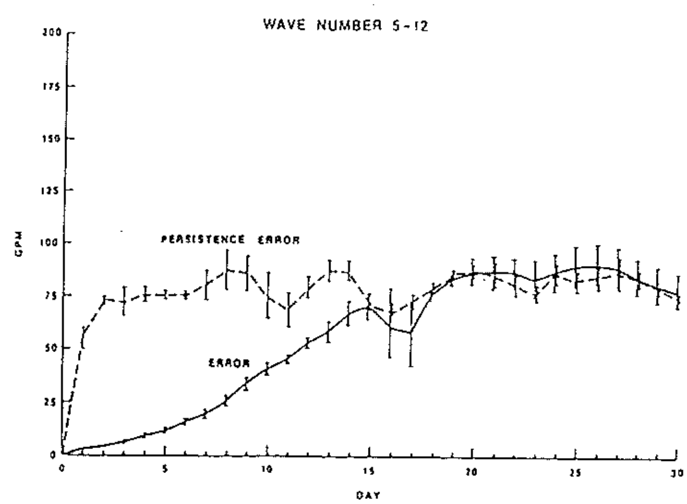


Fig. 1. Root mean square error, averaged for six pairs of control and perturbation runs and averaged for latitude belt 40°N–60°N for 500 mb geopotential height (gpm), for (a) wavenumbers 0-4, and (b) wavenumbers 5-12. Dashed line is the persistence error averaged for the three control runs. Vertical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

Figure 2 shows the root mean square between control and predictability runs averaged for 20° latitude belts centered at 6°N, 30°N and 58°N, respectively. The curve for 6°N has two remarkable features: the initial error growth rate is the largest, and the error equilibration value is the smallest. This suggests that the initial errors grow faster in the tropics. This could be due to the dominance of the moist-convective instabilities and inadequacy of the parameterizations of moist processes. The smallness of the equilibration value indicates smaller day-to-day variability in pressure and temperature fields in the low latitudes. This could be due to the smallness of the Coriolis parameter and lack of geostrophy. The results for the u and v components are qualitatively similar. The errors of observation in the tropics are already closer to the maximum possible value and therefore it takes only a few more days for the initial error to grow to a magnitude comparable to that between two randomly chosen maps. The above conclusions wll be valid even for an idealized case of uniform and high density observations over the globe, but in reality the situation is much worse in the tropics. The data network is sparse and the scale of the tropical disturbances is only 2000-3000 km. Based on these results it has been concluded that if the theoretical upper limit for deterministic predictability of synoptic scales is about two weeks for the mid-latitudes, it is only 5-7 days for the tropics.

c) The Northern Hemisphere winter is more predictable than summer.

Although the growth rate of the initial error is larger during the winter season compared to the summer season (Fig. 3), the equilibration value of the error is much larger in winter compared to that in summer, and therefore in winter it takes longer for the error to be comparable to the error between randomly chosen charts. This conclusion is supported by the results of operational numerical weather prediction models.

d) The Northern Hemisphere is, in general, more predictable than the Southern Hemisphere.

We have examined several pairs of control and predictability integrations for the same season for the Northern and Southern Hemispheres separately. It was found that the error equilibration value is generally higher for the Northern Hemisphere compared to the Southern Hemisphere. The error growth rates as well as the error equilibration values do not show large seasonal variation in the Southern Hemisphere. It is likely that the presence of strong zonally asymmetric forcing functions in the Northern Hemisphere enhance its predictability. The predictability of an ocean covered earth was found to be smaller than either the Northern or the Southern Hemisphere.

e) Some variables are more predictable than others.

Rainfall was found to be less predictable than circulation parameters. In the tropics, pressure and temperature are less predictable than wind velocity and, in general, all variables are less predictable in the tropics compared to the mid-latitudes.

f) Some initial conditions are more predictable than others.

Since the error growth rate depends upon the nature of the instabilities, and the growth rate of instabilities strongly depends upon the structure of the basic large scale flow, it is quite reasonable to expect a strong initial condition dependence of predictability. It is also likely that the data deficiency in certain preferred regions, for certain large-scale flow structures, might produce unusually large growth of initial error field.

g) The growth rate for spatially random initial error fields is smaller than for systematic initial errors.

We have carried out a few predictability experiments in which the random initial error field was spatially smoothed over the oceans only. This produced spatially coherent error fields over the oceans but the error remained random over the land. The error growth rate

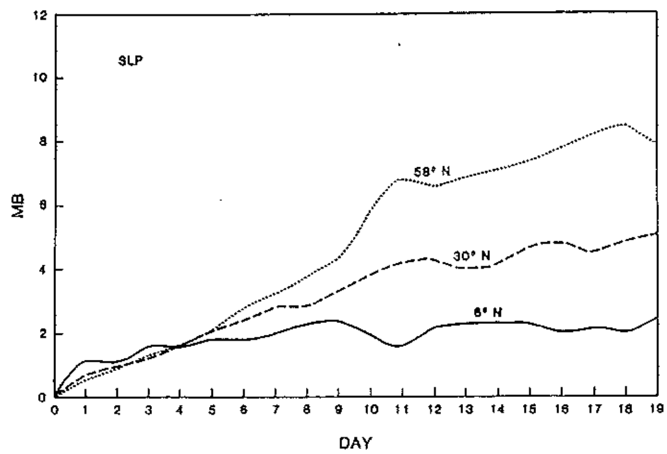


Fig. 2. Root mean square as a function of time between a summer control and a predictability run for sea level pressure (mb). Solid line, dashed line and dotted line refer to an average over 10° latitude belt centered at 6°N, 30°N and 58°N, respectively.

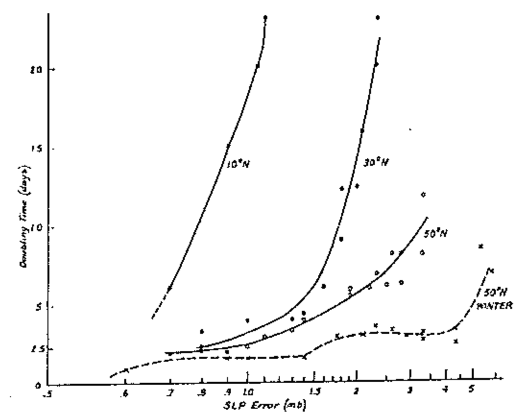


Fig. 3. Error doubling time in days along the ordinate, and magnitude of the error in mb along the abscissa for 20° latitude belt centered at 10°N, 30°N and 50°N for the summer season and at 50°N for the winter season.

in this case was larger than that for the random errors over the whole globe. This experiment was intended to simulate possible large systematic errors over the oceans. The results suggested that the lack of good data coverage over the oceans might be a possible source of error in defining the initial structure of the planetary waves and might therefore reduce the predictability at those scales. These results also suggest, albeit indirectly, that space observing systems, with uniform coverage over the whole globe to define the initial conditions, might lead to higher predictability compared to the conventional observational network with high data coverage only over the land.

h) The growth rate of the error depends upon the magnitude of the error.

Initially, small errors grow fast, but as the magnitude of the error increases, the rate at which the error grows decreases. Figure 3 is a summary of several predictability intergrations which shows that for any latitude, hemisphere, and season, the error doubling time increases with the magnitude of the error. Very large doubling times do not represent high predictability, but they only indicate that the error has grown to be so large that it cannot double again.

PREDICTABILITY OF SPACE-TIME AVERAGES

It has been shown[11] that the inherent dynamical predictability of the observed planetary waves in the atmosphere is great enough to make the errors in the predicted monthly means significantly smaller than the errors arising from small random perturbations in the initial conditions. Since space-time averages are dominated by the low-frequency planetary waves, the limit of predictability of space-time averages is not completely determined by the growth rate of the fastest growing synoptic scale instabilities, but by their interactions with the planetary scales. There is also additional predictability due to the influence of the boundary conditions at the earth's surface[12]. The boundary forcings due to anomalies of sea surface temperature, soil moisture, sea ice and snow, etc., can produce significant changes in the monthly and seasonal atmospheric circulation, and since these boundary forcings change slowly compared to the atmospheric motions, they can enhance the predictability of time averages.

The space-time averages for the tropics are potentially more predictable because the tropical planetary scale circulations are dominated by Hadley, Walker, and monsoon circulations which are intrinsicaly more stable than the mid-latitude Rossby regime. Interaction of these large scale overturnings with tropical disturbances (easterly waves, depressions, cyclones, etc.) is not strong enough to make the former unpredictable due to unpredictability of the latter. Tropical disturbances are initiated by barotropic-baroclinic instabilities, but their main energy source is latent heat of condensation. Although their growth rate is fast and they are deterministically less predictable, their amplitude equilibration is also quite rapid and they attain only moderate intensity. The intensity and geographical locations of Hadley and Walker cells is primarily determined by the boundary conditions and not by synoptic scale disturbances. It is reasonable to assume that frequency and tracks of depressions and easterly waves is primarily determined by the location and intensity of Hadley and Walker cells, and distribution of SST and soil moisture fields. It is highly unlikely that tropical disturbances will drastically alter the character of the large scale tropical circulation. This is in marked contrast to the case of mid-latitudes where interaction between synoptic scale instabilities and planetary scale circulations is sufficiently strong for baroclinically unstable disturbances to render the large scales less predictable. The mid-latitude circulation consists of baroclinic waves, long waves, and planetary waves of different wave number and frequency, so that all space and time scales are important. In contrast, the tropical circulation has a clear scale separation; the large scale Hadley and Walker cells, on the one hand, and the synoptic scale disturbances on the other. The mid-latitude atmospheric anomalies show a rapid decay of autocorrelation function, whereas tropical atmospheric anomalies persist for several months. Since the atmospheric dynamics by itself is not known to have any mechanism for long term memory, persistence of tropical sea surface temperature anomalies can change the location and intensity of Hadley and Walker cells, which can produce persistent anomalies of precipitation. Similarly, anomalies of soil moisture can be very important in determining the intensity of tropical stationary heat sources for which the maxima occur over the continents.

For favorable structures of the large scale flow, the tropical heating anomalies can produce significant changes in the mid-latitude circulation either by poleward propagation of Rossby waves or by changes in the intensity of the Hadley cell and the accompanying zonal flows which interact with the mountains and heat sources in the mid-latitudes. It is therefore likely that the tropical boundary forcings can enhance the predictability of the extratropics also. A discussion of the role of boundary conditions on monthly and seasonal predictability has been presented earlier by Shukla[13].

SUMMARY

Classical predictability studies using the GLAS climate model suggest that the short range weather forecasting is more difficult for the tropics compared to the mid-latitudes. On the other hand, the prospects for predicting monthly and seasonal averages in the tropics are better than those in the mid-latitudes because the fluctuations of time averaged tropical flows appear to be primarily determined by the slowly varying boundary forcings at the earth's surface. It is hoped that a systematic study of predictability of a variety of observed large scale atmospheric flows might provide some insight into the possible causes for why some initial conditions are more predictable than others. The task of forecasting weather would be greatly facilitated if we could identify some characteristic features of the large scale flow which determine its predictability because then we could predict the predictability of the initial state.

REFERENCES

1. E.N. Lorenz, Tellus, **21**, 289-307 (1969).
2. E.N. Lorenz, J. Atmos. Sci., **26**, 636-646 (1965).
3. J.G. Charney et al., Bull. Amer. Meteor. Soc., **47**, 220-220 (1966).
4. J. Smagorinsky. Mon. Wea. Rev., **91**, 99-164 (1963).
5. Y. Mintz, WMO-IUGG Symposium on Research and Development Aspects of Long-Range Forecasting. World Meteorological Organization, Tech. Note No.66, 141-155 (1964).
6. C.E. Leith, Methods in Computational Physics, Vol. 4. New York, Academic Press, 1-28 (1965).
7. R. Jastrow and M. Halem, Bull. Amer. Meteor. Soc., **51**, 490-513 (1970).
8. D.L. Williamson and A. Kasahara, J. Atmos. Sic., **28**, 1313-1324 (1971).
9. J. Smagorinsky. Bull. Amer. Meteor. Soc., **50**, 286-311 (1969).
10. J. Shukla, D. Straus, D. Randall, Y. Sud, and L. Marx, NASA Tech. Memo. 83866, 282 (1981) (NTIS No. N8218807).
11. J. Shukla, J. Atmos. Sci., **38**, 2547-2572 (1981).
12. J.G. Charney and J. Shukla, in Monsoon Dynamics, Cambridge University Press, Editors: Sir James Lighthill and R.P. Pearce, 99-109 (1981).
13. J. Shukla, in Proceedings of the seminar on "Problems and Prospect in Long Range Forecasting," ECMWF, Reading (1982).