Essay on Dynamical Long-Range Forecasts of Atmospheric Circulation

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Abstract

The feasibility of monthly and seasonal forecasts is considered. The gross features of departures of meteorological variables from climatology (anomalies) are the targets of forecasts, and the anomalies can be divided into two modes, i.e., free modes and forced modes. The free modes are the anomalies that are predicted under the specification of climatological external forcings for the surface temperature, that are free from the anomalous forcings, whereas the forced modes are the anomalies that correspond to the anomalous components of external forcings. The GCM (general circulation model) is, in some cases, capable of predicting the free mode at least one month ahead (particularly the most extraordinary blocking event in January, 1977), and is, in other cases, marginal. However, the capability could be increased further by improving the GCM. In addition, recent studies have revealed that there are growing evidences for the feasibility of prediction of forced modes over the United States through the teleconnection process from the sea surface temperature anomalies over the equatorial Pacific.

Yet the GCM approach is expensive and may be limited in improving mathematical accuracy, to a satisfactory extent. As a remedy, the possibility of anomaly models are being investigated.

1. Introduction

What are the long-range forecasts (LRF) of atmospheric circulation? Let us define it in this paper as the "Forecasts of time-mean state of atmospheric circulation or gross weather, the time range of which is beyond the limit of deterministic prediction (say about 2 weeks)." The feasibility of the LRF is, of course, a crucial question. The nature of the LRF is very likely probabilistic in the sense that the ensemble mean as well as the standard deviation are only meaningful quantities in the forecasts.

As is the case in prediction problems in general, two approaches can be considered for the LRF, *i.e.*, the empirical and the dynamical predictions. With the empirical methods, there has been a great deal of studies (see review by Nicholls, 1981; Namias, 1968, 1978). The methods are based on statistical theories such as the regression, the trend, and the analogue methods. They are relatively easy to implement, and there have been many ongoing researches and operations. According to the survey of the WMO (World Meteorological Organization) in

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1979, national meteorological services in at least 32 countries are interested in the LRF, and are currently issuing monthly (25 countries) or seasonal (15 countries) outlooks, using the empirical technique. The only problem is that these empirical forecasts are marginal in skill.

The second approach for the LRF, is the dynamical method, which is based on the numerical simulation with general circulation models (GCM) one way or another. Mathematically speaking, it is a unique advantage for this approach to handle highly non-linear relations, which can not be yielded by the statistical methods. The implementation is more costly, and yet the demand for the investigation along this line is strong.

2. Atmospheric variability

For many years in the past, searches have been made for the existence of natural periodicities in the atmospheric parameters. If there is any, it would be useful for understanding the mechanism of variation, and it could be a help for the LRF.

In the 1940's it was not easy to detect the periodicity longer than 5 days except the obvious ones. At present, one can mention a number of frequency spectral peaks, that is, the 42 month broad-band periodicity in the surface pressure or oceanic temperature in the equator, QBO (quasi-biennial oscillation), the semi-annual oscillation, the 50-day periodicity in the tropics, the 16 day planetary waves in middle latitudes, and equatorial Kelvin waves. Most of these oscillations are not simple normal modes (except the 16 day wave and Kelvin wave), but the consequences of non-linear processes.

The study of mid-latitude planetary waves has its own long history. The approach is closely connected with the dynamic instability theories and the general circulation studies. As a result, the basic characteristics have been gradually made clear, such as the three-dimensional structure of mid-latitude westerlies, the lateral and vertical propagation of ultra-long waves, and the generation and maintenance of standing and transient planetary waves (for example, van Loon *et al.*, 1973; Hirota and Sato, 1969; Hayashi and Golder, 1977; Lau, 1978).

However, for the purpose of the LRF, it is important to investigate the overall behavior of the hemispheric circulation rather than to decompose the circulation fields spectrally and to study the detail of dynamics for each component.

Investigation on the hemispheric teleconnection pattern of the surface pressure and of geopotential height is another effort of searching for existence of regular standing waves (Lorenz, 1951; Kutzbach, 1970). In fact, forecasters in the United States have long utilized certain patterns of strong teleconnection for the LRF following the classic work of Walker and Bliss (1932). These studies have established the empirical facts on the large-scale atmospheric oscillation. Van Loon and Rogers (1978) confirmed the seasaw oscillation in the Atlantic. Wallace and Gutzler (1981) identified the finite numbers of action centers on the hemisphere, and suggested that there are 5 categories of teleconnection patterns. Yet the multiple equilibria were not proved to exist in the monthly mean state. If they existed, (Charney and DeVore, 1979) the LRF could become substantially simpler. Two kinds of teleconnection patterns are fairly well defined in reality, and the blocking action patterns have been classified accordingly. Can one resynthesize the real atmospheric variability with some of the known periodic processes? The answer appears to be no.

In the global analysis, the component of the Southern Oscillation explains 18% of the normalized variances of monthly mean surface pressure (Kidson, 1975). Brier (1968) found the QBO to explain only about 2% of the monthly variance in the sea-level zonal wind index in the Northern Hemisphere (Trenberth, 1978). That is to say, the dynamic model that will be used for forecast is desirable to test the capability of simulating these periodicities. But even if it is achieved, it is not practically sufficient only with these regular fluctuations alone to attain a reasonable depiction of the observed monthly mean pattern. Thus, the overall behavior of the real atmosphere remains complex.

Dividing the observed surface pressure data in the monthly mean and its deviation, Madden (1976) estimated the signal-to-noise ratio, where the noise is the natural variability of monthly means and the signal is the interannual variability in his definition. The results revealed that the ratio is not large in the middle latitude (40°-60°N); however, it is large outside these latitudes. An interpretation of this result is that the variability in the middle latitudes is possibly unpredictable. A question is whether this interpretation is correct. Even if the interpretation is not correct, this fact may hint that there is considerable challenge lying ahead for the LRF.

Wishful thinking is that an advanced knowledge of GCM's may handle the prediction of the atmospheric internal variability (free modes), including simulation of blockings, some of quasi-periodic processes, and some of the teleconnection patterns. But even if the predicted internal variability turns out to be below the noise level, another hope is that the response to anomalous external forcings can be detected, particularly utilizing equator-midlatitude teleconnection, for example (Bjerknes, 1966). It is important to note that empirical evidences of feasibility is being accumulated (Namias, 1976; Davis, 1978; Barnett, 1981). It is a recent view that the predictability may depend on season as well as location.

An extensive study has been carried out on the phenomena of El Niño, Southern Oscillation, and teleconnection processes, and a systematic behavior is being unraveled (for example, Wyrtki, 1975; Rasmusson and Carpenter, 1981; Horel and Wallace, 1981). These findings have raised a new surge of excitement and enthusiasm on the LRF in the research community. It is at least certain that the dynamic approach lends itself to study causal relationship. We are now on the verge of intense investigation and assessment of feasibility for the LRF.

3. An example of the GCM forecasts of a blocking case

An example of one-month integration with a GCM will be displayed by a case of blocking event for January, 1977. This case includes a long-sustained stationary ridge over the Aleution area, resulting in the most widespread record cold in the eastern part of North America. A number of GCM's was run for one month, starting with the initial condition on 00 GMT, January 1 or 2.

Figure 1 illustrates the results of a most successful simulation (Miyakoda *et al.*, 1982). It shows the geopotential height pattern at 500 mb level, averaged over 30 days for Day 0-30. The GCM employed was the N48L9-E4 finite difference model, where N is the horizontal resolution, representing the grid number between a pole to the equator, L9 is the 9 vertical levels, and the E4 is a physics, which is advanced compared with the A2-physics. Among a number of GCM's applied to this case, the performance of the N48L9-E4 was the second best, and that of the R30L9-A2 was one of the poorest. The R30L9-A2 denotes the spectral truncation in the rhomboidal version at the zonal wavenumber 30, L9 is again the 9 vertical levels, and the A2 physics.

Figure 2 is the Hovmöller diagram, which is the time-longitude chart of the geopotential height in the zonal belt between 40° and 50°N latitude, delineating the time sequence of circulation for one-month. The figure shows the comparison of three Hovmöller diagrams, *i.e.,* the observation, the good simulation with the N48L9-E4 model, and the poor simulation with the R30L9-A2 model. In the successful case, the stationary ridges are well maintained throughout January as the reality did, whereas in the other case, the erroneously developed trough over the North Pacific pushed the ridge downstream, resulting in a zonal flow pattern around the Northern Hemisphere, and the historical

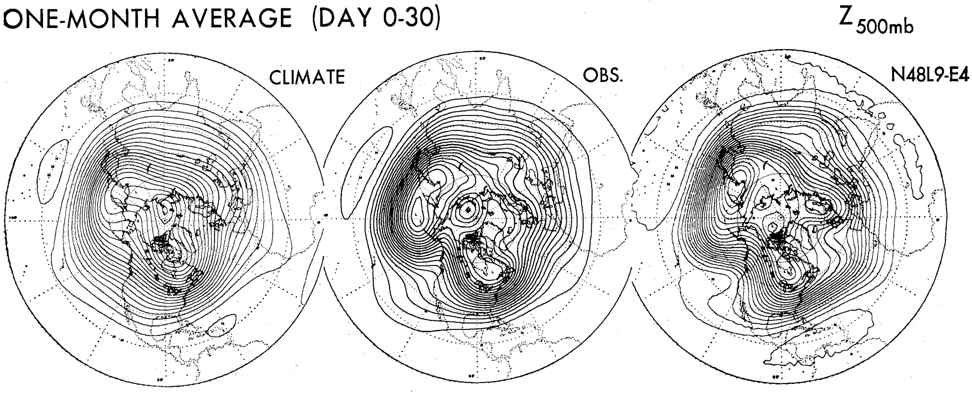

Fig. 1 Comparison of the monthly forecast and observation. The maps are the monthly mean 500 mb geopotential height from Day 0 to Day 30 in January 1977: the prognostics by the N48L9-E model (right), the observation (middle), and the climatology for January (left). The contour interval is 30 meters.

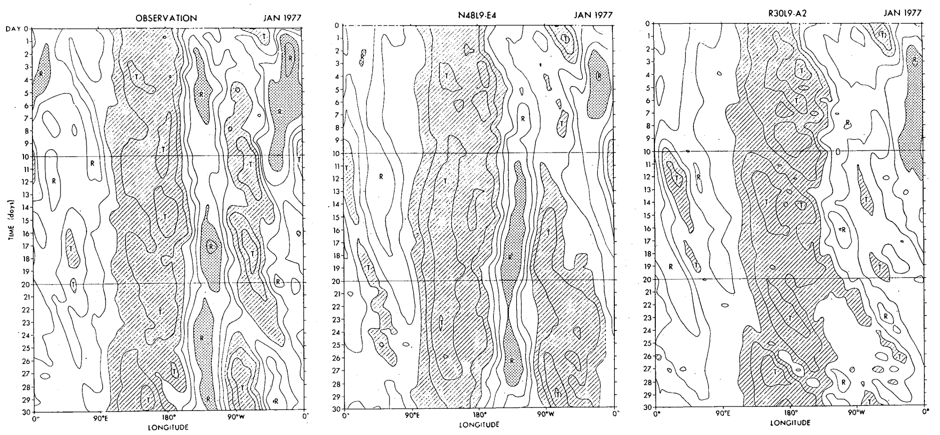

Fig. 2 Comparison of the best and the poorest forecasts in Hovmöller (time-longitude) diagram of the 500 mb geopotential height between 40° and 50° latitude from Day 0 to Day 30 in January 1977: the prediction by the N48L9-E model (middle), the prediction by the R30L9-A model (right) and the observations (left). The contour interval is 60 meters. The troughs and the ridges are marked by T and R, respectively, and the extreme value regions are shaded or stippled.

coldness was missed by a large margin. It is our view that a model qualified for the use of the LRF should be capable of simulating blockings, because they are linked to almost all the extreme anomalies in climate on record.

4. Time-mean predictability

Figure 3 is the skill score with the N48L9-E model for January, 1977. The score is represented by the correlation coefficients of the anomaly of the geopotential height at 500 mb. There are a number of scores for the same simulation, only differing in time averaging length. As was demonstrated by several investigators such as Smagorinsky (1969) and Gilchrist (1977), the predictability is raised as the averaging length is increased. Leith (1973), Jones (1975) and Madden (1976) discussed that the standard deviation of a time series in the first order Markov process is reduced by increasing the averaging length. It is interesting to note that not only the standard deviation or the rms error decreases, but also the score is also improved in terms of correlation coefficients, and probably the ratio of rms error and persistence. This is a favorable and important aspect for the LRF.

Let us next proceed to show an example of various realizations of forecasts by changing only the initial conditions. Figure 4 is the correlation and rms error curves for the ensemble mean of Z500 mb anomaly which were all obtained by the R30L9-E4 model. The initial conditions are: January 1, 00 GMT, 1977 with the GFDL analysis and the NMC (National Meteorological Center, Washington, DC), and January 2, 00 GMT, with the GFDL analysis. All these initial conditions are supposed to be good estimates of the truth. The figure indicates that scores do not deviate appreciably from each other until about Day 15, and then they start to diverge after about Day 20, implying that for one-month integration a single realization is marginally adequate as a representing a probabilistic value. It is interesting and important to note, however, that the divergence of curves is not too large in the 30 day range. In other words, the GCM could calculate successfully some signals even below the so-called noise level of monthly mean variability.

The same procedure can be applied to the 20 day mean scores. The resulting curves are located a little better than those of the 10 day mean. The degree of divergence of three realizations is slightly less than the 10 day mean score.

Shukla (1981) recently discussed the predictability of time-mean circulation, using the control and perturbation run approach for three different year Januaries. He concluded that the effect of initial condition is retained up to one month or beyond, and that predictability for the planetary scale waves is more than a month. Thus, it is reasonable to regard monthly fore-

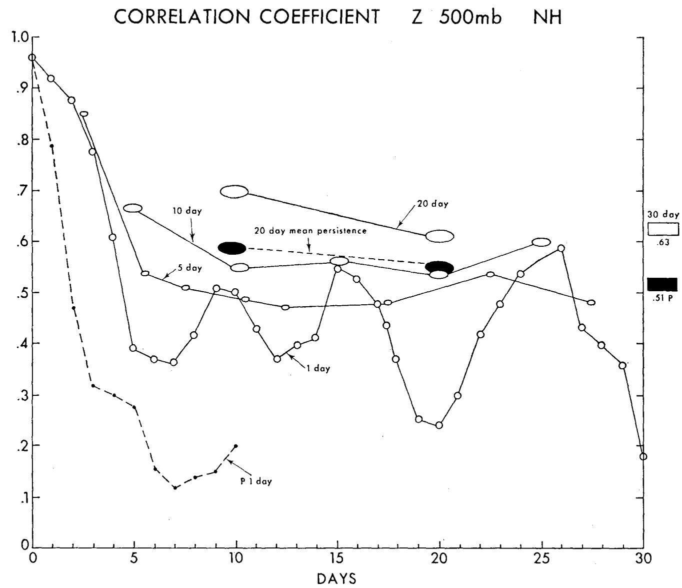

Fig. 3 The time-mean predictability is shown by the correlation coefficients for the temporarily averaged anomalies of geopotential height at 500 mb between the prediction by the N48L9-E model and the observation in the case of January 1977. The coefficients for 1, 5, 10 and 20 day mean height fields are indicated by white circles or ovals, which are connected by solid lines. The 20 day mean persistence and the 1 day mean persistences are indicated by black circles or ovals, which are connected by dashed lines. The coefficient for the 30 day mean persistence are shown at the right outside of the diagram.

casts as the initial value problem.

In order to reach more general conclusions about monthly predictability, more samples are required. At GFDL, six cases experiment of the GCM one-month prediction is underway; three cases have been calculated. At this moment, it is too early to discuss these results.

Spar *et al.* (1976; 1978; 1979) who pioneered the one-month GCM forecast experiment concluded that "the model simulation exhibits no skill in reproducing monthly mean sea level pressure field, but the model does show some small but consistent skill relative to climatology in its simulation of the fields of 500 mb height and 850 mb temperature."

Gilchrist (1977) described the long-range forecast experiment over a period of 30-40 days, and mentioned as follows. "The experiments appear to suggest that the (5-layer) GCM used may, at least on occasions, exhibit some skill in simulating long wave behavior; and that an assessment of whether the use of actual rather than climatological SST improves the forecast is inconclusive."

Almost all investigators, who have studied the monthly forecasts using reasonable GCM's, have mentioned that the predictability limit of the time-means (30 day mean, but even 20 day and 10 day mean) appears to be a month or longer, though they have been cautious. It is also true, that the quality of real GCM forecasts have been currently marginal. Can the quality be improved in the near future? The answer is yes, and the key is further advancement of the GCM and its accuracy in long-term integrations.

In the paper of Miyakoda *et al.* (1982), ensemble mean curves for various models are shown, indicating that three realizations for each model tend to be clustered together and that curves of different models are distributed systematically in the decreasing order of the skills. So far as one-month prediction is concerned, the quality of the GCM is extremely important. A poor model will not provide a good probabilistic forecast, no matter how many realizations are produced.

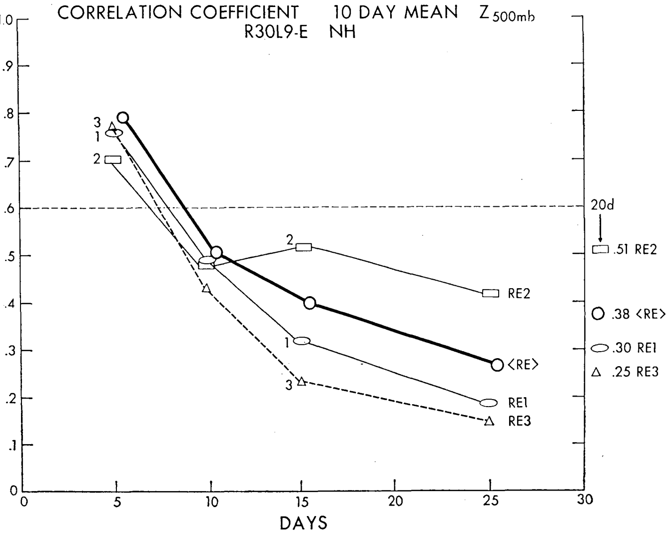

Fig. 4 The skill of probabilistic forecasts is shown by the correlation coefficients of 10 day mean 500 mb geopotential height between the prediction by the R30L9-E model and the observation. The curves marked by RE1, RE2 and RE3 are for three realizations corresponding to three different initial conditions (thin solid and dashed lines), and a curve marked by <RE> is for the ensemble mean of the three realization (thick solid lines). The correlation coefficients for the last 20 day mean fields are shown at the right outside of the diagram.

It is projected that the GCM prediction could be improved further by increasing the spatial resolution, refining the initial condition, incorporating better SGS (subgrid-scale processes), and perhaps properly including the anomalous external forcings (see Cubasch, 1981).

5. Probabilistic forecasts

Recognizing the inherent error in the initial condition, the forecast process is formulated to determine probabilistic distribution of phase points in the same context as classical statistical mechanics. Namely, the forecasts, starting with an initial cloud, produces the evolution of the projected cloud. Although standard deviation is not large initially, it will soon grow to a large value. The problem is how to obtain the ensemble of phase points. Epstein (1969) proposed the stochastic-dynamic method, in which uncertainty (or error) in the initial time is assumed, the equation of the first moment of errors for prognostic variables and of the second moment of errors are derived; and the system of equation is closed by ignoring the third moments. This approach was further developed by Epstein and Fleming (1971). Pitcher (1977) applied the model to the real case, though the model was simple. It is the authors' opinion, however, that this method has been limited. First of all, the stochastic-dynamic formulation can be possible, only if the dynamic equation is expressed by algebraic equations. The algebraic equations can be obtained in practice only for spectral "interaction" model and not for the spectral "transform" model. Secondly, the system of equations consist of quadratically nonlinear terms, and the number of derived equations is horrendous, so that it is prohibitively costly to solve the equations. Thus, although this theory is supposed to provide the most reasonable and legitimate approach to the probabilistic forecast, we do not think that it is worth all-out efforts of persuance.

Leith (1974) suggested the Monte Carlo method as the substitute of the stochastic-dynamic method. This is the so-to-speak brute-force method, in which a finite number of equally likely forecasts are generated, based on a single analysis, by perturbing the initial condition with a random number, and then statistics are applied to the multiple realizations in the forecasts.

Spar *et al.* (1978), who made three forecasts, all starting with the same initial data but randomly perturbed in different ways, concluded that random error in the initial state do not appear to represent the major source of forecast error, but major error in the monthly mean prognostic maps are either unknown systematic large-scale errors in the initial analysis or defects in the model itself. Hollingsworth and Savijarvi (1980) also mentioned in their ten day forecast experiments that the individual forecasts within the ensemble of perturbed forecasts deviated quite slowly from each other; all forecasts had the same failure in over-developing a trough over certain areas, for example. A problem here is the random perturbation; the uncertainty in reality is neither random nor that small. Figure 4 is also an example of an ensemble mean forecast with brute force method, but not Monte Carlo. The uncertainty derived from different analysis in the initial data is much larger than the usual specification of random perturbation.

A question is raised: how many samples are needed to establish a statistically valid result? Leith (1974) suggested that 8 samples are acceptable. Of course, even a factor of 8 requires a large amount of computing power compared with a single realization forecast. Is there any other way to make the calculation more economical? If not, the speed-up of the model's prediction is very vital in pursuing this approach. The efficiency of the GCM calculation ought to be radically improved.

6. External forcings

The definition of "external" may need an explanation. What is meant here is: the anomalous effects that are slowly varying in time scale of equal to or more than one-month. For example, the predictive anomalies of sea surface temperature (SST) are determined in the framework of the atmosphere-ocean model, but they are initially specified, and thence subject to slow evolution. Thus the SST anomalies are classified as the external anomaly forcing. On the other hand, the cloud coverage are, irrespective of the initial condition, quickly adjusted to the model (about 5 days—Gordon—personal communication). Thus the cloudiness is classified as the internal forcing in the same way as the precipitation. With this in mind, the external (anomalous) forcings related to the LRF are: (a) ocean, (b) soil moisture, and (c) snow and ice cover. It appears that the studies on these effects may hold great promise for the GCM integration beyond one-month, because the targets of the LRF are the determination of anomalous components, and these media hold good memories for these components. A similar opinion was expressed 15 years ago by Sawyer (1964). It is noted that for the time-scale of climate variation, there are other effects, that is the anomalous forcings in the vegetation, ozone, carbon dioxide, permafrost, continental ice-sheet, solar variability, volcanic activity, the aerosol, mountain glaciers, and the so-called anthropogenic effects. These factors will not be considered here, because of the likelihood of small effects on the seasonal time-range. In this respect, the problem of seasonal weather variation belongs to a disciplinary area different from that of climate variation.

6.1 *Oceanic forcings*

There were at least two ardent advocators of the ocean-atmosphere interaction in the past decades, *e.g.* Namias (1959; 1963) and Bjerknes (1959; 1966). Thanks to the perception and enthusiasm of these pioneers, the study of the SST impact has been appreciably advanced compared with other external forcing effects.

Perhaps the issue may be divided into three categories, (a) tropics *in situ,* (b) equator-midlatitude teleconnection, and (c) midlatitude *in situ* and downstream effect.

(a) Tropics *in situ*

Since the tropical atmosphere is conditionally unstable, any small trigger can generate a sizeable scale of cumulus convection. The trigger can be the SST anomaly, and that is what's happening along the ITCZ (Intertropical Convergence Zone). Shukla (1975), based upon a GCM study, indicated that the Indian rainfall decreased in the monsoon season when SST over the western Arabian Sea becomes colder.

(b) Equator-midlatitude teleconnection

Bjerknes (1966; 1969), based on his remarkable insight into observational data, reached a hypothesis that there is a teleconnection process from the equatorial ocean to the mid-latitude atmospheric circulation. Certainly enough, Rowntree (1972), Julian and Chervin (1978), and more recently, Keshavamurti (1981), confirmed Bjerknes' postulate, using the GCM. It is concluded that the SST warm anomaly over the equatorial eastern Pacific (El Niño region) induces anomalous convective rain, releasing latent heat, which in turn increases momentum transport in the Hadley circulation, and leads to strengthening of the subtropical jet, accompanied by shifting and deepening of the Aleutian low.

It was in the last several years, however, that the real impact of this process on the LRF over the middle- and high-latitudes has been realized. The recent strategy of short-term climate variability study is to focus on the global teleconnection from the Southern Oscillation. The study of Southern Oscillation phenomenon has its own long history of research from Walker and Bliss (1932) through Troup (1965), and Bjerknes (1969) and Krueger and Gray (1965) to Wyrtki (1973), Krueger and Winston (1975) and Rasmusson and Carpenter (1981) for the Northern Hemisphere and from Pittock (1973) through Streten (1975) and Trenberth (1975) to Nicholls (1977) for the Southern Hemisphere.

From the forecasting standpoint, Quinn and Burt (1972) suggested the use of the Southern Oscillation Index (SOI) (monthly mean pressure differences between Easter Island and Darwin) for the prediction on occurrence or non-occurrence of the heavy rainfall over the central and western Equatorial Pacific in more than 1-2 months lead time. Harnack (1979) and Henricksen (1979) may be the first who used the SOI as one of the predictors for winter temperature in the eastern United States. Barnett (1981) found, based on linear prediction technique, that SST can be used to predict air temperatures over North America one and more seasons in advance, particularly in the winter time, and that the SST and sea level pressure over the equatorial and tropical Pacific Ocean are superior as predictors to their mid-latitude counterparts. A recent study has emphasized further this point, describing that the most crucial SST source region to the United States appears to be the 140°-180°W longitude equatorial zone. Warm episodes in equatorial Pacific SST tend to be accompanied by below-normal heights in the North Pacific and the southeastern United States and above-normal heights over western Canada (Horel and Wallace, 1981). Chen (1981) showed that lagged cross-correlations between SOI and the 700 mb heights are significantly high in winter with SOI leading the height by one to two seasons. An interesting feature is the tendency for more pronounced North American negative anomalies of height and North Atlantic positive anomalies associated with the high SOI values. The impact of the SST over west equatorial Pacific to the climatic variability over China was reported by Fu (1979a, b). In connection with the equatorial ocean, statistical forecasts of a wind anomaly associated with the Pacific Hadley circulation using SST data, have significant and appreciable skill (Barnett and Hasselmann, 1979). A similar study was conducted by Fu and Li (1979), who found that the behavior of the North Pacific High is predictable, using the equatorial SST information of prior to one or two seasons. An observational study of Pan and Oort (1981)* has revealed a high correlation of variations between the SST anomalies over the middle Equatorial Pacific and the 200 mb westerlies in situ as well as over the North Pacific. A similar but weak effect was observed for the sector of the Atlantic Ocean by Rowntree (1976).

It is thus not surprising that the chain of processes may be extended to the Asian Monsoon phenomena, and eventually to the rainy season events over China and Japan. Rowntree (1979) noted that global mean temperature variations on a scale of a few years are driven to a substantial extent by variations in equatorial Pacific ocean temperature.

(c) Midlatitude *in situ* and remote effect

Namias (1963; 1975) pointed out the close relationship between the ocean and atmosphere in the North Pacific in the form of both the simultaneous and "downstream" response. Ratcliff and Murray (1970) discussed the lag association between the North Atlantic SST and the European surface pressure. Adem (1964; 1965) claimed that the SST anomaly provides useful information on the monthly forecasts. The groups of long-range forecasting in China discussed the lag association between the Kuroshio SST and the rainfall in the eastern part of China.

However, the GCM approaches have so far not been successful in detecting the clear-cut relation between the atmospheric circulation and the SST anomalies (Miyakoda—unpublished; Spar, 1973; Kutzbach *et al.,* 1977; Houghton *et al.,* 1974; Chervin *et al.,* 1976; Shukla and Bangaru, 1980).

Only the experiment of exaggerated anomalies of SST produced significant realistic local response in the models' atmospheric temperature. The ocean primarily serves as the moderator

* Pan, Y-H. and A. H. Oort, 1981: Observed sea surface temperature in the Equatorial Pacific Ocean and global climate anomaly. A seminar presented at GFDL.

to the atmosphere in terms of thermal effect, so it is not surprising that the ocean effect outside the tropics is not strong.

Using a simple model, Webster (1981) studied the mechanisms of the local and remote atmospheric response to SST anomalies at various latitudes, and found that the magnitude of the total diabatic heating diminishes significantly as the SST anomalies are placed progressively poleward. At high latitude, the response is small duc to the creation of an indirect zonal circulation in the vicinity of the anomaly which is related to the strength of the local basic flow.

Thus the reason for the failure in detecting a strong signal in the model study is partly due to the weak signal-to-noise ratio, and partly due to the poor simulation capability of the applied GCM's. Chervin *et al.* (1976) and Gilman (1978) stressed the necessity of adequate statistical design for the sensitivity experiments, particularly on the midlatitude SST anomaly effect. Egger (1977) computed the atmospheric response to a pool of the warm water in Newfoundland in the linearized equation, and argued the benefit of the linearity assumption for the relatively small anomalies.

Difficulty in detection of the causative factor was also once experimented in an observational study such as Davis (1976), who used 28 years of records of monthly anomalies of the North Pacific SST and sea level pressure, and concluded that the only evidence of predictable forcing influence was the SST field's response to anomalous sea level pressure, and not vice-versa.

It is only in recent studies that Namias (1978) and Davis (1978) have started to indicate that the North Pacific SST anomalies in summer are significantly correlated with next season's surface pressure particularly in the area of Aleutian Islands. Harnack and Landsberg (1978) also suggested that prior SST in the North Pacific may be effective predictors of subsequent atmospheric changes over the North American continent.

Marchuk (1975a, b) proposed to estimate the source of SST for the teleconnection process, and stressed that energy active regions of the world ocean are responsible for development of major weather anomalies.

6.2 *Land forcings*

Compared with ocean forcings, the knowledge on this subject is meager. The heat storage in the land surface is much less than that in the ocean, and therefore, it may be natural to consider that the land forcings are less important than the ocean forcings. However, in certain ways, the land can give a significant impact on the atmospheric circulation. These are realized through the snow-cover over the ground and the moisture content in the soil.

(a) Snow- and ice-cover

The primary effect of land snow/ice-cover is an albedo which affects not only the heat balance but also the surface melting snow. On the other hand, the effect of sea-ice is the insulation; the sea-ice modifies the thermal conduction between air and sea.

To give an example of the former effect, we refer to Chen's study on the comparison of the summer circulation between the years of heavy and little snow cover in winter over the Tibetan plateau. The study revealed that typical summer circulation comes about one month later in the years of heavy snow cover than in the years of little snow cover. Yeh and Fu (1980) further investigated the summer circulation for the years of heavy and little snow cover in March over Eurasia, and found that the 200 mb summer westerlies at 40°N over Eurasia are much stronger in the years of heavy snow cover than in the years of little snowcover.

(b) Soil moisture

The role of the soil moisture is to control the intensity of evapotranspiration, consequently affecting the surface temperature, and to influence the rainfall. The other role is to affect the surface albedo, and to modify the soil heat conduction.

It is now increasingly aware that the effect of soil moisture is important not only on the climate numerical experiment (Manabe and Holloway, 1975, Charney *et al.*, 1977; Mintz, 1981), but also on the short-range rainfall forecasts (Walker and Rowntree, 1977; Miyakoda *et al.*, 1981; Yeh and Chen, 1980).

Yeh and Fu (1980) made an observational study on the influence of soil moisture on the atmospheric circulation by comparing the case of extreme flood summer (very wet soil) with the case of an extreme drought summer (very dry soil) in eastern China. They found that the monthly mean soil temperature difference between the flood and drought July reaches as high as 8°C in large areas, and that the monthly mean air temperature between the two cases reached as high as 4°C. This widespread temperature difference led to drastic differences in the atmospheric circulation. They also noted that the influence of the soil moisture could last more than two months, whereas the snow cover effect could last more than three months. But overall, it has not been easy in other parts of the world except Africa to demonstrate the quantitative impact of the soil moisture in the empirical LRF either due to relatively weak signal or due to our ignorance.

Almost all current GCM's have been following the ground hydrology parameterization of Manabe (1969). The vegetation canopy is supposed to play a role in the evapotranspiration process, but most of the models have not yet incorporated this effect except NCAR (National Center for Atmospheric Research) model. It is certain, however, that the accuracy of soil moisture in the initial data is crucial for the LRF. This is because the temporal variation of soil moisture (internally predicted) is slow, and the initially specified condition of this parameter dominates at least the subsequent two months.

An attempt is underway to estimate the large scale distribution of near-surface soil moisture by remote sensing from satellites. Past experience indicated that this task is not easy at all (NASA, 1980). The problem of soil moisture has been a common concern for many decades by hydrologists, agronomists, geographers, meteorologists, climatologists and paleo-climatologists, and they concur that the problem has not been solved. It is known that the hydrological parameters in soil vary over several orders of magnitude within relatively short distance, say 10 meters. Therefore, the distribution of soil moisture at 200 km grid networks has been regarded as a mathematical outcome or at best a product of parameterized hydrological process in GCM. The GCM's treat the soil moisture over the scale of entire continents, whereas the hydrological models handle the soil moisture only over the scale of catchment. In other words, the fundamental difference between the two schools is the disparity of the grid size. In future, in order to increase the accuracy of hydrological parameters in the LRF, this gap has to be narrowed. Indeed, the estimate of initial soil moisture pattern (or the evapotranspiration pattern) is a brand new venture.

7. Anomaly model approach

In the present and the next sections, we will focus on anomaly models. This approach is entirely different from the GCM approach we have dealt with in the preceeding sections. The LRF with GCM will be practically limited, because the system becomes inevitably huge, cumbersome and expensive for increasing accuracy. Obviously any GCM still involves bias, which is by no means small. In order to remove this bias, it may take decades of hard and tedious work. In addition, the precision of the computer might pose the intrinsic limit for further improvement of accuracy in long-range integration of the GCM.

7.1 The principle of the anomaly model

In the situation of impending limitation, an alternative that can be thought of is the anomaly model. This model is one of the families of two-separate equation system. An idea is to divide variables into two components, *i.e.,* the basic component and the deviation. As is known, there are various ways of division depending upon the purposes, that is, zonal averages and the perturbation (eddies); ensemble means and the deviation (turbulence); time means and the departure (fluctuation), and the climatological normals and the anomalies.

Concerning the ensemble average system, we have already discussed in Section 5, in connection with the stochastic-dynamic approaches (Epstein, 1969; Friedman-Keller equation in turbulence theory). The zonal mean model was proposed by Thompson (1957), who first mentioned the inherited limit of predictability with the conventional numerical weather prediction and pointed out the merit of the zonal average approach. The system of zonal mean equations was used extensively by Blinova (1957) and Saltzman (1978), the reason being presumably that this system is well connected with the most of the theoretical studies. This category, however, branches into two schools. One school was to use the equation for zonal mean variables and the linearized perturbation equation (Saltzman, 1968; Derome and Wiin-Nielsen, 1971; Verneker and Chang, 1978). Another school was to set up the equations of first and second moments, terminating the series by closure assumption (Gambo and Arakawa, 1958; Kurihara, 1970). Blinova mentioned, based on the practical experience, that the chief difficulty of the first school lies in determination of the zonal mean flow. In this respect, the second school is capable of predicting zonal mean quantity theoretically. Indeed these approaches have contributed profoundly to understanding of dynamics, but practical application has not been attempted.

In this respect, the anomaly model approach appears somewhat different. The variables are divided into the climatological normal and the anomaly, and yet only the equation for the anomaly components is used. Namely, omitting the equation for the normal, the observed normals are utilized. The uniqueness of this model lies in this point. This anomaly model was proposed by the Long-Range Numerical Weather Forecasting Group in Peking (1977; 1979), and it has been extensively applied to real data. Opsteegh and Van den Dool (1980) also used this type of model for the study of LRF, though the equations are linear.

We will, however, discuss mostly the anomaly model of Peking. The equation for the anomaly includes the Reynolds terms, but in the present model, these terms are ignored, and besides the current model uses the geostrophic approximations. The system consists of two major equations. One is the potential vorticity equation for the atmosphere, and the other is the thermal equation for the underlying ocean and land. The two equations are connected at the earth's surface, through the interfacial conditions, which are the heat balance relation, and the mass, heat and stress continuities.

Then the most crucial assumption is introduced, *i.e.*, the stationarity of the atmospheric vorticity equation, but the thermal equations for the ocean and land are kept time-dependent. The reason for this arrangement is to simplify the system by filtering out the solution of transient Rossby waves in the atmosphere. This treatment could also be derived by the concept of two time systems, *i.e.*, slow and fast. The monthly mean standing components are considered to be subject to the slow process of adaptation (adjustment) to the ocean and land thermal forcings.

Monin (1972) described a similar idea in terms of the A-AL system, that is, the atmosphere and the active layer of the underlying surface. He stated that "the simplification of the A-AL system, filtering out the short-term synoptic processes from their solutions, can be derived by neglecting the partial derivatives with respect to time in all equations except those of the heat content of the active layer of the ocean; and numerical experiments with such simplified equations could help to clarify the feasibility of this approach to long-range weather forecasts."

7.2 *Results of the anomaly model*

Figure 5 is an example of one-month forecast for the spectacular month of January 1977, based on the coupled ocean-atmosphere anomaly model. The initial conditions for the anomaly model are: SST and the land surface temperature and 500 mb anomaly geopotential height for one-month mean from December 1 to 31, 1976. The climatological atmospheric wind vectors for January were applied. The atmospheric model has the horizontal resolution of 5° and the one-layer in the vertical.

The figure shows the predicted anomaly of geopotential height at 500 mb for one-month average from 1 to 31 January, 1977. The solution corresponds to "forced mode" in the sense that it is the adapted solution to the SST anomaly and land surface temperature anomaly.

The same figure includes the counterpart of

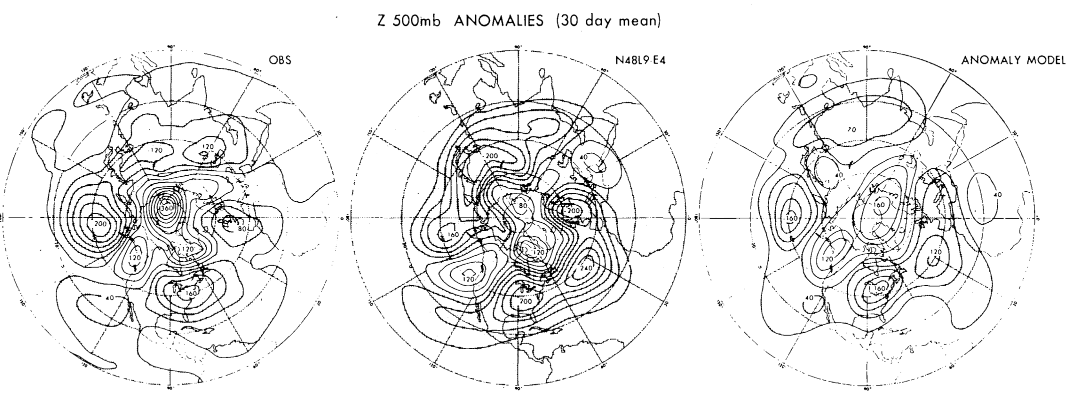

Fig. 5 Comparison of the monthly mean predicted anomalies of 500 mb geopotential height: the observation (left), the prognostic of free mode by the N48L9-E GCM (middle), and the prognostic of forced mode by the one-layer anomaly model (right). The contour interval is 30 meters, and the negative regions are shaded.

Table 1. Correlation coefficients of the anomalies of Z′ (geopotential height) and T′ (temperature) between the prediction and observation over the Northern Hemisphere.

Cases			Z′ Correl.	Z′ Persist.	T′ Correl.	T′ Persist.
Aug.	→	Sept. 1965	0.36	0.24		
Dec. 1976	→	Jan. 1977	0.72	0.56		
Jan.	→	Feb. 1978	0.22	0.30	0.29	0.58
″	→	″ 1977	0.05	0.34	0.18	0.35
″	→	″ 1976	−0.16	0.07	0.07	−0.01
April	→	May 1978	0.05	0.19	0.25	0.32
″	→	″ 1977	0.21	0.07	0.33	0.28
″	→	″ 1976	0.30	0.25	0.20	0.26
July	→	Aug. 1978	0.16	0.23	0.28	0.40
″	→	″ 1977	0.17	0.42	0.26	0.46
″	→	″ 1976	0.29	0.47	0.15	0.27
Oct.	→	Nov. 1978	−0.06	0.32	−0.01	0.30
″	→	″ 1977	−0.29	−0.07	−0.01	−0.05
″	→	″ 1976	0.16	0.21	0.32	0.50

the GCM, *i.e.*, N48L9-E4, which we described earlier. Therefore the GCM solution corresponds to "free mode", *i.e.*, the consequence of the anomaly in the initial condition and dynamical interaction. An interesting and an important point is that the GCM and the anomaly forcing model, in essence, are quite different, and yet the solutions in both models are similar to each other in this case. The total prediction should be the free plus the forced modes.

Some readers may be interested to know the computer time consumed for these calculations. Using the ASC (Advanced Scientific Computer) of Texas Instruments at Princeton, the GCM took 60 hours to obtain the result in this figure, whereas the anomaly model took 15 seconds, though the anomaly model has the hemispheric domain. Note that the same anomaly model needed 45 min. with the computer in Peking. The three-layer anomaly model is also working, and in fact this gives better results than a one-layer anomaly model. The computer time with the three-layer model is 1 min by the Princeton computer for the same calculation above, whereas 2 hours were needed by the Peking computer.

At the Institute of Atmospheric Physics at Peking, 14 cases of one-month forecasts have been performed, using atmospheric one-layer models. The skill score of these results is shown in the Table. In addition, two-month forecast, based on three-layer model, has been made. These preliminary studies appear to indicate that the forced mode of the anomaly model has some skill.

7.3 *Anomaly model in the future*

The performance of the current anomaly model is far from satisfactory. In order to improve the anomaly model, what can be done? A number of processes should be refined to the level of quality close to the GCM. Above all, the primitive equation system is required instead of the geostrophic approximation, because the important signal from equatorial SST has to be included. Opsteegh and Van den Dool (1980) and Hoskins and Karoly (1981) used the primitive equation for their anomaly model, and discussed the teleconnection effect of Bjerknes. Chen and Xin in Peking (personal communication) have already succeeded in constructing the primitive equation anomaly model.

A question may arise as to whether the stationarity for the atmospheric equations is absolutely essential. If the stationarity is abandoned, the problem becomes the initial value problem, and consequently not only forced mode but also the free mode come in to the solutions.

An investigation is underway at Princeton on this problem with the anomaly model. It is not yet clear that the anomaly model approach is worthy of an all-out endeavor. A serious ambush might be waiting for us. In the non-stationary system, the prediction is no longer deterministic but probabilistic. More accuracy may be required to obtain the proper solution of transient components. In that case, should the sophistication of the anomaly model be reconsidered (in the area of space resolution, SGS processes and numerical algorithm)?

The original equations for the anomaly components include Reynolds terms and anomaly external forcing terms. These terms are the source of potential problems. Do these terms generate the ambush?

Even for the seasonal forecasts, should the free mode be considered, and therefore, the nonstationarity be retained? Our view is that the free modes sometimes are predictable even beyond one month, and for this reason, it is better to keep both, but the system becomes expensive.

In summary, as the overall strategy for the LRF, the GCM study has to be continued and developed further. The basic research must go along this line. The GCM approach is indispensable for understanding of the atmospheric and oceanic phenomena and processes. To what extent the accuracy can be increased only by the pure GCM is an important and interesting question.

8. Conclusions

Summarizing this article, the conclusions are listed below.

(1) It is essential to investigate and establish the range of time-mean predictability. So far as monthly forecasts are concerned, free mode components are dominant over forced mode components. Time-mean free mode anomaly components appear to be predictable for one-month, but more samples are needed.

2) Search for the oceanic external forcing has been successful. On the other hand, the knowledge on the land external forcing is extremely meager. Predictive capability of these forcings is crucial for the seasonal forecasts.

(3) For the proper development of the LRF study, the GCM approach is important and indispensable. Yet there may be a limitation on the pure GCM forecasts for seasonal range. An anomaly model may provide a remedy as the accurate and economical forecasting method. It may be wise to pursue both approaches for the study of the LRF. The computational burden for the anomaly model may be substantially small. However, an investigation on the potential of the anomaly model has not been completed.

(4) For the free mode components in particular, the probabilistic forecasts are required instead of the deterministic forecasts. It is desirable to have reasonal and economical methods for dynamical and statistical treatment in terms of attaining the adequate mean and standard deviation of the forecasts and specifying the initial data.

The light at the end of the tunnel remains dim. But a number of hopeful clues have been collected.

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力学方式による長期予報についてのエッセイ

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このエッセイは一ケ月予報および季節予報の可能性を論じたものである。予報の対象は，グロス・ベッター量の気候値からのずれ，すなわちアノマリで，アノマリは自由モードと強制モードとに大別される。ここで自由モードというのは，海洋表面の温度条件として，気候値を与え（アノマリではなく），モデルから求められる解で，

それに対し，強制モードとは，アノマリ水温の境界条件の下に得られる強制解のことである。

現在のところ，GCM（大気循環モデル）は，場合によって，少くとも一ケ月先まで，自由モード解をかなり正確に求めることができる（特に，1977年1月のもっとも異常なブロッキングの場合）。しかし，時によって，その予報は余り正確ではない。

われわれの研究の結果によれば，GCMはまだ改善できる余地がある。その上，強制モード解に関し，非常に希望的な資料がある。太平洋の赤道近辺における水温のアノマリから，遠隔伝達のプロセスを通して，アメリカ上空の気温（強制モード）を予測できる可能性があり，それを示唆する事実が着々と蓄積されつつある。

とは云うものの，GCM方式による長期予報は，大変，高価につく。将来，その精度が向上できるとしても，それにも限界があるかも知れない。もし，そうだとすれば，その代りとして，アノマリ・モデルが難点を解決する可能性がある。