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CHAOS AND PREDICTABILITY IN FORECASTING THE MONSOONS

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Day-to-day evolution of weather is only predictable up to ten days or so in advance. This can be understood in terms of the chaotic nature of atmospheric dynamics. On the other hand, skilful longer range predictions of seasonally averaged rainfall have been successfully made, as exemplified by the monsoon forecasts from the India Meteorological Department. This dichotomy is explored using the prototype Lorenz 3-component chaotic model. The model is applied to the Indian monsoon problem, with break and active monsoon periods corresponding to the Lorenz-model regimes. The dichotomy is resolved by taking into account the impact of lower boundary forcing anomalies on the regime probability density function. By studying the impact of such anomalies in a chaotic model, it can be seen that seasonal prediction is necessarily probabilistic, and requires ensemble integration techniques when tackled using dynamically-based forecast models.

Key Words: Chaos; Predictability; Forecast; Monsoon Breaks; Lorenz 3-Component Chaotic Model; Butterfly Effect; Tropical Convergence Zone (TCZ)

Introduction

The unpredictability of weather is legendary, and despite the best efforts of man and technology, reliable predictions of the day-to-day evolution of weather can only be made up to a week or so ahead.

The scientific reasons for such unpredictability are now well established. Despite well formulated and precisely known deterministic laws of motion, the atmosphere is a chaotic system, whose evolution is sensitive to starting conditions. As a result, the influence of the smallest imaginable error in the initial conditions for a weather forecast will eventually have an influence on the evolution of daily weather. This sensitivity is vividly characterized by the "butterfly effect"; the flap of a butterfly's wings in Delhi, could make the difference between a fine or stormy day in London a month or so later.

The first precise mathematical model that demonstrated the existence of chaos in a simple nonlinear dissipative system was formulated by Lorenz[1]. His three component equations

$$\dot{X} = -\sigma X + \sigma Y,$$

$$\dot{Y} = -XZ + rX - Y \qquad \ldots (1)$$

and $$\dot{Z} = XY - bZ$$

are not a rigorous truncation of the equations for the large-scale atmosphere, nevertheless the behaviour of these equations is a good qualitative guide to the predictability of weather.

Superficially, it would appear that beyond the limit of predictability of day-to-day evolution of weather, there is no prospect of skilful atmospheric prediction. Despite this, longer-range predictions are routinely made. Most famous of these are the seasonal monsoon predictions of the India Meteorological Department now made for over 100 years using models based on empirical relationships between monsoon and worldwide climatic predictors. Whilst there is no doubt that these predictions are skilful[2] the question arises as to why such long-range predictions are possible in a fundamentally chaotic atmosphere.

To resolve this conflict, the dynamics of the Lorenz model are discussed in detail in the next section, particularly the differences between predictions of the first and second kind. Then in the subsequent two sections an attempt is made to use the model to study, conceptually at least, the predictability of the Indian monsoon both on timescales of up to 10 days and timescales of a season. Some practical remarks on the development of dynamical models for long-range monsoon prediction are made in the last section.

Properties of the Lorenz Model

Fig. 1 shows a number of integrations of the Lorenz model (eq. 1) in the phase space spanned by the three model variables. The lighter background shows the famous Lorenz attractor: the model climate. This attractor is clearly inhomogeneous; it has two distinct regimes. Coincidentally, the attractor itself has a butterfly shape.

In Fig. 1 are shown the result of three ensemble integrations of the Lorenz equations. The ensembles start from different parts of the attractor. The ensemble of initial conditions, a small ring of points, can be thought of as representing some uncertainty in the initial state. The three panels show that the unpredictability asociated with finite-time integrations of the Lorenz model depends very strongly on the initial conditions themselves. For example, in the first panel all members of the ensemble of points make a transition from the left hand regime to the right hand regime. In this sense the regime transition is very predictable.

In the second and third panels the evolution of the Lorenz state vector is much less predictable. In the second case one could say that there was about a 40% chance of a regime transition, whilst in the last case there is virtually nothing that can be said about the likely final state.

It is fairly easy to understand qualitatively the behaviour of these ensemble integrations in the Lorenz model. In particular it can be seen that most of the ensemble dispersion occurs at the middle bottom of the attractor, in a neighbourhood of the origin of phase space ($X=Y=Z=0$). This in turn is associated with a particularly unstable fixed point of the equations at the origin. (There are also unstable fixed points near the regime centroids; however, compared with the origin, these instabilities are not particularly severe).

Following the terminology of Lorenz[3], we can refer to these types of initial value forecasts as "predictions of the first kind". By contrast, "predictions of the

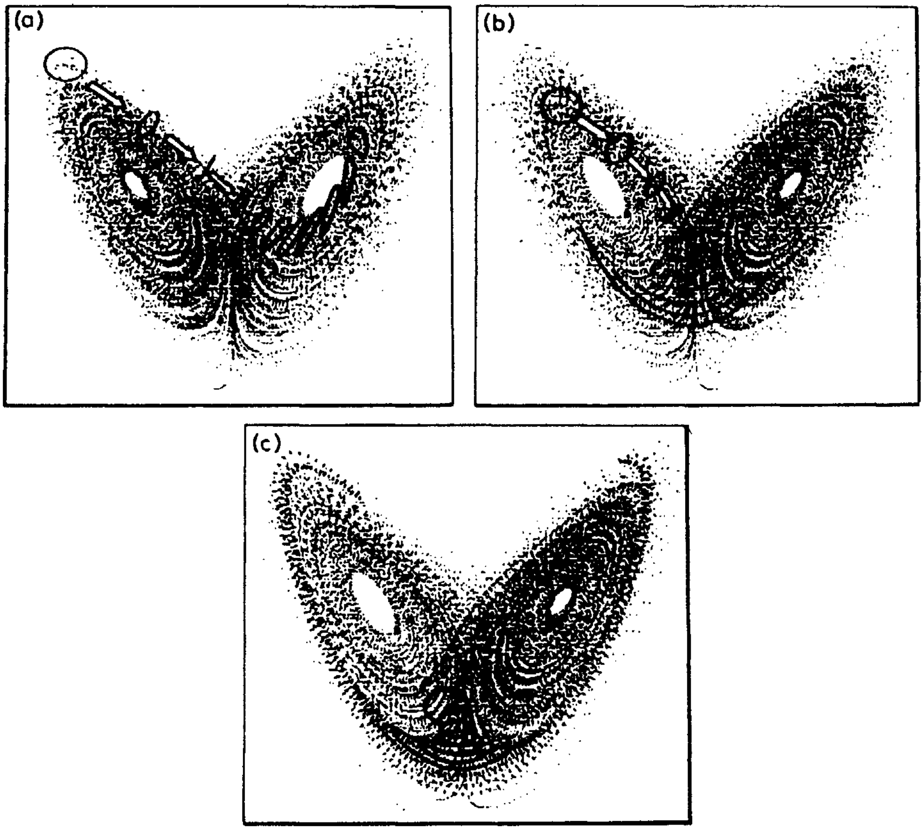

Fig 1 Phase-space evolution of an ensemble of initial points on the Lorenz attractor, for three sets of initial conditions, superimposed on the Lorenz attractor

second kind" are not initial value problems, rather they are concerned with how the attractor might change as some system parameter is increased. (For example, how climate changes as atmospheric CO_2 is doubled is a prediction of the second kind).

Understanding the difference between predictions of the first and second kind are important for a conceptual appreciation of the difference between monsoon prediction on the daily and on the seasonal timescale (*see* the next sections); we therefore discuss these issues further.

We can study a prediction of the second kind by introducing some fixed normalised "forcing" into the Lorenz equations

$$\dot{X} = -\sigma X + \sigma Y + aF_X$$

$$\dot{Y} = -XZ + rZ - Y + aF_Y$$

and

$$\dot{Z} = XY - bZ + aF_Z \qquad \ldots (2)$$

and ask how the Lorenz climate changes as a is increased from zero.

The result of one such experiment is given in Fig. 2 in terms of the probability density function (PDF) associated with the state vector of the Lorenz

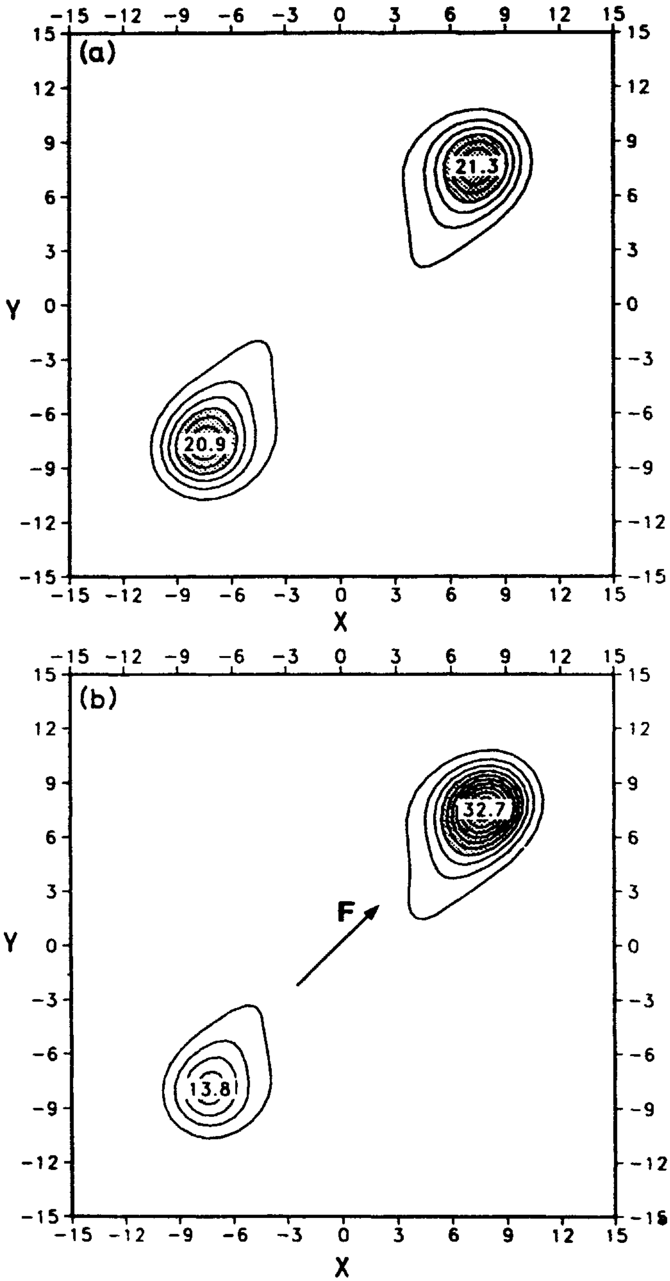

Fig 2 Probability density function of the Lorenz model, low-pass filtered to remove oscillations around a regime centroid. *a*) from the unforced model. *b*) with a constant forcing in the X-Y plane pointing between the regimes.

model. In the original model (1), the PDF is symmetric between regimes, so that the probability of finding the system in one regime is equal to the probability of finding it in the other regime.

The influence of a forcing vector which points from one regime to the other, on the state vector PDF, is shown in Fig. 2*b*. It can be seen that the probability of finding the system in the positive *X*-*Y* regime is now larger than that of finding it in the other regime.

This result may seem straightforward, but there are two subtleties. Firstly note that the effect of forcing is not to translate the whole attractor in the direction of forcing. The phase-space coordinates of the regime centroids are largely unchanged by the forcing. The reason for this is that the effect of the forcing is felt most keenly by the state vector when it is in a neighbourhood of the unstable fixed point near the origin (just as errors in initial conditions amplify most strongly in the vicinity of the origin). When the state vector resides in a regime, the effect of the forcing is relatively small. (This is analogous to the effect of applying a small force to a pencil balanced on its tip—the effect of the small force can be quite large. Applying the same small force when the pencil is falling has much less effect).

The second important point to note about this numerical experiment is that in both Figs 2*a* & *b*, the evolution of the state vector is chaotic. In other words predictions of the first kind in either (1) or (2) are limited by sensitivity to errors in the initial state. However, despite this sensitivity to initial state, the effect of the applied forcing in (2) is itself predictable in terms of changes to the PDF of the system.

Monsoon Regimes

What have these remarks to do with atmospheric prediction, and with monsoon forecasting in particular? As mentioned in the introduction, the Lorenz equations are not themselves truncations of the equations for the large-scale atmosphere. On the other hand they do have qualitative similarities. For example. the inhomogeneous regime structure of the real climate is well known in studies of the atmosphere. For example, in higher latitudes (e.g., over London), the weather can persist in an unsettled state for many weeks. During this period, the winds are predominantly from the west, generally strong, and carry with them rain-bearing weather fronts. Suddenly the character of the weather will change corresponding to a settled spell with light or even easterly winds. In winter this settled weather can be rather cold; in summer it is generally warm. These qualitative remarks can be made precise using cluster analysis techniques (e.g., Mo and Ghil, 1988).

Is there similar regime-like behaviour during the summer monsoon? It is well known[5] that within the summer monsoon season, the large-scale rainfall oscillates between active spells with good rainfall, and weak spells with little rainfall. These weak spells are often referred to as "monsoon breaks". In general such large-scale rainfall is associated with the so-called "tropical convergence zone" (TCZ), a region where lower tropospheric winds are convergent. For Indian longitudes, there are two favourable locations of the TCZ; one associated with convergence over the heated continent, giving the active monsoon phase, the other associated with convergence over the equatorial Indian ocean, giving the break phase. As shown by Sikka and Gadgil[6], the PDF of the TCZ is bimodal. The evolution between active and break periods is aperiodic; but with a preferred timescale of a few weeks. Typically the transition time between break and active spells is shorter than the residence time of the spells themselves.

Whilst comprehensive general circulation models of the atmosphere appear able to simulate such intraseasonal variability[6], large-scale numerical weather prediction models (such as the European Centre for Medium Range Weather Forecasts-ECMWF-model) have difficulty in predicting transitions, e.g. from active to break phase, beyond the first week of prediction.

Based on these similarities, and others presented below, the present author would like to put forward the Lorenz model paradigm in discussing long-range monsoon predictability. In this paradigm, the two regimes of the Lorenz model correspond to the active and break periods of the monsoon. To be definite, let us suppose that the positive *X-Y* regime in Fig 2*a* corresponds to the oceanic TCZ, with reduced monsoon rainfall, and that the negative *X-Y* regime corresponds to the continental TCZ with enhanced monsoon rainfall. A simplification of the weather forecast problem applied to the monsoon would be the prediction of regime transitions, from active to break period or *vice versa.* (Of course in the first day or so of the forecast period, one is able to predict much more detail; perhaps this simplified view is more appropriate between about 5 and 10 ahead). The seasonal forecasting problem, on the other hand, is not concerned about predicting specific regime transitions, but rather about forecasting changes to the probabiltiy of occurrence of the strong and weak monsoon regimes.

Lower Boundary Forcing

We now introduce a further important concept. Atmospheric motion is bounded below by the surface of either land or ocean (or indeed ice). Heat and momentum are "exchanged" through this surface. The temperature of the surface is therefore an important boundary condition that influences atmospheric circulations. Sea surface temperature (SST) is a particularly important boundary condition in that it is coherent over large spatial scales, and it generally varies slowly on the timescale of individual weather events, but is not constant from year to year. The particular importance of the lower boundary conditions on monsoon predictability has been discussed by Charney and Shukla[7].

Since, as far as the atmosphere itself is concerned, SST is an external variable, the influence of changing SST on the monsoon can in some ways be thought of as a prediction of the second kind. Now it is known from observations that year to year variations in tropical Pacific SST associated with the El Nino/Southern Oscillation event have a strong influence on interannual variations in the monsoon[8,9]. Therefore, for conceptual purposes, let the external forcing F in the Lorenz model (2), represent an index of anomalous tropical Pacific SST. (As Webster and Yang[10] have emphasised, in reality the interaction between the monsoon and the El Nino is 2 way).

The paradigm then goes as follows. In a "normal" situation ($F=0$ as in Fig 2*a*) the seasonal mean monsoon rainfall comprises aperiodic active and break spells with a climatological PDF. With El Nino SST (F as in Fig 2*b*), the monsoon continues to fluctuate aperiodically between active and break spells, however, the PDF is now biased towards the break spells, and the time-mean rainfall is lower than normal. During a cold El Nino event (these are sometimes referred to as La Nina events) in which tropical Pacific SST falls by up to several degrees (F reversed from its direction in Fig. 2*b*), the regime PDF is now biased towards the opposite active spell, and time-mean rainfall is higher than normal.

Now these results refer to shifts in the PDF's of a chaotic system. Hence, in any one given season, the best that one can say is that the probability of lower than average rainfall is increased during an El Nino event, or increased during a La Nina event. Because of the chaotic dynamics, there is not a one-to-one

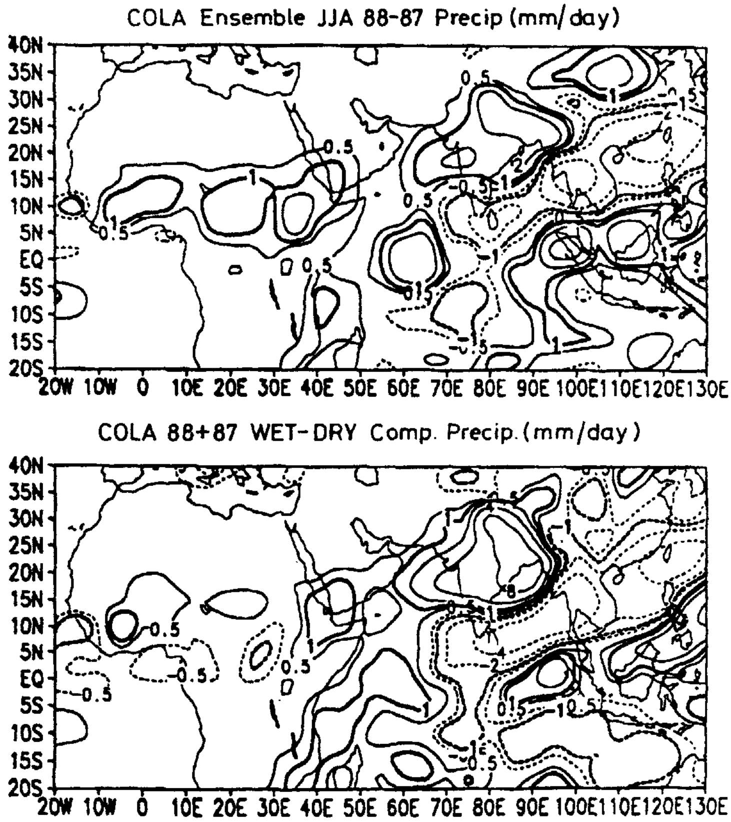

Fig 3 *a*) Ensemble-mean JJA difference rainfall between seasonal integrations of the University of Maryland COLA general circulation model integrated with observed SST from 1988 and 1987 respectively. The initial conditions for the ensemble were taken from observed analyses from 1, 2 and 3 May of 1988 and 1987 (respectively). *b*) Composite difference between active and break periods of the monsoon from within the seasonal GCM integrations (courtesy of M Fennessy) link between the SST anomalies and monsoon rainfall, and there is still a chance of above average rainfall during an El Nino event.

One of the principal testable hypotheses of such a paradigm is that the patterns of interannual fluctuations in monsoon rainfall, should correspond to patterns associated with the active and break spells. Observations[11] and modelling studies (M. Fennessy, *personal commun*) appear to lend some support to this notion. Results from the modelling study of M Fennessy are quite dramatic in this regard, and are shown in Fig. 3. The University of Maryland COLA general circulation model (GCM) was integrated over two summer seasons with observed SSTs for 1987 and 1988. The difference in seasonal mean rainfall (Fig 3a) was compared with the composite difference in rainfall between active and break periods within a season (Fig. 3*b*). Over much of the Indian Ocean and adjoining land masses, the patterns of interannual and intraseasonal rainfall agree closely.

The main purpose of this paradigm is to suggest that whilst the detailed evolution of the monsoon may be nonlinear and chaotic, seasonal prediction may be possible through the influence of lower boundary forcing on the regime PDFs. Again, for emphasis, one important consequence of this is that seasonal predictability will never be perfect.

To illustrate this, consider the following. Suppose we integrate a comprehensive atmospheric weather prediction model from 1 May of some year for four months, to the end of August, and let us also suppose for the sake of argument that we know exactly what the SST anomalies are through the season. Over the simulated summer season June-August (JJA) the model will make a number of transitions between active and break spells, and the JJA seasonal average rainfall is determined by the relative frequency of active to break spells. This, however, is a poorly sampled estimate of the attractor's PDF. Hence, if we now made a second integration from one day later (2 May), the relative frequency of active and break spells in the seasonal integration will not be the same as from the first integration, because of the chaotic nature of the regime transitions. We may have to perform many integrations from different starting conditions, before we can determine reliably the PDF of the active and break regimes, given the SST anomalies. However, any one of the estimated frequencies could correspond to what actually happens.

Such a set of ensemble calculations has been performed using the ECMWF model. The model has been integrated from 9 different atmospheric initial conditions for two contrasting monsoon seasons 1987 and 1988. For each season, and for each pair or ensemble members, the difference between the JJA rainfall in 1987 and 1988 has been calculated. Finally the fraction of positive and negative rainfall differences within the ensembles have been calculated. These are shown in Fig 4.

In Fig 4, it can be seen that for 1987 over India the ensemble indicates a probability of a relatively dry monsoon season generally exceeding 60%. Over the African Sahel, on the other hand, the probability of a relatively weak monsoon in 1987 is generally much higher, in excess of 90%. The stronger probabilities for the Sahel region correspond to the fact that chaotic intraseasonal variability is much smaller in that area than over India.

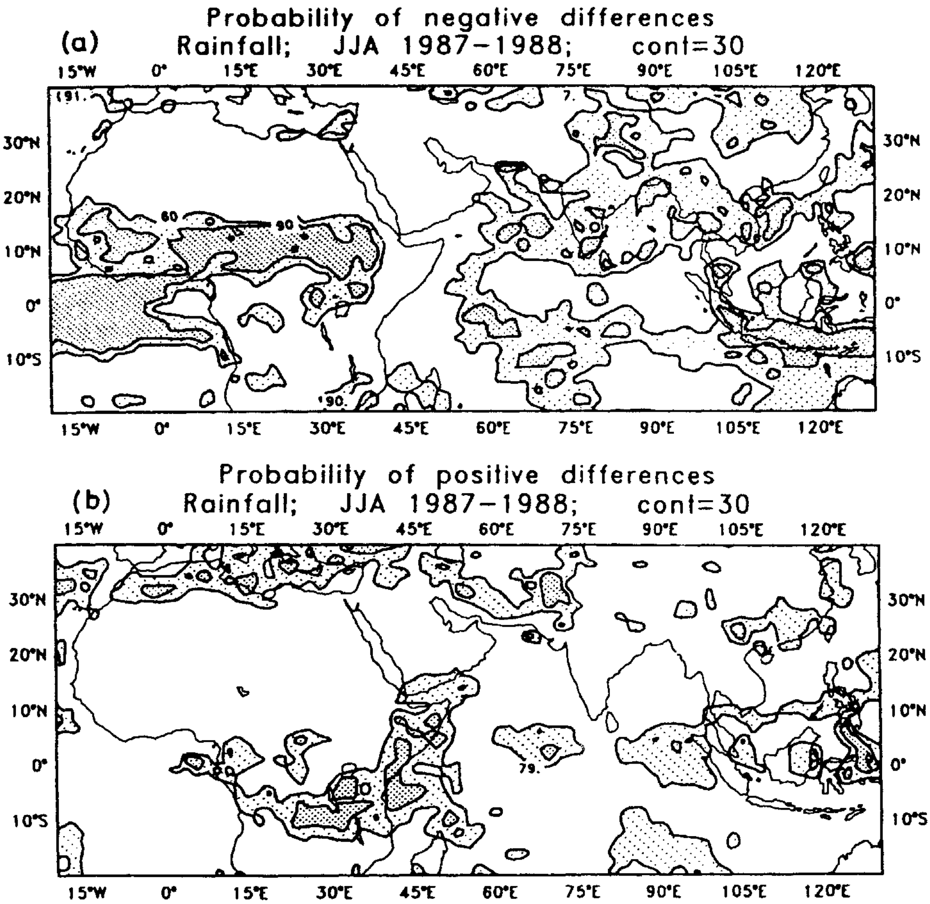

Fig 4 Probability estimates of rainfall over parts of the tropics based on 9-member ensembles of 120-day integrations with observed SST, based on the ECMWF numerical weather prediction model. JJA 1987-JJA 1988. Probability (%) that rainfall difference is *a*) negative, *b*) positive. Contours are 60% and 90%.

We have highlighted the role of the tropical Pacific SST anomalies on the monsoon. However, they are not the only important lower boundary anomalies that influence the monsoon. SST's of other ocean basins play a role, as do land surface forcing. It has been known for many years that Eurasian snow cover in the seasons immediately preceding the monsoon can be important, and modelling experiments have confirmed this[12].

Seasonal Monsoon Prediction using Dynamical Models

It has been suggested that despite the chaotic day-to-day evolution of weather, seasonal prediction is possible because of the influence of the lower boundary conditions on the regime PDFs associated with the climate attractor. The relative influençe of these boundary conditions is larger in the tropics than in the extratropics for reasons discussed by Charney and Shukla[7]. In the case of the monsoons, these regimes corresponds to active and break periods. In order to be able to assess reliably the impact of lower boundary conditions on the regime PDFs, it is necessary to integrate a weather prediction model many times from different initial conditions.

In some cases, it may be sufficient to persist the lower boundary anomalies occurring at the beginning of the forecast, throughout the whole forecast period. However, in general, it is necessary to be able to predict the evolution of the atmosphere's lower boundary conditions throughout the seasonal forecast period. To do this one must couple the atmosphere to the underlying land surface and ocean, and treat the SST as a truly dynamical internal variable of the system, governed, like the atmosphere, by precisely known physically-based laws of motion[13]. Of course, relative to the whole system, the forecast problem is a prediction of the first kind, though in this case it is the initial values of the ocean (and land surface) that are important (and that determine the limit of predictability), rather than the initial conditions of the atmosphere. Such coupled models are at present at the stage of development, and operational seasonal prediction using such coupled models has not yet begun in earnest. It may take many years before such dynamical models are more skilful than the empirical model predictions of the India Meteorological Office. However, seasonal dynamical monsoon prediction is not many years away, and, chaos not withstanding, our expectations of success are high.

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