

Modeling strategies arising from the empirical prediction of the monsoon on intraseasonal time scales

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1. Introduction

There has been steady progress in improving short-term numerical weather prediction through the years much of it coming from improvement of initial conditions and better models. For example, initial data from satellite has improved simulations in the southern hemisphere to the extent that forecast skill now is undistinguishable for that of the northern hemisphere. In addition, forecasts have been made more useful by estimating the uncertainty of a forecast by doing Monte Carlo forecasts with multi-member ensembles providing rather than one forecast a probability density function (pdf) of the future state of the system.

Yet, problems still remain. Almost all models fail in simulating intraseasonal variability and forecasting skill of the phenomenon is very low. One possibility is that this lack of skill is due to errors introduced by poor convective parameterization. For example, it is possible that excessive and premature high-frequency convection destroys the low-frequency intraseasonal signal. Indeed, convective parameterization stands at the heart of both weather and climate forecasting. There appear to be three paths towards the solution of the prediction problem of intraseasonal variability assuming that convective parameterizations lie at the heart of the problem:

- (i) Continue to strive for an improvement of parameterizations;
- (ii) Try something completely new such as introducing “super-parameterization” of convection in which cloud-resolving models are introduced within each grid box of a model.
- (iii) Attempt to use the identifiable physics of the slow manifold suggested by empirical prediction schemes developed for intraseasonal prediction to build a new class of models.

The search for an improvement in cumulus parameterization is now in its fifth decade. Yet, irrespective of the scheme or model used, there appears to be limited improvement in our ability to simulate intraseasonal tropical variability. Occasionally, a “tweaking” of a model will cause ISO-like variability to occur suddenly in a model. But, further tweaks often cause the ISO to disappear. It appears to us that the existence of a phenomenon that is the dominant feature of the tropics should not rely on a small change in a sub-grid scale parameter. Thus, while there certainly are severe problems with cumulus parameterizations, especially in the tropics, determining how to improve them is difficult.

An alternative approach is to go to finer and finer model resolutions and introduce cloud-resolving models into the model system. Whereas there may be eventual merit in such an introduction, we feel that there are three immediate drawbacks:

- (i) First, the cost is prohibitive in terms of computer requirements. The enormous investment into an idea that may or not work would seem premature. Randall et al. (2003) states that a “Manhattan Project” is required to solve the cumulus parameterization problem and introduce cloud resolving sub-models into the system. In the same paper an example of an improved MJO simulation is shown using the super-parameterization. Yet, one cannot be sure if the improvement is due to a “tweak” and whether or not the appearance of MJO is “real”. Beyond knowing that stand-alone cloud resolving models simu-

late clouds better than their the traditional gross-scale parameterization cousins there is no fundamental theory that tells us that cloud scale resolution of models will improve simulations of the ISO.

- (ii) We are concerned that the uncertainties of the current grid scales 50-100 km are merely translated to the smaller cloud-resolving scale, and:
- (iii) If the system were to prove to be useful and valuable, we are concerned that the very large computer requirement would lead to a decrease in the number of ensemble runs. This would be a pity as using Monte Carlo techniques has become the basis of the application of forecasts and the generation of risk analyses.

Perhaps these two modes of convective parameterization will eventually bear fruit. What we can say with more certainty is that there is an urgency to forecast tropical intraseasonal weather as it impacts a very large proportion of global society, especially in the boreal summer. Currently, we can make use of empirical forecasts such as those developed by Webster and Hoyos (2003) (described below) but, although the skill is impressive, the spatial scale of the forecasts is large. But it is possible that the empirical forecasts can be used to improve current models and possible point towards a new type of model.

2. The Importance of Forecasting Intraseasonal Monsoon Variability

During the summer of 2002, drought conditions persisted over India for nearly a month following a later than average arrival of seasonal monsoon rain. By the end of summer, the average Indian rainfall was 711 mm or 19% below normal. With the exception of the area near the foothills of the Himalaya in the very north of India, where above average rainfall occurred, most of India was in deficit with the state of Rajasthan 64% below normal. Figure 1 shows the geographic locations referred to in this report. The failure of the 2002 monsoon rains was not anticipated. The official Indian Meteorological Department forecast called for an essentially normal monsoon with mean rains about 1% lower than normal. The effects were disastrous to India's agrarian economy especially since the drought occurred early in the monsoon season when agriculture is at a most susceptible stage. The severe reduction in agricultural productivity resulted in hardship and suffering for millions of people and a significant economic loss to the country. Only stores of rice accumulated over a period of years by the Government of India prevented a major loss of life.

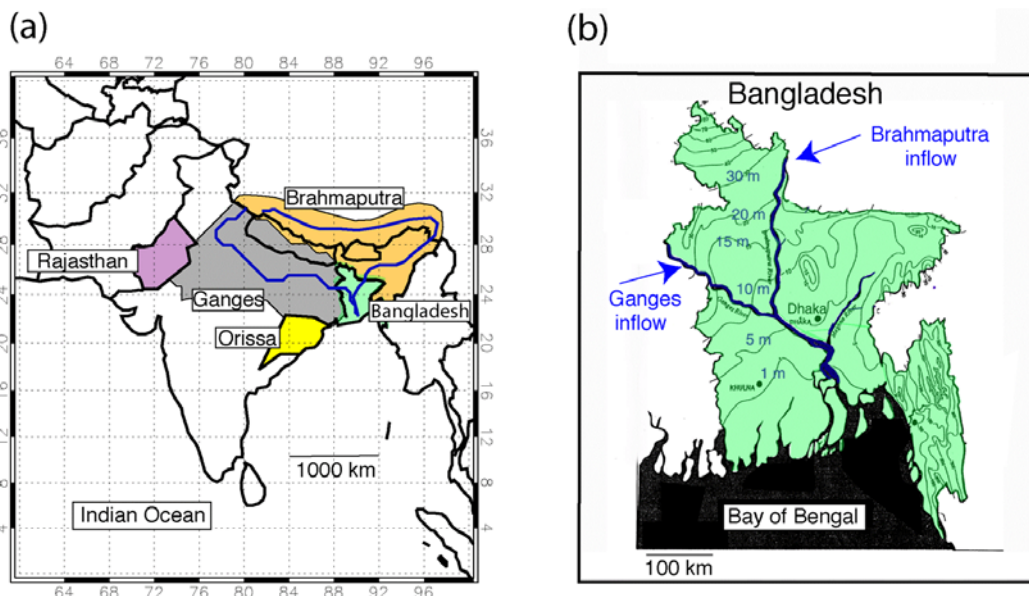


Figure 1: Geography of locations discussed in the text. (a) Brahmaputra (brown) and Ganges (gray) catchments, the Indian states of Orissa (yellow) and Rajasthan (violet), and the country of Bangladesh (green). (b) Detail of Bangladesh and the entrance points of the Brahmaputra and Ganges into the delta. Isopleths show elevation of delta above mean sea-level (m)

Figure 2 shows rainfall distributions for the four years 1999-2002 plotted in pentads (averages over 5-day periods) with the climatological long-term average summer rainfall superimposed for the Ganges Valley using GOES Precipitation Index (GPI) produce. Within any one summer there are large oscillations in the magnitude of precipitation with periods of 10-40 days. These oscillations give the intraseasonal variability of the monsoon: the “active” and “break” periods. Of particular interest is the evolution of the rainfall in the summer of 2002. Substantial summer monsoon rains commenced in June, although relatively belated compared to climatology, and were followed by a near complete cessation of rainfall from the middle of July to early August.

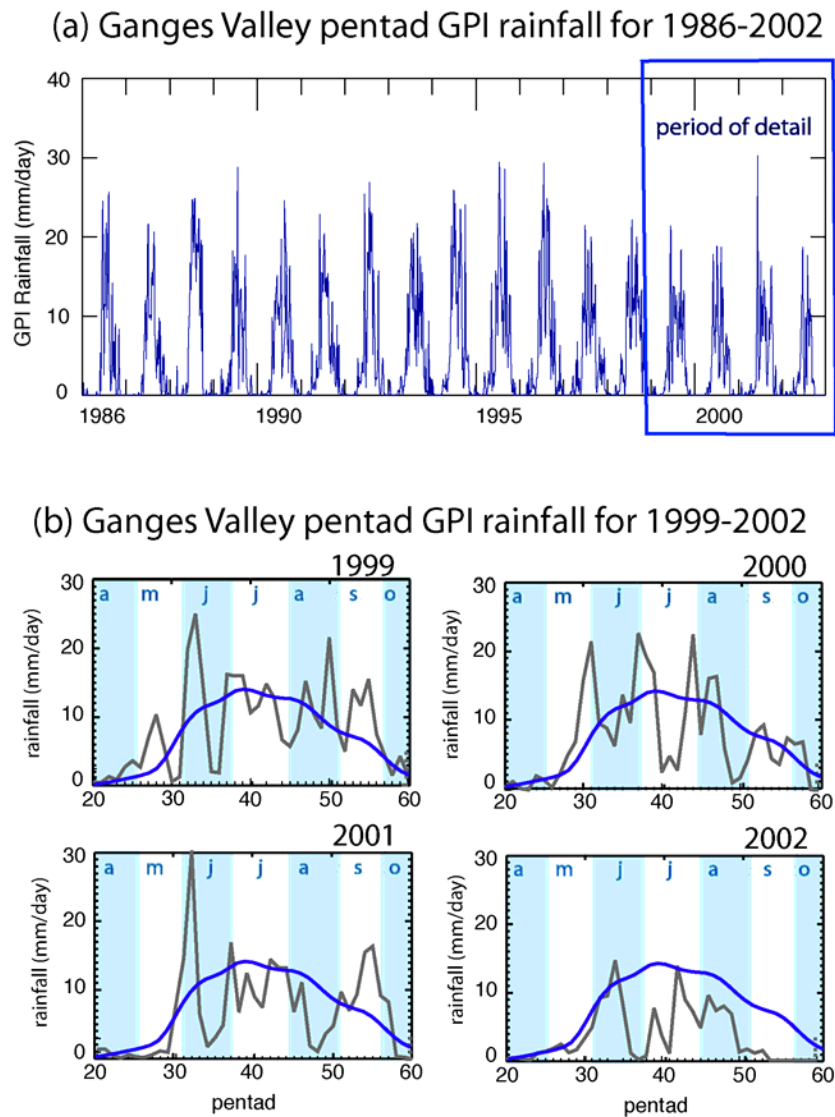


Figure 2: Precipitation for the Ganges valley (see Figure 1) for the period 1999-2002. Each year is dominated by peaks (“active” monsoon periods) and valleys (“breaks” in the monsoon). The smoothness of the long-term averaged precipitation (blue curve) suggests that there is no preferred timing for intraseasonal variability and that it occurs randomly throughout the summer. Light blue and white background bands indicate months (“a” April, “m” May, etc.)

The mid-season drought of 2002 had very serious consequences. But what if the drought, and its cessation, had been forecast? Would a forecast have made any difference to the agriculture and water resource management in India? The potential impact is revealed in a preliminary report by the Asian Disaster Preparedness Center (ADPC) on the consequences of the 2002 Indian drought:

“... The dry spell starting from mid-July to the first week of August 2002 in most parts of India, caused serious dislocations in water management and agricultural operations. The revival of monsoon conditions in the second week of August eased the water stress situation to some extent. Assuming that a prediction of the July drought had been available by the third week of June 2002, and of the revival of the monsoon rains by second week of July 2002, the forecasts would have made the following differences. In most parts of India agriculture operations start in second week of June and farmers make heavy investments during this period for land preparation, seedbed preparation, nursery raising and transplanting of seedlings. The water resource managers make decisions on allocation of water for various purposes (irrigation, hydroelectricity generation) on the assumption of normal rains. The prediction of likely dry spell in mid-June with a lead-time of weeks could have motivated farmers to postpone agriculture operations, saving investments worth of billions of dollars. The water resource managers could have introduced water budgeting measures, such as minimizing water availability for water consuming crops and maximizing water for low water consuming crops, and by rationing water use for hydroelectric power. Similarly, the prediction of the revival of monsoon rains by the second week of July would have motivated the planners and farmers to undertake contingency crop-planning by mobilizing resources such as seed availability and credit for choosing suitable crop varieties, carrying out mid-season corrections and undertaking crop life saving measures. These actions would have helped to preserve farm income and ensured food security and reduce relief expenditure by at least 60% of the present cost (i.e., around 6 billion US\$). Water resources could have been used to raise fodder crop in northwest India thus reducing the need for transportation of fodder from distant places at a huge cost. In summary, a 20-day forecast during monsoon 2002 in India could have mitigated the impacts of the droughts in several parts of India to a significant extent....”

Extract from draft of Initial Report on the Indian Monsoon Drought of 2002. Sri. A, Subbiah, Asian Disaster Preparedness Center (ADPC), Bangkok, Thailand. (ADPC, 2003)

It is clear from the ADPC draft report that timely, accurate 20-25 day forecasts could have made a significant difference to the agricultural and water resource communities of India and may have reduced vulnerability to the impending drought. In fact, the potential of forecasting sub-seasonal variability has been discussed in a number of documents. WMO (2001) noted that one of the most important problems, especially in monsoon regions is the forecasting of intraseasonal variability. In CFAB (2002), which deals with the impact of climate forecasts on agriculture in Bangladesh, it is noted that:

“... the minimum length of a forecast which will allow a farming community to respond and take meaningful remedial actions against either flood or drought is about 10 days. An optimal forecast period is in excess of 3 weeks...”

Unfortunately, tropical intraseasonal variability has proven difficult to simulate and even more difficult to predict. Slingo et al. (1996), Wu et al. (2002), Waliser et al. (2003) in comparisons of many models with observations, find little evidence of intraseasonal variability. In fact, Krishnamurthy and Shukla (2000) state that *“...intraseasonal component is intrinsically unpredictable ..”* a point echoed by Sperber et al. (2000) who stated that the overall predictability of the monsoon (i.e., the seasonal average rainfall) *“ ... is likely to be limited by the chaotic, internal variability of the monsoon system.”* The internal variations of the monsoon referred to here include intraseasonal oscillations. These statements have been tempered somewhat with a more realistic treatment of SST and the use of coupled ocean-atmosphere models (e.g., Waliser et al. 2001, 2002, 2003, Slingo et al. 1999), They have shown that the quality of simulations and, to some extent numerical prediction of intraseasonal oscillations can be improved. Whereas these improvements are encouraging, full numerical predictions of monsoon intraseasonal variability with skill necessary for useful applications to a user community are still goals for the future.

Despite the difficulties encountered by numerical modelers in simulating and predicting intraseasonal variations of the monsoon, it is clear that such forecasts would make a substantial difference to an agrarian com-

munity. In the absence of a numerical modeling based predictions, currently only empirical schemes show skill. There have been a number of attempts to predict intraseasonal oscillations in the tropics using empirical techniques. For example, von Storch and Xu (1990) used Principal Oscillation pattern (POP) techniques to identify and predict large-scale intraseasonal features in the tropics. Correlations between observations and predictions of the upper tropospheric velocity potential fields were about 0.6 after 7 days which was a considerable improvement on persistence. Waliser et. al (1999) developed a statistical model using filtered outgoing long wave radiation data (OLR) in the band 20-70 days. Correlations were found that were near 0.9 at 5 days but decreasing to about 0.5 at 20 days, similar to those found by Wheeler and Weickmann (2001) and Lo and Hendon (2000). Mo (2001) used Singular Spectral Analysis (SSA) and Maximum Entropy Method (MEM) techniques found correlations as high as 0.6 at 20 days.

Most of the empirical prediction schemes described above deals with intraseasonal variability of the global tropics. Webster and Hoyos (2003) take a different approach and concentrate on the intraseasonal oscillations in the South Asian monsoon region and emphasize quantities that have direct application as the prediction of regional precipitation and river discharge. The Webster-Hoyos scheme is a dynamically based Bayesian statistical model combining wavelet analysis and linear regression referred to as the Bayesian wavelet banding (WB) method. Predictors are chosen from detailed analyses of monsoon intraseasonal oscillations (MISOs), as described, for example, by Webster et al. (1998) and Lawrence and Webster (2001, 2002). These predictors are the Bayesian statistical priors.

3. Nature of Monsoon Intraseasonal Variability

MISOs are manifestations of the Madden-Julian Oscillation (MJO: Madden and Julian 1972) in the Indian Ocean-South Asian region during the boreal summer (Madden and Julian 1994). Overall, the MJO is a ubiquitous feature of the tropical atmosphere and is marked by distinct periods of eastward propagating convection (e.g., Madden and Julian 1994). Variance resides principally in the 20-40 day spectral band. The overall variance of the MJO is largest in the boreal winter (e.g., Hendon and Salby 1996). However, the summer MJO probably influences directly a greater proportion of the world's population than its boreal winter counterpart. This is because during summer the MJO has a tendency to extend northward from the equatorial eastern Indian Ocean to South Asia.

The northward extension of equatorial convection to South Asia during summer has been known for over two decades (e.g., Murakami 1976, Yasunari 1979, 1980, Sikka and Gadgil 1980). Four inferences can be made from these early studies: (i) convection is stronger in the eastern Indian Ocean than in the west; (ii) eastern Indian Ocean equatorial convection generally lags western Indian Ocean convection by a number of days although convection can grow *in situ* in the eastern Indian Ocean; (iii) a northward extension of convection occurs primarily in the eastern Indian Ocean, and; (iv) the northward extensions of convection coincides with the development of active periods of the monsoon over South Asia. These studies indicate that variations in the Indian monsoon rainfall are the consequence of very large-scale processes that encompass the entire Indian Ocean basin.

Figure 3 (adapted from Lawrence and Webster 2002) illustrates the prominent features of the MISO, discussed above. Figure 3a shows time-longitude sections for the 5°S-5°N latitude band for June and July 1996. Figure 3b is a time-longitude section of the OLR anomalies along the latitudes between 75-85°E'S, which encompasses the Indian peninsula, for the same period.

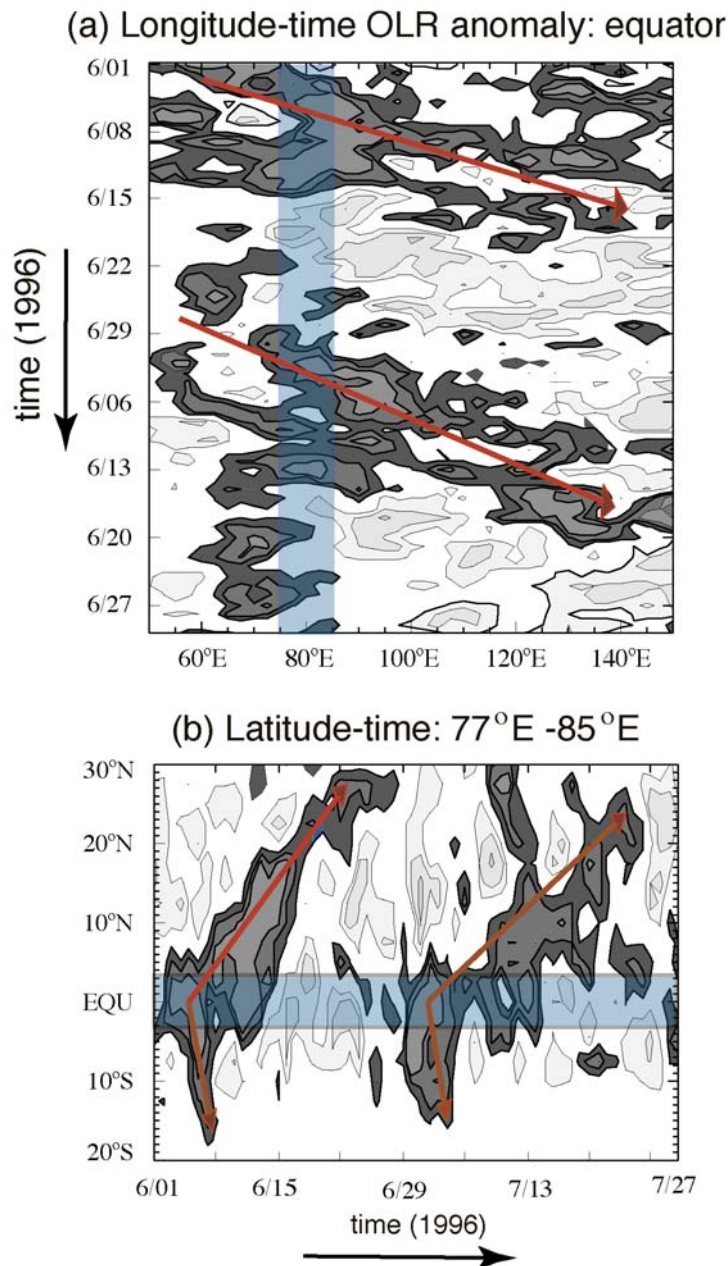


Figure 3: (a) Time-latitude sections (blue bar in panel b) of out-going longwave radiation (OLR) along the equator for the period June 1 to July 28, 1996. Convection propagates (blue arrows) eastward from the western Indian Ocean at 3-4 m s^{-1} . (b) Longitude-time section of OLR in the band 75°-85°E (blue bar in panel a) during the same period. Convection propagates northward from the eastern Indian Ocean to produce active phase of the monsoon 10 days later over the Indian subcontinent. (c) Same sections as panels a and b except as composited from 58 intraseasonal events. Panels (i) shows the latitude-time and longitude-time sections for all 58 MISOs. Panel (ii) shows MISOs that formed in the eastern Indian Ocean and propagated eastward. Panel (iii) shows the MISOs that formed in the eastern Indian Ocean. Adapted from Lawrence and Webster (2002)

Collectively, the two panels show two episodes of convection, each of which propagates eastward along the equator between 3-4 m s^{-1} before propagating northward in the eastern Indian Ocean at a speed of about 2 m s^{-1} . The evolution of the convective event takes about 4 weeks. Such a northward propagating event was encountered during the Joint Air-Sea Monsoon Interaction Experiment (JASMINE: Webster et al. 2002). Wang and Rui (1997) were first to describe morphology of the MISO as a coupled convective Rossby-Kelvin wave packet where the trailing and poleward propagating Rossby waves comprise the apparent bifurcation in the eastern Indian Ocean. Before the development of the convection in the eastern Indian Ocean, the tropical

Indian Ocean is warmer by about 0.5°C than after the convective phase of the oscillation (Webster et al. 1998, Lawrence and Webster 2002). These estimates come from the Reynolds's SST product. However, *in situ* measurements reported in Sengupta et al. (2001) and Webster et al. (2002) suggest that the oscillation of the SST during the evolution of a MISO may be a factor of two larger.

Lawrence and Webster (2002) extended an earlier analysis by Webster et al. (1998) by categorizing and compositing over 58 MISOs in the 24 summers from 1975-1999. Composites were based on the existence of a prolonged relative minimum in OLR (i.e., convection) in the eastern Indian Ocean (0.5°N , $85-90^{\circ}\text{E}$) on the 20-80 day timescales (see Lawrence and Webster 2002 for details on compositing strategy). A regression technique was used similar to that developed by Kiladis and Weickmann (1992). Figure 3c shows composite OLR anomalies identified by this process. Lawrence and Webster (2002) found that two-thirds of the MISOs developed *in situ* in the eastern Indian Ocean and about a third developed in the western Indian Ocean before propagating eastward. All of the events showed distinctive northward propagation. MISOs developing *in situ* do not appear to propagate eastward into the Pacific Ocean. The composite patterns shown in Figure 3c were essentially independent of the base location in the Indian Ocean or south Asian region (Lawrence and Webster 2002) indicating that the dominant physical processes determining convection in Indian Ocean/South Asian region were essentially the same.

Wang and Xie (1997) and Wang (this volume) offer explanations of the bifurcation related to the Rossby wave component of the madden-Julian oscillation. However, why the bifurcation of convection occurs in the eastern Indian Ocean is not known. Possibly, it is due to the proximity of the heated continent to the north (e.g., Webster 1983) and the impact of the resulting meridional cross-equatorial pressure gradient. This hypothesis would be consistent with a number of studies (e.g., Tomas and Webster 1997, Krishnakumar and Lau 1998, Tomas et al. 1999) that have suggested that the pressure gradient, the strongest to occur across the equator anywhere on the planet, results in large scale, low frequency instabilities. In any event, the northward moving branch of the bifurcation becomes an active period of the monsoon as it moves northward through the Bay of Bengal from where it extends across Central India and South Asia. Prior to the bifurcation and when convection is a maximum in the East Indian Ocean along the equator (day zero of the composite) the Indian subcontinent is generally dry and in a break phase. Overall, Figure 3 a-c strongly suggests that the MISO is a slowly evolving, very large scale and robust phenomenon.

4. Basis for existence of predictability of monsoon intraseasonal variability

If MISOs are inherently chaotic phenomena, how can their behavior be predicted? A similar question could be asked about the predictability of weather phenomena at higher latitudes. Weather events are made up of unstable chaotic baroclinic waves and as such they are inherently unpredictable. Prediction is successful in the short term because initial conditions of numerical models identify the existence of the baroclinic wave. The model physics can continue to describe the evolution of the baroclinic wave through its life cycle. Therefore, as long as the model identifies the existence of a disturbance, then predictability is possible over one life cycle. However, as the next instability may occur randomly in space and time, it is not possible to forecast the advent or location of ensuing chaotic instabilities. As the life cycle for baroclinic waves takes roughly 5-7 days, prediction is limited to this time scale. The model will produce physically consistent weather patterns forever but after one life cycle they become divorced from the initial conditions. Extraneous factors such very slowly evolving blocking situations or the positions of strong boundary effects may extend predictability but, in general, prediction is limited to one life cycle of the dominant chaotic phenomena.

If the MISO is the dominant internal dynamical feature of the monsoon circulation, then it should be possible to predict a MISO through one cycle of its evolution. That is, prediction should be possible for 20-30 days. The hypothesis is bolstered somewhat by noting that the MISO has a relatively very large scale and repeat-

able life cycle. Additionally, as it is thought that the onset of the monsoon is the first MISO of the summer (e.g., Flatau et al. 2001, Webster et al. 2002) then the onset of the monsoon should possess the same predictability.

5. Webster-Hoyos MISO prediction scheme

The similarity in form of MISOs, even though they vary somewhat in magnitude, duration and when they occur, allows the identification of a series of predictors that are physically based and are related strongly to the composite behavior of the phenomena.

The most important issue in a statistical scheme is the choice of predictors. Here a predictor is a physical factor that is tied physically to the MISO and for which there exists a long-term time series. The predictand of the statistical scheme is the average 5-day (pentad) precipitation over the Ganges Valley (see Figure 1). The predictors used in the Webster-Hoyos scheme are listed in the table. Each of these has been chosen from descriptions of MISO morphology and having strong relationships with the MISO. The behavior of the predictors relative to the occurrence of intraseasonal band precipitation in the Ganges Valley is shown in Figure 4. The two lines about the mean show the variance of the predictor and predictand at ± 1 standard deviation. In this illustration, data from 1986-2003 was used with composites comprised from 63 MISO events. The variance is important as it leads to probabilistic forecasts discussed later.

Physically Based Predictors	
1	OLR over central Indian Ocean
2	OLR over central India
3	Upper-tropospheric easterly jet: strength and location
4	Sea-level pressure over central India
5	200 mb zonal winds over eastern equatorial Indian ocean
6	Surface zonal winds over equatorial Indian ocean
7	Intensity of Somalia Jet at 925 mb
8	925 mb u-field over Arabian Sea
9	925 mb v-field over Arabian Sea

Table 1: Predictors used in the MISO statistical prediction scheme. Predictors are chosen so as to constitute a complete description of the evolution of the MISO.

The statistical scheme is described in detail in Webster and Hoyos (2003) and will not be repeated here except to point out the critical elements of the scheme. These are:

- Wavelet analysis of the predictand to identify statistically significant bands if they exist. . In the monsoon regions these exist at 5-20 days, 20-75 days, 75 –230 days and >365 days. These are referred to as the MISO bands. Predictor time series of each of the bands is produced.
- The predictors are banded in the identical manner to the predictand.
- Linear regression scheme is applied to advance each predictand time series forward, and,
- Reconstitute the time series to produce total forecast field.

The scheme is shown schematically in Figure 5. Examples of the forecasts are shown in the next section.

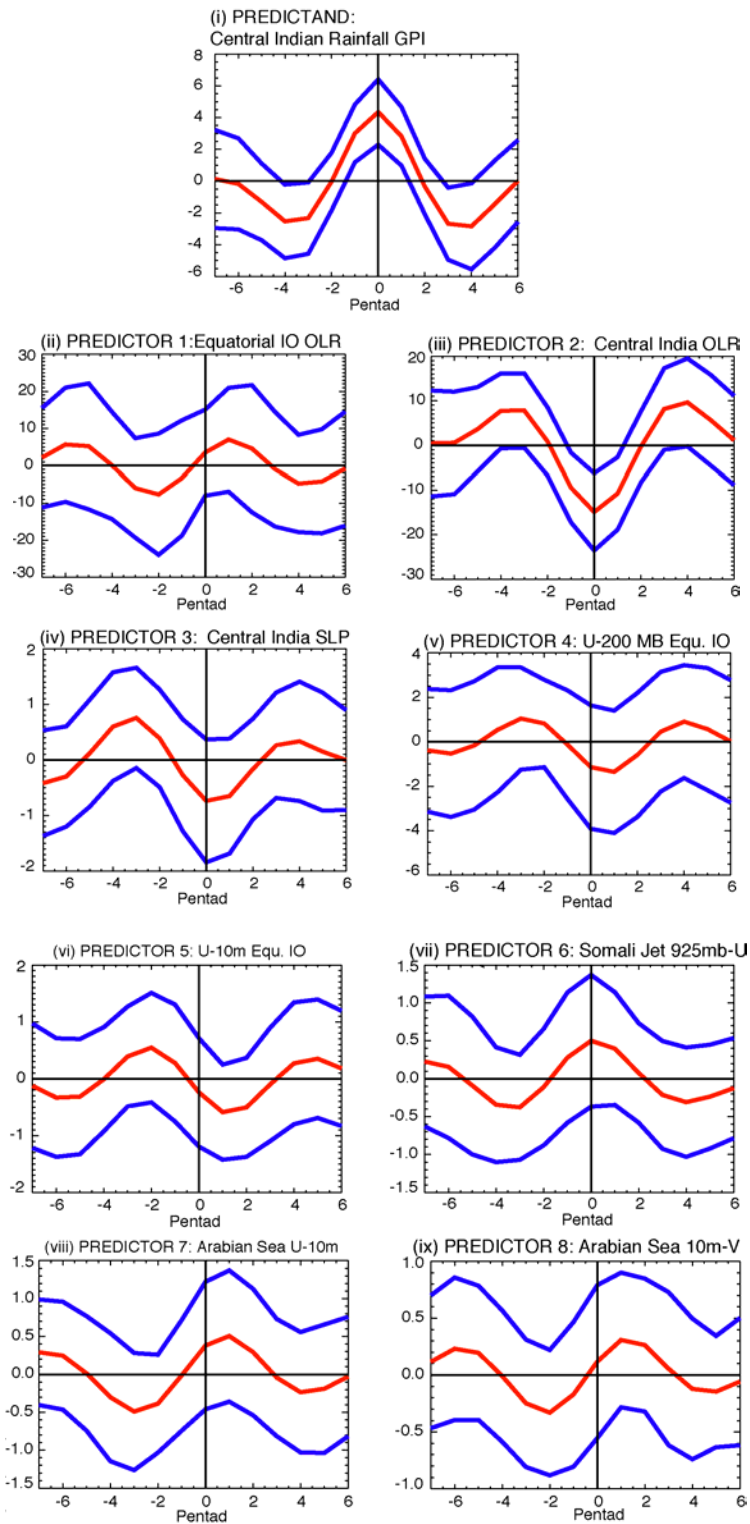


Figure 4: The predictand (panel i) and predictors (panels ii to ix) as listed in the table. The composite behavior of the predictand and predictors for -7 to $+7$ pentads (-35 to $+35$ days) are shown.

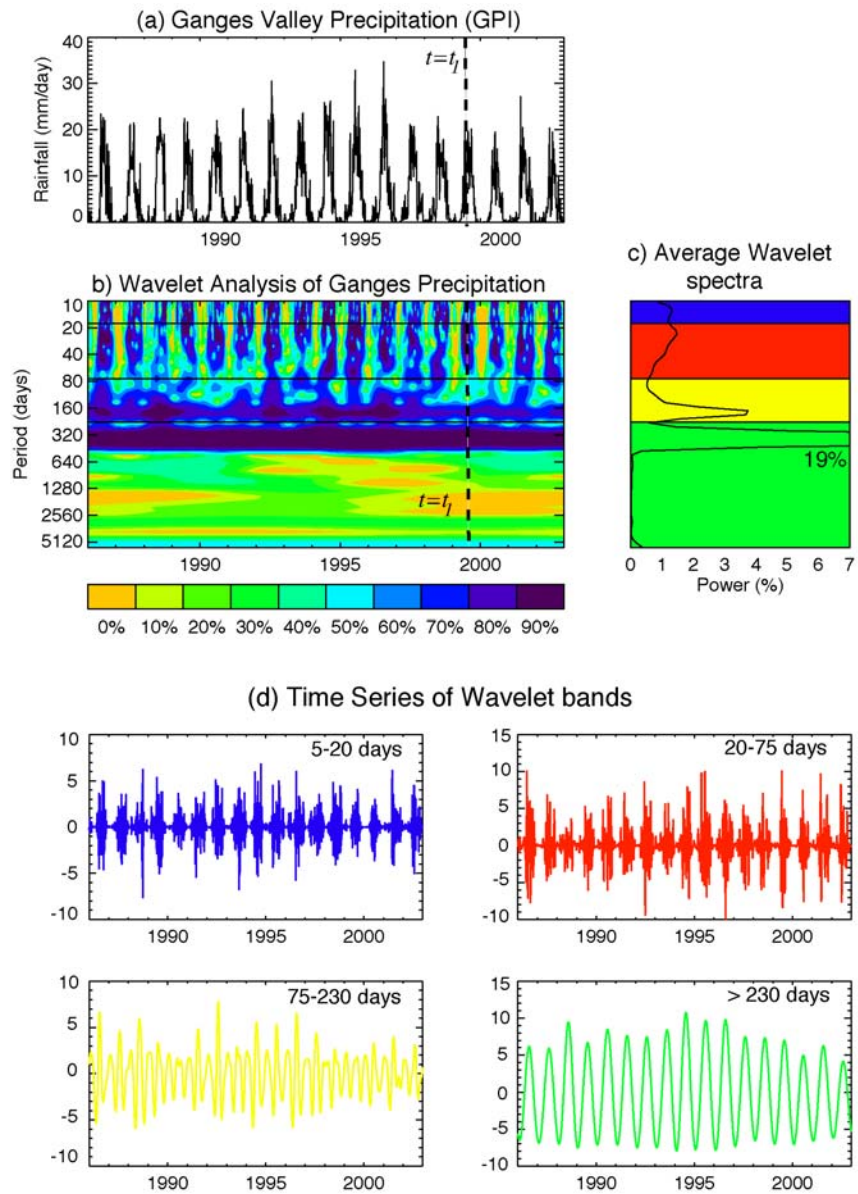


Figure 5: Description of the Webster-Hoyos “wavelet banding” (WB) technique: (a) Time series of a predictor, in this case the GPI rainfall estimate over the Ganges Valley from 1986 through 2002. (b) Wavelet analysis of the predictand for the same period. (c) The average wavelet spectra over the period 1986-2002. The wavelet bands are chosen from regions within the average spectra which are statistically significant. These bands are: 5-20 days, 20-75 days, 80-230 days and > 230 days. (d) Time series of the four wavelet bands. For a forecast initiated at $t=t_1$ (vertical line), wavelet analysis and the identification of the wavelet bands would be undertaken on data collected at $t < t_1$. Note that the resultant bands (panel d) possess amplitudes with varying coefficients. All of the predictors are banded identically. The wavelet banding is the basis of the statistical scheme.

Webster and Hoyos showed that the choice of predictors was a necessary condition but not sufficient. They used a number of schemes that used the total predictors identically to the Webster and Hoyos scheme. Specifically, the banded wavelet scheme was compared with a multi-variate regression scheme, a neural network scheme and a simple linear regression scheme. Even though the same predictors were used, the wavelet-banded method outperformed the other schemes with correlations of 0.85 to averages of about 0.6 at 20 days. The reasons for the better performance are very important and have significant implications for improving numerical forecasts of intraseasonal variability. We will return to this point later.

Figure 6 shows 20-day (4 pentads) forecasts for the Ganges Valley, as identified in Figure 1. Forecasts for the summers of 1999-2002 are displayed. The gray line represents the GPI observation record and the blue lines show the forecast values made 20 days prior using the WB technique with linear regression. To interpret the forecasts it is important to note that the blue curve shows the forecast made from information available 20 days (4 pentads) prior to the forecast. Overall, the 20-day forecasts manage to discern the phase of the major variations of the pentad GPI rainfall quite well. Most peaks and valleys align fairly accurately with the correct pentad. Whereas the amplitude of the forecasts is generally underestimated, it is rare that extrema in forecasts and evaluation fields are missed. Based on 10 years of hindcasts, the correlation between predicted and observed rainfall is 0.88 at 20 days.

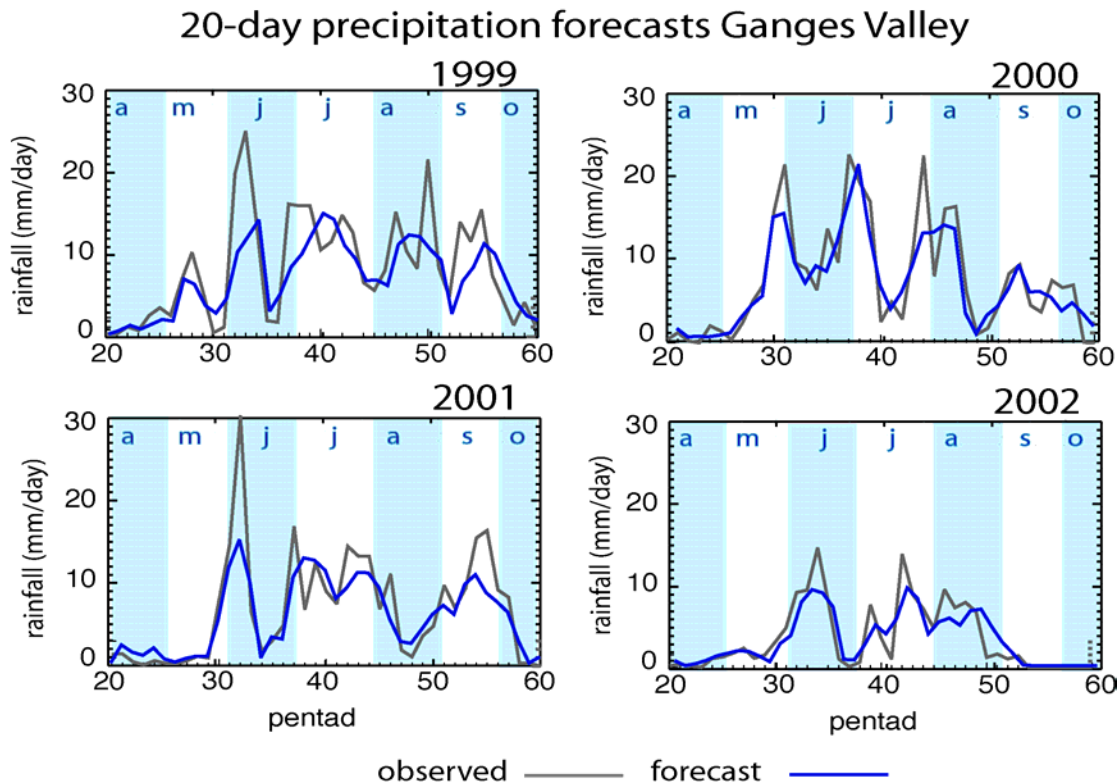


Figure 6: 20-day forecasts of precipitation averaged over the Ganges Valley (gray area Figure 1) for the summer of 1999-2000. Blue lines indicate 20 day (4 pentads) forecasts. Dark gray lines indicate observations of the area-averaged GPI precipitation product. The WB forecast scheme manages to forecast the phase of the rainfall variability with significant skill. Occasionally, the amplitude is underestimated by the scheme. Blue and white background denotes months.

Webster and Hoyos (2003) also used the wavelet-banding technique for the smaller regions of Rajasthan and Orissa, two states of India. Although the forecast were reduced in skill, they managed to foreshadow variability major intraseasonal variability 4 and 5 pentads in the future. Forecasts were also done for river discharge of the Ganges and Brahmaputra into Bangladesh with similar skill. This is to be expected as, for example, river discharge of the Ganges at the Bangladeshi border is a function of the integral of the precipitation over the Ganges catchment. Thus, if there is skill in the Ganges catchment precipitation forecast then there should be at least comparable skill in the river discharge out of the catchment.

Traditionally, empirical forecast techniques provide one forecast value and are, in that sense, deterministic. But is this one realization of the future a true indication of the future precipitation in the monsoon regions? Furthermore, for the forecast to be of maximum utility and so that it can be employed in risk analysis, a probability density function of the forecast is necessary. To do this we take advantage of the variability of the MISO's one to another. However, each event is different to some degree. For example, Figure 4a (the com-

posite of the Ganges precipitation relative to the rainfall maxima in the 20-75 day period band) shows considerable variability in magnitude. Although all of the predictors shown in Figure 4 show common behavior relative to the “day 0” of the composites, they also show variance. Below we discuss some preliminary work that takes care of the predictand and predictor variance and how this leads to a forecast in the form of a probability density function. This is done by the development of probability weight functions from predictor-predictand relationships. Through this method we will take full advantage of the Bayesian aspects of the problem.

For simplicity, consider a simple problem where there is one predictor $d(n)$ that is used to forecast predictand $p(n)$. Assume that we have data (predictand $p(t)$ and predictor $d(t)$) up to time $t=t_0$ pentads and we want to forecast p at $t=t_n$ n pentads ahead (i.e., $P(n)$). Furthermore, we have information about the statistical relationship between of $p(t)$ and $d(t)$ for a composite MISO as shown in Figure (4). This information refers to the relationships between the means and standard deviations. We propose the following forecast scheme:

- (i) Use the Webster-Hoyos scheme and use $p(t \leq 0)$ and $d(t \leq 0)$ to forecast a value of $P(n)$ from the particular case in question. $P(n)$ represents one possible value of the future state of p at some lag n similar to the examples shown in Figure 6. It provides no information of how probable that value would be.
- (ii) To establish a measure of uncertainty in $P(n)$ we use the statistical relationships between $p(t)$ and $d(t)$ for all previous MISOs. This information can be obtained from the composite MISO distributions such as those shown in Figure 4 to form joint probability functions. The joint-pdf adds the “uncertainty” shape of $P(n)$ about the predicted value found in (i).

This simple method applies a joint probability distribution about the forecast value arrived at by the Webster-Hoyos method. There are other methods that we can employ and these are being examined. For example, the coefficients of the banded regression coefficients are uncertain and their uncertainty can be assessed through the accuracy of previous forecasts. Given that we have 17 years of data, we have over 600 historical forecasts to determine the uncertainty in the coefficients. This uncertainty, so determined, would be the basis for Monte Carlo simulations using the Webster-Hoyos method. From the resultant spread of forecasts a pdf should emerge.

6. Conclusions and implications for numerical modeling:

The time scale of a forecast for optimal application in the agriculture and water resource sectors of monsoon regions appears to be about 15-25 days (ADPC 2003). We have argued that forecasts at longer time scales (e.g., the mean summer rainfall over the entirety of India) have a smaller practical value than forecasts of the intraseasonal variability as the forecast neither defines the geographical variability of the wetter and drier than average regions. Most importantly, the mean precipitation does not define the timing of the periods of excessive or reduced rainfall that occur on time scales of 15-30 days. As the seasonal mean precipitation does not define the sub-seasonal spatial or temporal structure of monsoon rainfall (Webster and Hoyos 2003), downscaling of seasonal forecasts is not possible. So, if we want to forecast intraseasonal variability, we are forced to forecast it directly and not as an artifact of a seasonal forecast.

We have shown that a relatively straightforward statistical scheme based on the physics of the intraseasonal oscillations is able to make forecasts with considerable skill on time scales that are useful for applications. Whereas the choice of the predictors is necessary, it is not sufficient to produce skillful forecasts. For example, Webster and Hoyos (2003) compared three other schemes (MARS, ANN and LIN) using the same predictors but without wavelet banding. Predictions from these three schemes show similar skill to other statistical efforts aimed at forecasting gross aspects of intraseasonal variability in the tropics (e.g., von Storch and Xu 1990, Waliser et al. 1999, Mo 2001, Lo and Hendon 2000, Wheeler and Weickmann 2001) but they are

far less skillful than the Webster-Hoyos wavelet banding method. Clearly, the discriminating feature of the method is the use of wavelet banding.

How can the results of the empirical scheme be used to improve numerical prediction of the intraseasonal variability of the tropics. We suggest two routes, one that suggests a way of using the statistical scheme as a diagnostic tool and the other that suggest a potentially new numerical path to prediction.

Diagnostic utility: Since the forecast scheme is physically based, skill comes from the interplay and sequencing of physical processes that have occurred during the training periods. From Figures 6 (and the many examples shown in Webster and Hoyos 2003), it is clear that the model is capable of recognizing a series of conditional processes that allow the monsoon rainfall to occur at a particular time, for the overall monsoon rains to be above or below normal (e.g., Figure 6) and capture the phasing of the intraseasonal events. It may be possible to construct the inverse problem and determine what is the reason for certain events occurring. For example, it is possible to determine what physical processes created the “false” onset in 1999 (Figure 6) versus the full onset of the monsoon rains noted in 2000 (Figure 6). Can examination of the predictors and their sequencing determine why the model produced forecasts of less total rainfall in 2002 over the Ganges Valley than in the other four years shown in Figure 6? Finally, is it possible to use the inverse model to help increase the skill in numerical models perhaps by examining the statistical predictors in comparison to the same physical processes produced by the numerical models as they evolve through time during a particular MISO?

Banding: Earlier, it was shown that there were two necessary conditions leading to predictive skill using the empirical model. First, the predictors must be physically based. If they are not, predictability may be a fleeting occurrence and may disappear from time to time. An example of this is the relationship between seasonal monsoon rainfall and indices of ENSO. For many years they relate strongly but tend to wane for decades at a time. It is clear that there is a relationship between the two phenomena but there must be physics that we do not understand that occasionally intercedes between the two. Thus, there is an absence of a third (or more) physically based predictor. The second necessary condition is the wavelet banding. Without the use of this technique all statistical techniques give the same level of skill if physically based predictors are chosen. What the banding technique does is “protect” the intraseasonal band from the “statistical confusion” introduced by high frequency events. If the reason that numerical models do so poorly in forecasting the intraseasonal band is because the slow manifold is eroded by poor representation of high frequency phenomena such as convection, then we need to incorporate the same “protection” that banding gave in the empirical model into the numerical models.

Our suggestion is simple and although it is not completely new may provide some improvement on the simulation and prediction of intraseasonal events. Two important papers (Krishnamurti et al. 1990, 1991) suggest a unique procedure for improving forecasting on intraseasonal time scales. Krishnamurti et al. (1990) noted that:

“...A major limitation of the extended integrations arises from a contamination of low frequency modes as a result of energy exchanges from the higher frequency modes. In this study we show an example on the prediction of low frequency mode to almost a month which is roughly 3 weeks beyond the conventional predictability. This was accomplished by filtering the higher frequency modes from the initial state. The initial state included a time mean state and a low frequency mode. The sea surface temperature anomalies on this time scale and the annual cycle were also prescribed....”

In a later paper Krishnamurti et al. (1991) utilized the scheme noting

“...By filtering out the high-frequency modes, we are able to delay the contamination of low-frequency modes for periods of the order of 1 month in global forecasts. (the study showed that) ... an initial state consisting of time-mean state, a low-frequency mode, and a specification of the sea surface temperature anomaly provides

useful forecasts for the occurrence of dry or wet spells.....(The main conclusion was that) the prediction of monsoonal low-frequency modes and the related dry and wet spells can be extended beyond the usual numerical weather prediction (NWP) predictability limit of 6 or 7 days. It appears that if the contamination from high-frequency modes is suppressed by an initial filtering, then the prediction of low-frequency motion through one cycle, a period of roughly a month, is possible... ”.

In essence, the studies found increased predictability for the same reasons that the statistical scheme was successful. The slow manifold was protected in both cases from high-frequency interference.

An immediate step forward might be to use the Krishnamurti method by filtering the initial data into bands. However, it should be noted that the improvement in the Krishnamurti et al. Forecasts, although extremely impressive, eventually broke down perhaps because the numerical model used allowed the generation of high-frequency noise from cumulus parameterizations that destroyed the initial low-frequency signal. This weakness could possibly be countered by developing a filtered slow manifold model that somehow only allowed low frequency components of convective heating (such as apparent in composites in Figure 4).

It is understood that the development of a new modeling strategy may not be particularly popular given the very large commitment into building models that are inclusive of all physical processes. Perhaps at some stage the high-frequency problems of the models may be improved to the extent that they do not erode the slow manifold and better simulations and predictions of the ISO occur. However, until then we have an immediate need for forecasts on the intraseasonal time scale and so the development of slow manifold models (in addition to the statistical schemes discussed earlier) may be the only method of improving forecasts in the short term.

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