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Long-range prediction of the low-frequency mode in the low-level Indian monsoon circulation with a simple statistical method

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ABSTRACT

The time evolution of the Indian monsoon is closely related to locations of the northward migrating monsoon troughs and ridges which can be well depicted with the 30–60 day filtered 850-mb streamfunction. Thus, long-range forecasts of the large-scale low-level monsoon can be obtained from those of the filtered 850-mb streamfunction. These long-range forecasts were made in this study in terms of the Auto Regressive (AR) Moving-Average process. The historical series of the AR model were constructed with the 30–60 day filtered 850-mb streamfunction [$\tilde{\psi}$ (850 mb)] time series of 4 months. However, the phase of the last low-frequency cycle in the $\tilde{\psi}$ (850 mb) time series can be skewed by the bandpass filtering. To reduce this phase skewness, a simple scheme is introduced. With this phase modification of the filtered 850-mb streamfunction, we performed the pilot forecast experiments of three summers with the AR forecast process. The forecast errors in the positions of the northward propagating monsoon troughs and ridges at Day 20 are generally within the range of $1 \sim 2$ days behind the observed, except in some extreme cases.

1. Introduction

Cadet and Daniel (1988) examined the daily time series of several meteorological variables observed by ships over the Southern Bay of Bengal. They found that the surface pressure and cloudiness exhibit a pronounced 30–50 day oscillation, which coincides with the monsoon life cycle. Based upon the low-frequency relationship between these two parameters and the summer monsoon's activity, Cadet and Daniel applied the fitting of an auto-regressive moving average process over a four-month period of the time series to predict dates of the peak of active/inactive monsoon with an accuracy of about a week. This study indicates that the statistical-empirical method developed with the quasi-periodic characteristics of the low-frequency mode is a feasible approach to forecast the life cycle of the Indian monsoon.

The life cycle of the Indian monsoon exhibits various (onset-active-break-revival-decay) phases. It has been shown by previous studies (e.g., Krishnamurti and Subramanyam, 1982) that these monsoon phases were established by the northward migration of the low-level 30–50 day transient monsoon troughs and ridges that originated around the equator. It is because the northward migration of these low-level transient troughs and ridges cause, respectively, the deepening and filling of the stationary monsoon trough over northern India. The time evolution of this stationary monsoon trough results in the intensification and weakening of the low-level Indian monsoon and its life cycle.

As far as the operational forecast over the Indian monsoon region is concerned, it is important to provide the real-time forecast of the Indian monsoon life cycle. Some operational centers, e.g., the European Centre for Medium Range Weather Forecasts (ECMWF), currently issue the real-time 10-day forecasts. As pointed out by Heckley (1985), even the ECMWF operational model may not show too much skill beyond two to three days for the monsoon forecasts. To extend this limit of the Indian monsoon forecasts to two to three weeks, the statistical-empirical method is an alternative. In view of the promising outcome of Cadet and Daniel's statistical forecasts of the Indian monsoon activities, we propose a modification of Cadet and Daniel's approach to predict the low-level transient monsoon troughs and ridges with the real-time data series over a limited time period. The modification of making Cadet and Daniel's approach operational is described in Section 2. Presented in the next section are forecast experiments and results. Finally, some concluding remarks are given in Section 4.

2. Scheme

Adopting the auto-regressive process, Cadet and Daniel (hereafter referred to as CD) (1988) developed a simple statistical procedure to forecast the break/active cycle of the Indian monsoon. Their procedure is outlined as follows.

(1) The time series of the 30–50 day filtered sea-level pressure and cloudiness were developed over an entire year period (January–December) at any observational station with the Butterworth bandpass filter (Murakami, 1979).

(2) The auto-regressive (AR) integrated moving average model of order 9 (Box and Jenkins, 1976) was then applied to fit the first 4-month (January–April) filtered data so that one can develop the historical series of the AR model. Based upon the AR model, forecasts were made for a time period requested.

(3) Step 2 was repeated by shifting one day with the 4-month window until the forecasts reach the end of the year.

(4) The 30–50 day Butterworth bandpass filter was applied again to the forecast output from the AR process.

The summer season is obviously far away from the beginning and end points of the data time series. The phase of the low-frequency mode portrayed by the filtered data time series during summer seasons is not affected by the bandpass filtering process. However, as revealed from our previous studies (e.g., Chen and Murakami, 1988; Chen et al., 1988a, b), the phase of the low-frequency mode depicted by the filtered data time series is usually *skewed* in the beginning and the end portions of these time series. Thus, the forecasts produced by the CD statistical scheme with the filtered data time series generated from the real-time data of a limited time period would be *spoiled* by the end effect of the bandpass filtering, which is reflected in the low-frequency mode's phase depicted in the filtered data time series.

Of course, we cannot expect that the CD statistical forecast scheme can be used for practical operation as a full-physics operational forecast model. Moreover, the end effect of the Butterworth bandpass filter on the filtered time series of a limited time period also makes it unrealistic to apply the CD statistical scheme for the operational forecast purpose. In fact, it is well beyond the capability of the currently operational forecast models to predict a significant portion of the life cycle of the Indian monsoon circulation. However, the CD statistical scheme may potentially be used for the benchmark long-range forecasts, if the aforementioned deficiency of this scheme can be eliminated. To serve this purpose, a proposed modification of the CD scheme is introduced.

Based upon the assumption that the low-frequency mode is quasi-periodic, the modification of the CD scheme proposed here is to reduce the end effect of the bandpass filtering. This modification is described in the following:

(1) Within the 4-month filtered data time series, we first determined the date which has the mirror phase of the end in this time series by tracing backward in time.

(2) We then artificially extend the *real* data time series from the end date forward in time for 45 days ($\sim$one life cycle of the low-frequency mode) with the backtracking original data time series from the date selected in Modification Step 1.

(3) The 30–60 day Butterworth bandpass filter was applied to the artificially extended real data time series to develop a new filtered time series in which the phase of the last low-frequency cycle within the 4-month period is not skewed seriously.

(4) The newly formed 4-month filtered data time series are used in the AR forecast process. In other words, Step 1 of the CD statistical scheme would be replaced by the modification presented here.

3. Forecast experiments and results

For convenience of the later discussion, the combination of the CD scheme and the proposed modification to it is denoted as the CYWN scheme. This scheme was applied to the domain of (45°–100° E, 10° S–30° N) covering most of the Indian monsoon region for all forecast experiments performed in this study. The data used in this study were generated by the ECMWF Global Data Assimilation System. As revealed from previous studies (e.g., Krishnamurti and Subramanyam, 1982; Chen et al., 1988b), the life cycle of the Indian monsoon is determined by the interaction between the stationary Indian monsoon trough located in central India and the northward-propagating 30–60 day monsoon trough/ridges. Because of this reason, our major effort in this study is to forecast the northward propagation of the transient monsoon troughs/ridges.

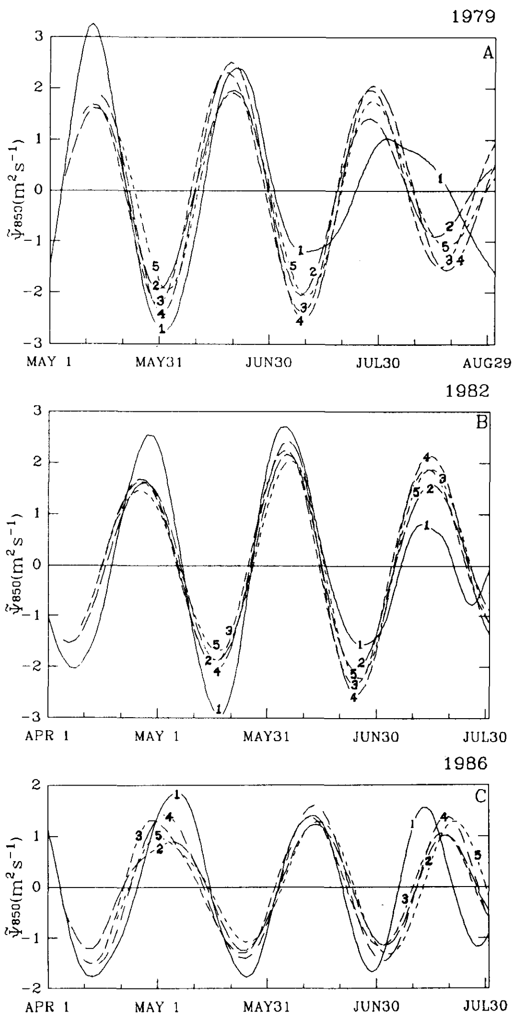

Fig. 1. Time series of the observed (Day-0; solid line), filtered 30–60 day, 850–mb streamfunction, $\tilde{\psi}$ (850 mb), at (75° E, 15° N) and forecasts of this variable for Day 5(2), 10(3), 15(4) and 20(5).

The 30–60 day filtered velocity potential at 200 mb, $\tilde{\chi}$ (200 mb), has often been used to delineate characteristics of this low-frequency mode. As indicated by the $\tilde{\chi}$ (200 mb) at (75° E, 15° N) (not shown), this low-frequency mode was relatively regular in the monsoon region over most of 1979, 1982 and 1986. We thus performed the forecast experiments with the CYWN statistical scheme for these three years as the pilot testing. Moreover, the 30–60 day filtered times series of the 850-mb zonal wind, $\tilde{u}$ (850 mb), at (65° E, 15° N) is used as a life-cycle index of the Indian monsoon. Krishnamurti and Subramanyam (1982) suggested that the monsoon onset date is defined as $\tilde{u}$ (850 mb) = 0 at this point between May and June. With this definition, the monsoon onset of 1979 occurred in the middle of June and those of 1982 and 1986 took place in the beginning of and in early June, respectively. Thus, we initiated the AR forecast process of the CYWN scheme one month earlier for 1982 and 1986 than for 1979.

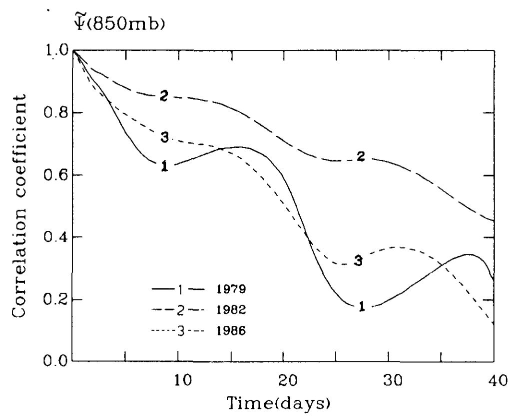

Fig. 2. Correlation coefficients (abscissa) between time series of observed and forecasted $\tilde{\psi}$ (850 mb) of Day 1 ⋯ 40 forecasts at (75° E, 15° N).

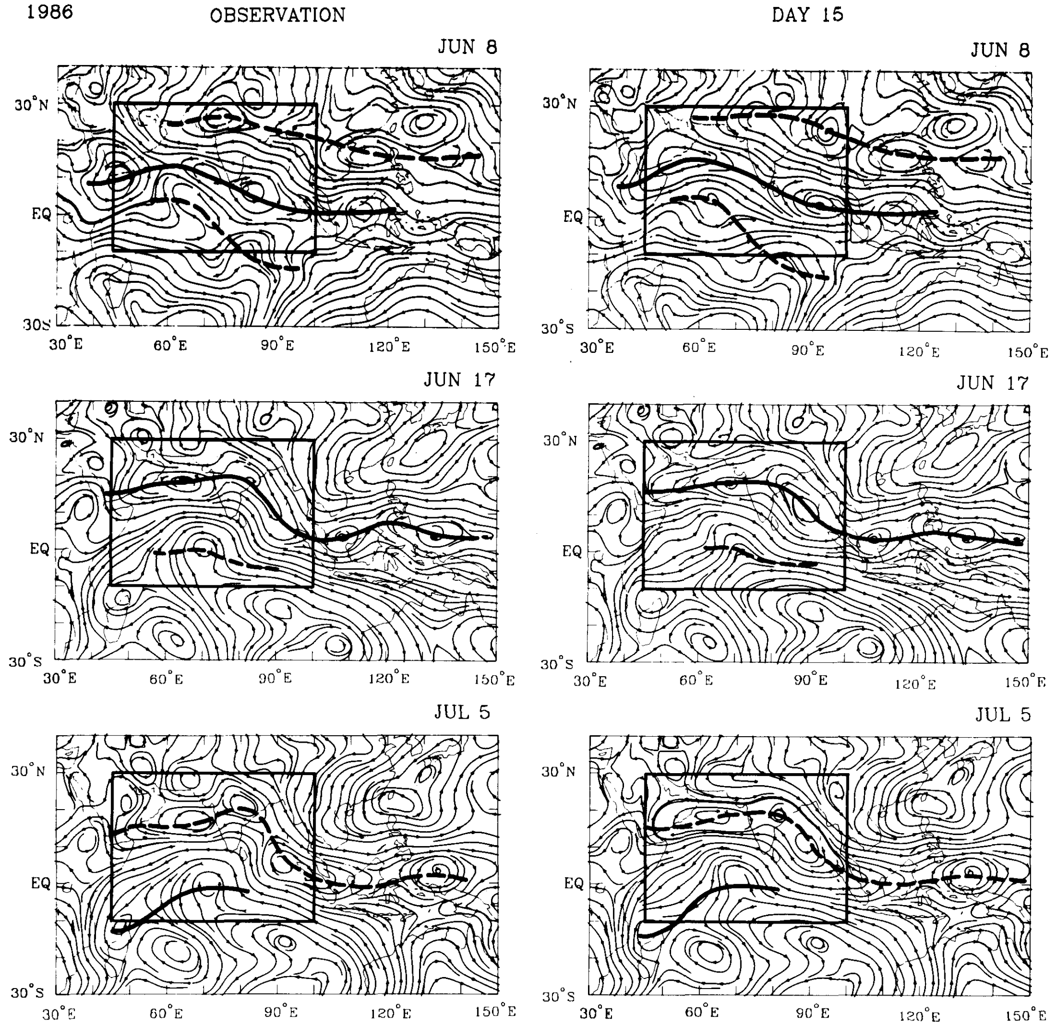

Fig. 3. The 850-mb streamline (thin solid line) constructed with the wind fields obtained from $\tilde{\psi}$ (850 mb) and the 30–60 day transient monsoon troughs (thick solid line) and ridges (thick dashed lines) for observation and the Day-15 forecasts of 8 June, 17 June and 5 July 1986. The inner rectangle is the computational domain.

The monsoon onset and revival occur when the 30–60 day transient monsoon troughs arrive at about 15°N (Krishnamurti and Subramanyam, 1982). In order to have a feeling of the $\tilde{\psi}$ (850 mb) forecasts with the CYWN scheme, the forecasted $\tilde{\psi}$ (850 mb) time series for Day 5, 10, 15 and 20 at (75°E, 15°N) against the observed (Day-0) $\tilde{\psi}$ (850 mb) time series (solid line) are shown in Fig. 1. As revealed from this figure, the observed $\tilde{\psi}$ (850 mb) time series exhibit a larger intra-seasonal variation in amplitude than the forecasted $\tilde{\psi}$ (850 mb) time series. As far as the forecast of the Indian-monsoon life cycle is concerned, latitudinal locations of the northward migrating monsoon troughs and ridges are, in fact, more important than their amplitudes. These locations are decided based upon the streamline maps constructed with the forecast $\tilde{\psi}$ (850 mb) fields. Thus, the concern regarding the amplitude of the forecasted $\tilde{\psi}$ (850 mb) never constitutes any difficulty in our pilot forecast experiments with the CYWN scheme.

Although the $\tilde{\psi}$ (850 mb) time series of Day-5, -10, -15 and -20 forecasts shown in Fig. 1 look subjectively alike, we do need an objective and quantitive means of measuring the forecast limit. The correlation coefficient between the observed and forecasted $\tilde{\psi}$ (850 mb), $\sigma_{\tilde{\psi}}$, is computed to serve this purpose. It is shown in Fig. 2 that $\sigma_{\tilde{\psi}}$ of all three summers at (75° E, 15° N) can reach above 0.6 for the Day-20 forecasts. In fact, $\sigma_{\tilde{\psi}}$ of both 1982 and 1986 can reach 0.6 even for the Day-30 forecasts. But, we shall limit the acceptable forecast of the 30–60 day monsoon troughs/ridges portrayed with the $\tilde{\psi}$ (850 mb) field of the Day-20 forecasts, so that the skillful forecast performance of the CYWN scheme can be maintained.

To illustrate the performance of the CYWN forecast scheme for the low-frequency mode of the low-level monsoon circulation, we randomly pick the streamline maps of the Day-15 forecasts of the 1986 case for June 8, June 17 and July 5 (Fig. 3) for demonstration. The rectangular domain outlined by solid line is the computational domain. The streamlines inside and outside the computational domain were plotted with the forecasted and observed $\tilde{\psi}$ (850 mb) fields, respectively. The trough and ridge lines of the 30–60 day monsoon mode at 850 mb are denoted, respectively, by thick solid and thin lines. As shown in Fig. 3, forecasts may not reproduce every detail of the low-frequency monsoon troughs and ridges. Regardless of the stage of the monsoon life cycle, the east-west extent and the latitudinal locations of these troughs and ridges were well predicted.

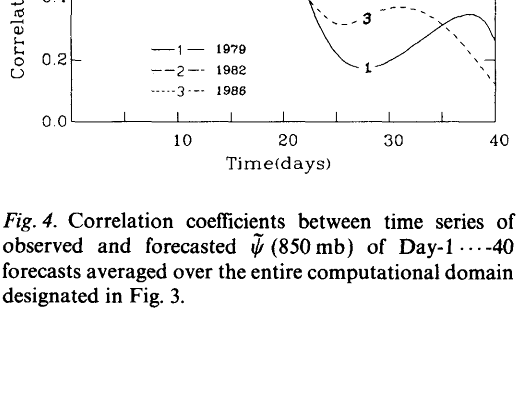

Fig. 4. Correlation coefficients between time series of observed and forecasted $\tilde{\psi}$ (850 mb) of Day-1 $\cdots$ -40 forecasts averaged over the entire computational domain designated in Fig. 3.

We also used the area-averaged correlation coefficient between the observed and forecasted $\tilde{\psi}$ (850 mb) fields over the entire computational domain, $\sigma_{\tilde{\psi}A}$, to evaluate the synoptic pattern of forecasts. Shown in Fig. 4 is $\sigma_{\tilde{\psi}A}$ as a function of time. The $\sigma_{\tilde{\psi}A}$ values of 1979 and 1982 reach above 0.6 for the Day-20 forecasts, although those of 1986 are slightly less than the values for the Day-20 forecasts. Certainly, we cannot expect that the values of $\sigma_{\tilde{\psi}A}$ are as much as those of $\sigma_{\tilde{\psi}}$ at the specially selected locations of (75° E, 15° N). At least, values of $\sigma_{\tilde{\psi}}$ shown in Fig. 2 and of $\sigma_{\tilde{\psi}A}$ shown in Fig. 4 are comparable. This situation indicates that the forecast performance of the CYWN scheme over the entire computational domain is not too much inferior to the specially selected point.

Sikka and Gadgil (1980) showed that the monsoon cumulus convection migrates northward with the northward propagation of the low-frequency monsoon trough from the equator to the foothills of the Himalayas. To evaluate the precise location of the forecasted monsoon troughs and ridges, the $y-t$ diagrams of the 30–60 day OLR anomalies at 75° E superimposed with locations of the observed (thick dashed lines) and forecasted (thick solid lines) low-frequency monsoon troughs and ridges of the Day-15 forecast are shown in Fig. 5. The locations of troughs and ridges were relatively well predicted, except the second cycle of the 1979 monsoon variation between middles of July and August. The forecast location errors of these troughs and ridges are generally within the range of 1–2 days behind the observed.

It was claimed by CD that the irregularity of the low-frequency mode's phase caused the forecast failure of this low-frequency mode by the CD scheme. As revealed from the $\tilde{\chi}$ (200 mb) and $\tilde{u}$ (850 mb) indicies, the phase irregularity of the low-frequency modes did exist in the three summers forecasted in this study. In spite of the exact time period of the low-frequency mode's phase irregularity, the forecast performance of the CYWN scheme for the low-frequency modes over the monsoon life cycle during the three years does not show any distinct difference. However, as

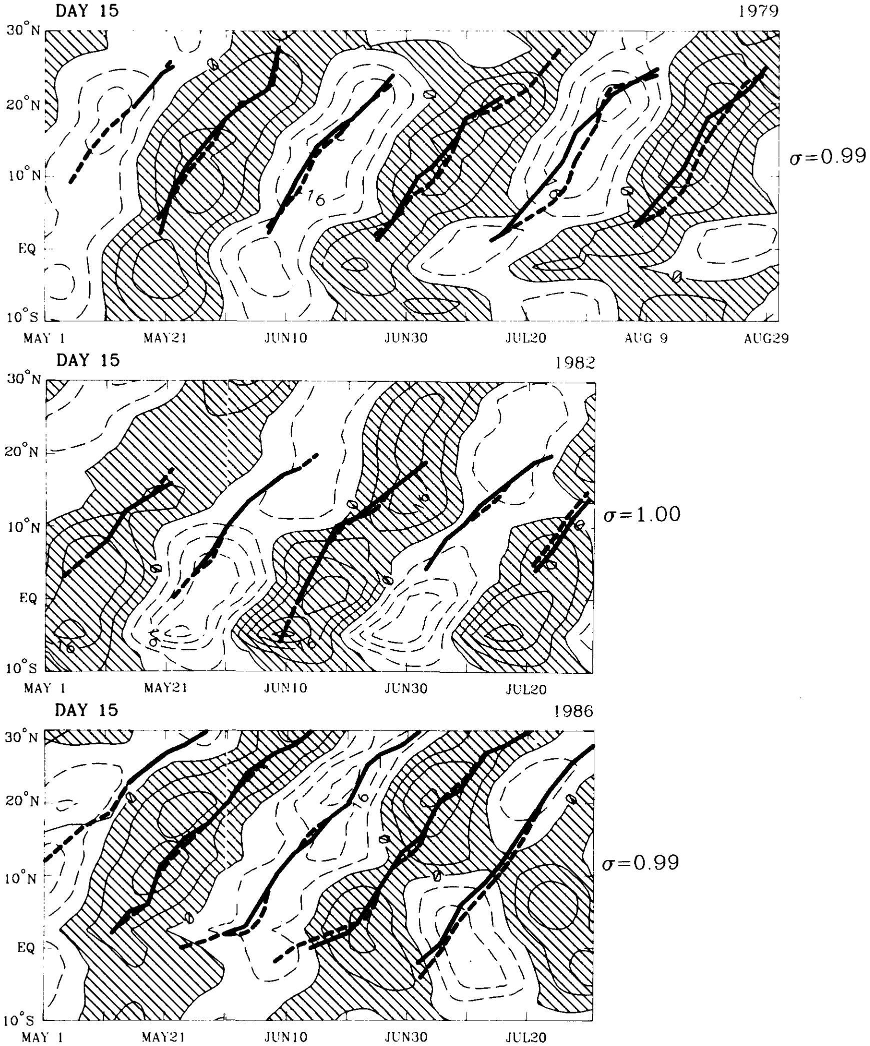

Fig. 5. The $y-t$ diagrams of 30–60 day filtered OLR anomalies at 75° E; negative values are shaded. The observed (thick dashed lines) and the Day-15 forecasted (thick solid lines) locations of the 30–60 day transient monsoon troughs and ridges are superimposed on the negative and positive filtered OLR anomalies, respectively. The contour interval of the filtered OLR anomalies is 8 wm^{-2}.

experienced by CD, the success of the CYWN scheme for these three years does not mean that this scheme can yield good forecast skill for all monsoon life cycles.

4. Concluding remarks

The life (onset-active-break-revival-decay) cycle of the Indian monsoon exhibits significant interannual variation, but the quasi-periodic behavior of the Indian monsoon life cycle is the most unique phenomenon found anywhere around the globe. Numerous studies, e.g., Krishnamurti and Subramanyam (1982), Chen and Yen (1986) and others, demonstrated that the life cycle of the Indian monsoon resulted from the interaction between the stationary monsoon trough over central India and the northward-propagating, 30–60 day monsoon troughs/ridges in the lower troposphere. The locations of these transient monsoon troughs/ridges play a vital role in the time evolution of the Indian monsoon life cycle. Therefore, if we could predict the northward propagation or locations of the transient monsoon troughs/ridges two to three weeks ahead, we should be able to make long-range forecasts of the Indian monsoon activity.

Cadet and Daniel (1988) proposed the autoregressive moving average process to forecast the low-frequency mode of the surface pressure and cloudiness with the bandpass filtered time series of these two variables in the Southern Bay of Bengal. Because the filtered data over the entire year were used, they did not face the phase skewness of the filtered-data time series during the summer season. This phase skewness is caused by the end effect of the filtering process on the data time series of a limited time period. We introduced a modification to Cadet and Daniel's scheme to reduce the phase skewness of the filtered-data time series. This modification was accomplished by extending the real-data time series from the end date with the real data backtracked from the date, which possesses a mirror phase of the filtered-data time series at the end date. A relatively skillful performance was yielded in the long-range forecast experiments for 1979, 1982 and 1986 monsoons with this approach. The Day-20 forecast errors of locations of these troughs and ridges do not exceed 2 days, except in extreme cases.

Recently, Krishnamurti et al. (1990, 1991) proposed to forecast the low-frequency mode with a full-physics multilevel forecast model in which the high-frequency modes were excluded from the initial conditions. Although cumulus activity of forecasts is sensitive to the initial high-frequency mode, Krishnamurti et al. yielded skillful performance of the 30-day forecasts of the low-frequency mode. In spite of the feasibility of Krishnamurti et al.'s approach, the statistical-empirical approach of forecasting the transient monsoon troughs/ridges presented in this study is so simple and straightforward. One can easily adopt this forecast process into a personal computer and workstation, since the SAS software package is so popular.

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REFERENCES

Box, G. E. and Jenkins, G. M. 1976. *Time series analysis: forecasting and control.* Holden-Day Editor, 575 pp.

Cadet, D. L. and Daniel, P. 1988. Long-range forecast of the break and active monsoons. *Tellus 39A*, 121–138.

Chen, T.-C. and Yen, M.-C. 1986. The 40–50 day oscillation of the low-level monsoon circulation over the Indian Ocean. *Mon. Wea. Rev. 114*, 2550–2570.

Chen, T.-C. and Murakami, M. 1988. The 30–50 day variation of convective activity over the western Pacific Ocean with emphasis on the northwestern region. *Mon. Wea. Rev. 116*, 892–906.

Chen, T.-C., Yen, M.-C. and Murakami, M. 1988a. The water vapor transport associated with the 30–50 day oscillation over the Asian monsoon regions during 1979 summer. *Mon. Wea. Rev. 116*, 1983–2002.

Chen, T. C., Tzeng, R.-Y. and Yen, M.-C. 1988b. Development and life cycle of the Indian monsoon: Effect of the 30–50 day oscillation. *Mon. Wea. Rev. 116*, 2183–2199.

Heckley, W. A. 1985. *The performance and systematic errors of the ECMWF tropical forecasts (1982–1984).* Tech. Report No. 53, ECMWF, Reading, England, 97 pp.

Krishnamurti, T. N. and Subramanyam, D. 1982. The 30–50 day mode at 850 mb during MONEX. *J. Atmos. Sci. 39*, 2088–2095.

Krishnamurti, T. N., Subramanyam, M., Oosterhof, D. K. and Daughenbaugh, G. 1990. Predictability of low-frequency mode. *Meteor. Atmos. Phys. 44*, 63–83.

Krishnamurti, T. N., Subramaniam, M., Daughenbaugh, G., Oosterhof, D. and Xue, J. 1991. *One-month forecasts of wet and dry spells of the monsoon.* FSU Rept No. 91-1, Department of Meteorology, Florida State University, Tallahassee, FL 32306, 56 pp., (Available from Dr. T. N. Krishnamurti).

Murakami, M. 1979. Large-scale aspects of deep convective activity over the GATE area. *Mon. Wea. Rev. 107*, 994–1013.

Sikka, D. R. and Gadgil, S. 1980. On the maximum cloud zone and the ITCZ over Indian longitudes during the southeast monsoon. *Mon. Wea. Rev. 108*, 1840–1853.