MONSOON DYNAMICS (1981), Cambridge University Press,
Editors: Sir James Lighthill and R. P. Pearce

Part Ib

Modelling and theoretical studies

6

Predictability of monsoons

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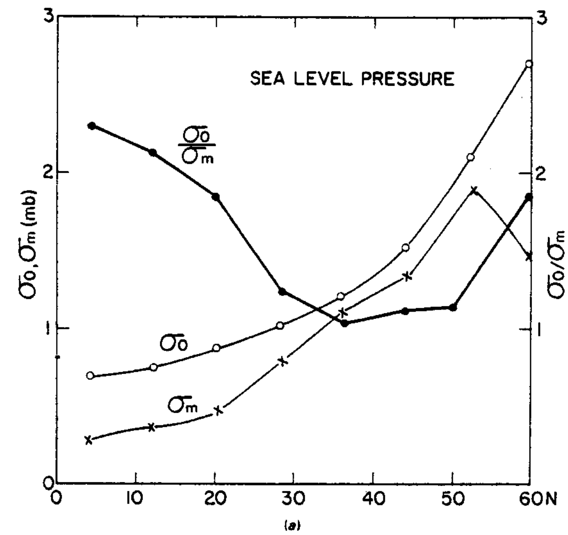
It is shown by numerical simulation that the variability of average pressure and rainfall for July due to short-period flow instabilities occurring in the absence of boundary anomalies can account for most of the observed variability at midlatitudes but not at low latitudes. On the basis of the available evidence it is suggested that a large part of the low-latitude variability is due to boundary anomalies in such quantities as sea-surface temperature, albedo and soil moisture, which, having longer time constants, are more predictable than the flow instabilities. Additional variability due to long-period natural fluctuations would likewise be more predictable.

The degree of predictability of monsoons is a matter of considerable social and economic importance. Large agrarian populations exist in monsoon areas, and monsoon rains have a critical influence on food production and human welfare. The long-range prediction of average rainfall could be of immense value for water management and agricultural planning. In this chapter, evidence that mean flow conditions and precipitation patterns at low latitudes are in principle more predictable than those at high latitudes is presented. Among the low-latitude circulations are the African and Asian monsoons and perhaps also the southeasterly monsoon flow east of the North American Cordillera. In particular we wish to show that the natural flow instabilities on synoptic scales account for most of the interannual variability of monthly mean quantities at midlatitudes, but cannot explain the observed variability at low latitudes. The latter, we suggest, is due partly to fluctuations in such boundary parameters as sea-surface temperature, albedo, ground moisture and vegetation and partly to flow fluctuations of large planetary scales. Since the boundary parameters and the planetary-scale flows vary on much larger time-scales than the synoptic-scale flow instabilities, they should be predictable for longer periods of time. They have not yet been so predicted, but we believe that they can be.

The possibility of longer-range prediction at low latitudes occurred to one of the authors of this chapter during the course of an investigation, by Charney *et al.* (1975, 1977), of the effects of albedo and ground moisture changes on mean July rainfall in, or adjacent to, monsoonal regions. Numerical simulation experiments showed that large changes in rainfall could easily be produced by changes of albedo. To assess the significance of these changes, three randomized numerical experiments were performed with the general circulation model of the Goddard Institute for Space Studies (GISS), in each of which a random alteration to a previously calculated control integration was made by introducing at each grid-point over the globe a random perturbation of temperature, wind and sea-level pressure in the middle of June and continuing the integration through July. The spatial variability of the random perturbations corresponded to Gaussian distributions with zero means, and standard deviations of 1 °C in temperature, 3 m s^{-1} in horizontal wind components and 1 mb in surface pressure. Owing to flow instabilities, the individual perturbed flows began immediately to differ from one another and from the control flow until by early July the daily weather fluctuations had become so different that it seemed possible to regard the variability of the July averages as approximating the variability of the model flow from one July to another. The experiments showed remarkable persistence in mean July rainfall despite the random fluctuations in the daily weather patterns. On closer examination it was found that while the variances among the model-generated July averages approximated the variances among the observed July averages in midlatitudes, they fell far short in low latitudes. To account for the low-latitude discrepancy, we were led to consider the factors responsible for the actual variability at low and at middle latitudes. Two of the most important are the natural fluctuations due to flow instabilities that would exist under prescribed boundary conditions, and the fluctuations due to anomalous variations in the boundary conditions themselves. The two are not independent because there is close coupling between the flow instabilities and the boundary anomalies. However, the boundary anomalies are not observed to be so large as to change the statistical properties of the flow instabilities significantly, and therefore the latter may be studied independently. The reverse is not necessarily true because the boundary anomalies manifest themselves largely through shifts in position and intensity of the flow instabilities.

Let us consider first the natural fluctuations. Lorenz (1969) has shown that deterministic predictability is limited fundamentally by the growth of uncertainty due to flow instabilities. If the uncertainty is initially confined to observations of the very small-scale components of the flow, it will spread to larger and larger scales by a combination of flow instability and nonlinear interaction, until eventually it will extend to the principal weather fluctuations and cause them to become random and unpredictable. Since the rate of growth of uncertainty at small scales is extremely rapid, it is of little avail to increase the accuracy and spatial resolution of the observations beyond what is required to specify the main, energy-bearing, synoptic scales of motion. Uncertainty grows to synoptic scales within a day or two, after which it is the basic instabilities at these scales, and their nonlinear interactions with still larger scales, that determine the further growth of error. When the error enters the synoptic scales, its doubling time is about two days, and as the error amplitude increases and uncertainty is extended to still larger scales, the growth rates diminish. Numerical simulations of error growth set an upper limit to the predictability of the transient synoptic-scale motions of the atmosphere of about two weeks (Charney *et al.*, 1966; Smagorinsky, 1967). However, the larger-scale components of the flow remain predictable for longer periods.

It was in the framework of these ideas that the numerical studies of variability in mean July conditions were performed. Insertion of a rather large random perturbation (1 °C in temperature, 3 m s^{-1} in horizontal wind components and 1 mb in surface pressure) at each grid-point of the numerical model on June 18 caused individual synoptic systems to become effectively random by the beginning of July. It was then assumed that each such July simulation represented a random element of an ensemble whose statistical properties would approximate those of an actual time series of Julys if the seasonally varying Earth's surface boundary conditions were replaced by their seasonally varying climatological averages and if the variances due to timescales of the order of a month or longer could be ignored. We were, of course, aware that the longer fluctuating timescales could also contribute to the total variance, but were unable to carry out longer-period integrations to test their effects because of unavailability of additional computer time. Four



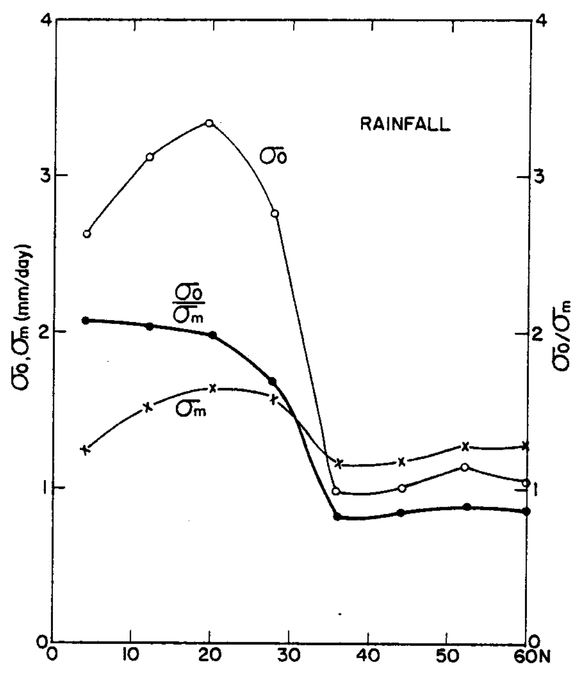


Fig. 6.1. Model and observed zonally-averaged standard deviations as functions of latitude, and their ratio, for: (*a*) mean July sea-level pressure; and (*b*) rainfall. Observed values are for land stations and model values are for grid-points over land.

six-week integrations with four independent sets of randomly perturbed initial conditions were available for comparison. Figs. 6.1*a* and 6.1*b* show the zonally-averaged standard deviations, $\sigma_m(p)$ and $\sigma_m(r)$, of the mean July sea-level pressures and rainfall among the four model runs as functions of latitude. For comparison, the observed standard deviations, $\sigma_o(p)$ and $\sigma_o(r)$, compiled from climatological data are also shown, together with the ratios of the observed standard deviations to the model standard deviations. The observed standard deviations were calculated for 380 stations in the northern hemisphere from mean July sea-level pressure and rainfall data for the 10 years, 1966–75.† It is seen that the ratios σ_o/σ_m are less than 1.5 for pressure at latitudes between 25° N and 55° N and for rainfall at latitudes greater than 30° N; at other latitudes the ratio is greater than 1.5 and for low latitudes it is greater than 2. Since the observations are for land stations, the model values are also taken for the grid-points over land. It is likely that, at all latitudes, the ratio σ_o/σ_m for both sea-level pressure and rainfall may be larger over the oceans compared to the land. Table 6.1 shows areal averages of σ_o, σ_m and σ_o/σ_m for both sea-level pressure and rainfall over three monsoonal and three midlatitude regions for which observational data were available. Again, it is seen that the calculated variability falls far short of the observed variability in the monsoonal areas, whereas it accounts for most of the observed variability in midlatitudes, the contrast being particularly marked for rainfall. Monsoon rainfall, and in general most low-latitude rainfall, is convective in character and is not as well simulated as other physical processes in numerical general-circulation models. However, since the GISS model simulates travelling synoptic disturbances, and in fact tends to overpredict rainfall over land, we have had no reason to assume that the low-latitude variability due to natural fluctuations on timescales of less than a month is underpredicted, and we conclude that synoptic fluctuations are capable of explaining most of the July variability at the higher latitudes, but not at the lower latitudes.

† The standard deviation $\sigma(a)$ at a grid-point or a station was defined as

$$\left(\frac{1}{n-1}\sum_1^n (a_i-\bar{a})^2\right)^{\frac{1}{2}}$$

where

$$\bar{a}=\frac{1}{n}\sum_1^n a_i.$$

For the model runs $n=4$, for the observations $n=10$.

TABLE 6.1. *Areally-averaged modelled and observed standard deviations of July mean sea-level pressure and rainfall for monsoonal and midlatitude regions. $\bar{\sigma}_o$ is the average value of standard deviation for the observations; $\bar{\sigma}_m$ is the average value of standard deviation for the model.*

		Sea-level pressure (mb)			Rainfall (mm per day)		
		$\bar{\sigma}_o$	$\bar{\sigma}_m$	$\bar{\sigma}_o/\bar{\sigma}_m$	σ_o	$\bar{\sigma}_m$	$\bar{\sigma}_o/\bar{\sigma}_m$
African monsoon:	0° –20° N 10 °W–50 °E	0.713	0.354	2.01	1.900	1.328	1.43
Indian monsoon:	0° –30° N 70 °E–90 °E	0.702	0.455	1.54	4.390	1.433	3.06
N. American monsoon:	20 °N–40 °N 100 °W–70 °W	1.384	0.845	1.64	1.817	0.945	1.92
Europe midlatitude:	40 °N–60 °N 10 °W–50 °E	2.528	1.98	1.28	1.057	1.14	0.927
Asia midlatitude:	40 °N–60 °N 110 °E–170 °E	1.738	1.37	1.27	1.506	1.27	1.19
N. America midlatitude:	40 °N–60 °N 90 °W–60 °W	1.339	1.28	1.05	1.442	1.183	1.22

Chervin *et al.* (1976) have used the general-circulation model of the National Center for Atmospheric Research to calculate model standard deviations of the mean January 850 mb temperature from five random January simulations. Comparing with observed standard deviations determined by Crutcher and Meserve (1970) from 14 mean January analyses, they find the model standard deviations to be systematically too small over the oceans, and they attribute this to the absence of ocean temperature anomalies in the model simulations. It can be seen from their charts that ratios of observed to model sigmas are especially large at low latitudes over both land and ocean, in agreement with our results for July.

Madden (1976) has attempted to infer the natural variability of monthly mean sea-level pressure for the months of January, April, July and October directly from a 74-year record of observations, combining successive 96-day sequences centred around each of these months, subtracting suitably smoothed climatological means, filtering out all non-random spectral components of frequency less than $\frac{1}{96}$ cycles per day, and assuming that the smaller-frequency spectral components are constant in amplitude and random in phase, i.e., by assuming white noise at frequencies less than $\frac{1}{96}$ cycles per day. The residual or "natural" variability is then due to the random daily synoptic noise fluctuations, and it is assumed that these may be modelled by a first-order Markov process which gives white noise at sufficiently low frequencies. The deviation of the natural from the observed variability is then considered to be due to a potentially predictable signal. Madden's definition of natural variability differs from ours by including fluctuations of period up to 96 days and boundary-induced fluctuations of periods less than 96 days, but it resembles ours by excluding systematic fluctuations or 'signals' of longer period. Madden was unable to compare his results with observation much below 30° N, but in regions where comparison with observation were possible, his results agree qualitatively with ours, and his conclusion, that the natural variability can explain the actual interannual variability from about 40° N to 60° N, whereas it falls far short south of 40° N, is likewise in agreement with ours.

We now cite evidence for our hypothesis that fluctuations in boundary conditions can account for a large part of the additional variability at low latitudes, whereas they are usually too small to produce a signal strong enough to be discerned above the noise of the natural variability in midlatitudes.

Let us first consider the midlatitude signal to noise ratio. Here, investigation has concentrated on the possible influence of sea-surface temperature anomalies on downstream mean flow conditions. A number of numerical simulation experiments have been performed to evaluate the effects of such anomalies in the Pacific and Atlantic oceans on the downstream flow. We may cite those of Spar and Atlas (1975), Spar (1973*a*, *b*) and Chervin *et al.* (1976). In none of these did significant changes appear downstream when the anomalies were comparable in amplitude to those normally observed; in some cases small systematic changes were observed but only over the boundary anomalies themselves as might have been expected. However, Kutzbach *et al.* (1977) re-examined the results of Chervin *et al.* (1976) and claimed to have found systematic changes in the storm tracks and intensities. While we cannot rule out the possibility that significant downstream changes may be induced by unusually large or widespread sea-surface temperature anomalies (Davis, 1978; Namias, 1971, 1978), we may infer from the existing numerical simulations that large signal to noise ratios are not usually to be expected.

The case for a strong signal to noise ratio at low latitudes stands in sharp contrast. Numerical simulation experiments of Rowntree (1972, 1976) gave support to Bjerknes' (1966, 1969, 1972) hypothesis based on observation, that equatorial sea-surface temperature anomalies produce large changes in the mean tropical Hadley circulation. Another such experiment by Shukla (1975) showed that a decrease in sea-surface temperature of between 1 to 3 °C over an area in the Arabian Sea of approximately 1000 km × 1000 km produced a statistically significant reduction of more than 40% in the monsoon rainfall over India. The reality of this effect is further supported by the observational evidence found by Ellis (1952) and by Shukla and Misra (1977) for the existence of a significant relationship between sea-surface temperature anomalies in the Indian Ocean at about 10° N (along ship lanes) and rainfall over India. With respect to albedo, observational evidence for large changes accompanying the recent drought in sub-Saharan Africa has been presented by Otterman *et al.* (1976) and by Norton and Mosher (1977) from analyses of satellite observations. The effects of such changes on rainfall in monsoonal and semi-arid border regions have been shown by Charney *et al.* (1977) also to be large and to be easily discernible above the random noise.

The low-latitude variability in flow pattern and rainfall due to fluctuations in ocean surface temperatures tends to be large because of the highly nonlinear relation between saturation vapour pressure and temperature, because of the instability of the tropical atmosphere for moist adiabatic processes, and because small temperature changes induce large thermal winds.

To account theoretically for the smallness of the ratio of 'natural' synoptic-scale variance to observed variance at low latitudes, one must show that the flow instabilities at low latitudes are intrinsically weak and that the more intense instabilities of midlatitudes cannot influence the low-latitude circulation by mechanical propagation of energy. The theories of baroclinic instability and wave-energy propagation seem to provide a partial answer. Charney (1947), Eady (1949), Kuo (1952) and others have shown that the flow instabilities of midlatitudes are due primarily to the strong meridional temperature gradients that exist there. Such gradients are not to be found at low latitudes. Also, it may be shown that the midlatitude instabilities cannot propagate their energies into the low latitude easterlies. A simple extension by Charney (1969) of a theory of Charney and Drazin (1961) shows that eastward-propagating Rossby waves originating in the midlatitude westerlies are trapped by zonal easterlies, and since the tropical circulations south of 30° N are dominated by easterlies, they are protected from the disturbances in the westerlies. The GISS general circulation model used for calculating the natural variances has been found to represent the large midlatitude temperature gradients and the low-latitude easterlies quite well (Stone *et al.*, 1977). Although intrusions of large-amplitude midlatitude disturbances into the Indian monsoon sometimes occur (Ramaswamy, 1962), according to Ramamurthy (1969) such cases are infrequent and confined mainly to upper levels. At these levels the mean zonal winds do sometimes become westerly and thus permit the southward propagation of midlatitude disturbances. In the limited six-week integration period of our numerical experiment such events did not occur. However, a subsequent long-period extension of one of the runs did produce an intrusion of a midlatitude trough over India. Events of this kind, though infrequent, could obviously increase the model variance.

We have presented evidence from numerical experiments and from observation that natural fluctuations of short period (less than 30 days in our numerical experiments, and less than 96 days in Madden's analysis of observations) are adequate to account for most of the observed variability at midlatitudes, but are not capable of explaining the variability at low latitudes, say below 30° N. In addition, we have cited evidence based on numerical simulation experiments and statistical analyses of observations that anomalies in sea-surface temperature and in ground albedo are capable of producing large variances. Since these anomalies are usually of long duration, the possibility arises that mean monthly conditions at low latitudes, such as monsoon rainfall, may be predictable with some accuracy. It remains, of course, to be seen whether, and to what extent, the combination of the boundary anomalies with the flow instabilities will account for the actual variances. Natural variations of long period, such as fluctuations in the tropical branch of the Hadley circulation driven by fluctuations in the eddy transports of heat and momentum at midlatitudes, may very well contribute. But if such fluctuations exist, it seems likely that they, too, being of longer period, will be predictable for longer periods of time. Thus we suggest that the synoptic-scale flow instabilities which limit prediction so drastically at midlatitudes have less influence at low latitudes and therefore leave room for the longer-period and more predictable signals to make themselves felt.

Clearly, more observational, numerical and theoretical analyses must be performed to assess the relative importance of the various factors producing tropical variability. Above all, we consider that attempts at longer-range prediction in low latitudes should concentrate first on the observation and prediction of fluctuations in such variables as sea-surface temperature, vegetative cover, albedo and ground moisture. Such observations can in principle be made from polar orbiting or geostationary satellites.

References

Bjerknes, J. (1966) A possible response of the atmospheric Hadley Circulation to equatorial anomalies of ocean temperature. *Tellus*, **18**, 820.

Bjerknes, J. (1969) Atmospheric teleconnections from equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163.

Bjerknes, J. (1972) Large-scale atmospheric response to the 1964–65 Pacific equatorial warming. *J. Phys. Oceanogr.*, **2**, 212.

Charney, J. G. (1947) The dynamics of long waves in a baroclinic westerly current. *J. Meteor.*, **4**, 135.

Charney, J. G. (1969) A further note on large-scale motions in the tropics. *J. Atmos. Sci.*, **26**, 182.

Charney, J. G. and Drazin, P. G. (1961) Propagation of planetary scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, **66**, 83.

Charney, J. G. *et al.* (Panel on Int'l. Meteor. Cooperation to the Comm. on Atmos. Sci., NAS/NRC) (1966) The feasibility of a global observation and analysis experiment. *Bull. Amer. Met. Soc.*, **47**, 200.

Charney, J. G., Stone, P. H. and Quirk, W. J. (1975) Drought in the Sahara: A biogeophysical feedback mechanism. *Science*, **187**, 434.

Charney, J. G., Quirk, W. J., Chow, S. and Kornfield, J. (1977) A comparative study of the effects of albedo change on drought in semi-arid regions. *J. Atmos. Sci.*, **34**, 1366.

Chervin, R. M., Washington, W. M. and Schneider, S. H. (1976) Testing the statistical significance of the response of the NCAR general circulation model to North Pacific Ocean surface temperature anomalies. *J. Atmos. Sci.*, **33**, 413.

Crutcher, H. L. and Meserve, J. M. (1970) Selected level heights, temperatures and dew points for the Northern Hemisphere. NAVAIR 50-1C-52 Rev., Naval Weather Service Command, Washington, DC.

Davis, R. E. (1978) Predictability of sea level pressure anomalies over the North Pacific Ocean. *J. Phys. Oceanogr.*, **8**, 233.

Eady, E. T. (1949) Long waves and cyclone waves. *Tellus*, **1**, 33.

Ellis, R. S. (1952) A preliminary study of a relation between surface temperature of the North Indian Ocean and precipitation over India. M.S. thesis, Department of Meteorology, Florida State University.

Kuo, H. L. (1952) Three-dimensional disturbances in a baroclinic zonal current. *J. Meteor.*, **9**, 260.

Kutzbach, J. E., Chervin, R. M. and Houghton, D. D. (1977) Response of the NCAR general circulation model to prescribed changes in ocean surface temperature. *J. Atmos. Sci.*, **34**, 1200.

Lorenz, E. N. (1969) Three approaches to atmospheric predictability. *Bull. Amer. Met. Soc.*, **50**, 345.

Madden, R. A. (1976) Estimates of the natural variability of time-averaged sea level pressure. *Mon. Wea. Rev.*, **104**, 942.

Namias, J. (1971) The 1968–69 winter as an outgrowth of sea and air coupling during antecedent seasons. *J. Phys. Oceanogr.*, **1**, 65.

Namias, J. (1978) Multiple causes of the North America abnormal winter 1976–77. *Mon. Wea. Rev.*, **106**, 279.

Norton, C. C. and Mosher, F. R. (1977) An investigation of surface albedo variations during the recent Sahel drought. Report on NASA Grant NGR 50-002-215, Space Science and Engineering Center, University of Wisconsin.

Otterman, J., Walter, L. S. and Schmugge, T. J. (1976) Observations from ERTS of overgrazing and cultivation impact on the earth's surface. *Space Research*, **16**, 15.

Ramamurthy, K. (1969) Forecasting Manual, Part IV, India Meteorological Department.

Ramaswamy, C. (1962) Break in the Indian summer monsoon as a phenomenon of interaction between the easterly and the sub-tropical westerly jet streams. *Tellus*, **14**, 337.

Rowntree, P. R. (1972) The influence of tropical east Pacific Ocean temperatures on the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **98**, 290.

Rowntree, P. R. (1976) Response of the atmosphere to a tropical Atlantic Ocean temperature anomaly. *Quart. J. Roy. Meteor. Soc.*, **102**, 607.

Shukla, J. (1975) Effect of Arabian sea surface temperature anomaly on Indian summer monsoon: A numerical experiment with the GFDL model. *J. Atmos. Sci.*, **32**, 503.

Shukla, J. and Misra, B. M. (1977) Relationships between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India. *Mon. Wea. Rev.*, **105**, 998.

Smagorinsky, J. (1967) Problems and promises of deterministic extended-range forecasting. *Bull. Amer. Met. Soc.*, **50**, 286.

Spar, J. (1973*a*) Transequatorial effects of sea surface temperature anomalies in a global general circulation model. *Mon. Wea. Rev.*, **101**, 554.

Spar, J. (1973*b*) Supplementary notes on sea surface temperature anomalies and model-generated meteorological histories. *Mon. Wea. Rev.*, **101**, 767.

Spar, J. and Atlas, R. (1975) Atmospheric response to variations in sea surface temperature. *J. Appl. Meteor.*, **14**, 1235.

Stone, P. H., Chow, S. and Quirk, W. J. (1977) The July climate and a comparison of the January and July climates simulated by the GISS general circulation model. *Mon. Wea. Rev.*, **105**, 170.