The Indian Monsoon

1. Variations in Space and Time

Sulochana Gadgil

Understanding the nature of the variation in the rainfall that occurs on different spatial scales (from that of a station or a taluk to that of the entire country) and on different time scales (from days to months, to the whole season, to inter-annual and longer), unraveling the underlying mechanisms and hence predicting the variation is the central problem of monsoon meteorology. In this series of articles, I shall attempt to address the 'how and why' of the Indian monsoon. I begin with a brief discussion of what we know about the nature of the observed variability of the rainfall on different regional and time-scales. What we understand about the physics of the monsoon and its variability will be considered in the next part. Finally I consider why we are not able to predict it better than we do and the challenges to be met for substantive improvement in understanding and prediction of the monsoon.

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Introduction

In common parlance, the word monsoon is used for the rainy season. We judge the behaviour of the monsoon in a specific year primarily on the basis of the total rainfall received in the rainy season. Thus, when the rainfall is well below the average, it is said to be a poor monsoon. The presence of a distinct rainy season is an important characteristic of the monsoonal regions of the world. Since rainfall is undoubtedly the most important facet of the climate over our region, its seasonal variation and impact on agriculture have been known for a very long time, certainly since the Vedic period. The first reference to measurement of rainfall received at different places in different seasons and the variation from one year to another is found in Kautilya's *Arthasastra* in the third century BC. Since the late nineteenth century, meteorological observations have been made with modern instruments at several stations in the country, and the India Meteorological Department has a dataset extending for well over a hundred years.

The word 'monsoon' is derived from the Arabic word 'mausam' for season.

While rainfall is critical for humans inhabiting the Indian region, the direction of the wind over the surrounding ocean was of paramount importance to the Arab sailors on their regular voyages to India and the Far Eastern countries from the 8th century AD. The meteorology of the Indian Ocean region was first described by these sailors from the information they gathered on the climate and particularly the winds of the routes they traversed. The word 'monsoon' is derived from the Arabic word 'mausam' for season and the Arab sailors associated it with the seasonal reversal of winds over the Arabian Sea. Meteorologists also tend to use a criterion involving the seasonal reversal in the direction of the wind to define the monsoonal regions of the world, but recognize that the associated seasonal variation in the atmospheric pressure pattern and rainfall are also major characteristics of the monsoon. Clearly for us, the variation of rainfall is the most important facet of the monsoon system.

The average monthly rainfall for some representative stations over different parts of India is shown in *Figure* 1. Over a large part of the Indian region, most of the rainfall occurs in the months of June to September during the summer monsoon season. Hence, the summer monsoon accounts for over 80% of the average rainfall over the Indian region (*Figure* 2). However, the rainy season over the peninsula extends beyond September (*Figure* 1). In fact, over the east coast of the southern peninsula, most of the rainfall occurs during October–November (*Figure* 1).

Over a large part of the Indian region, most of the rainfall occurs in the months of June to September.

Naturally over the long period of civilization the agricultural practices, the migration of nomads and various facets of our culture such as festivals have evolved in response to this seasonal cycle. However, it appears that in this modern era, major events on which heavy rainfall can have an adverse impact are planned, without taking into account the available extensive knowledge of

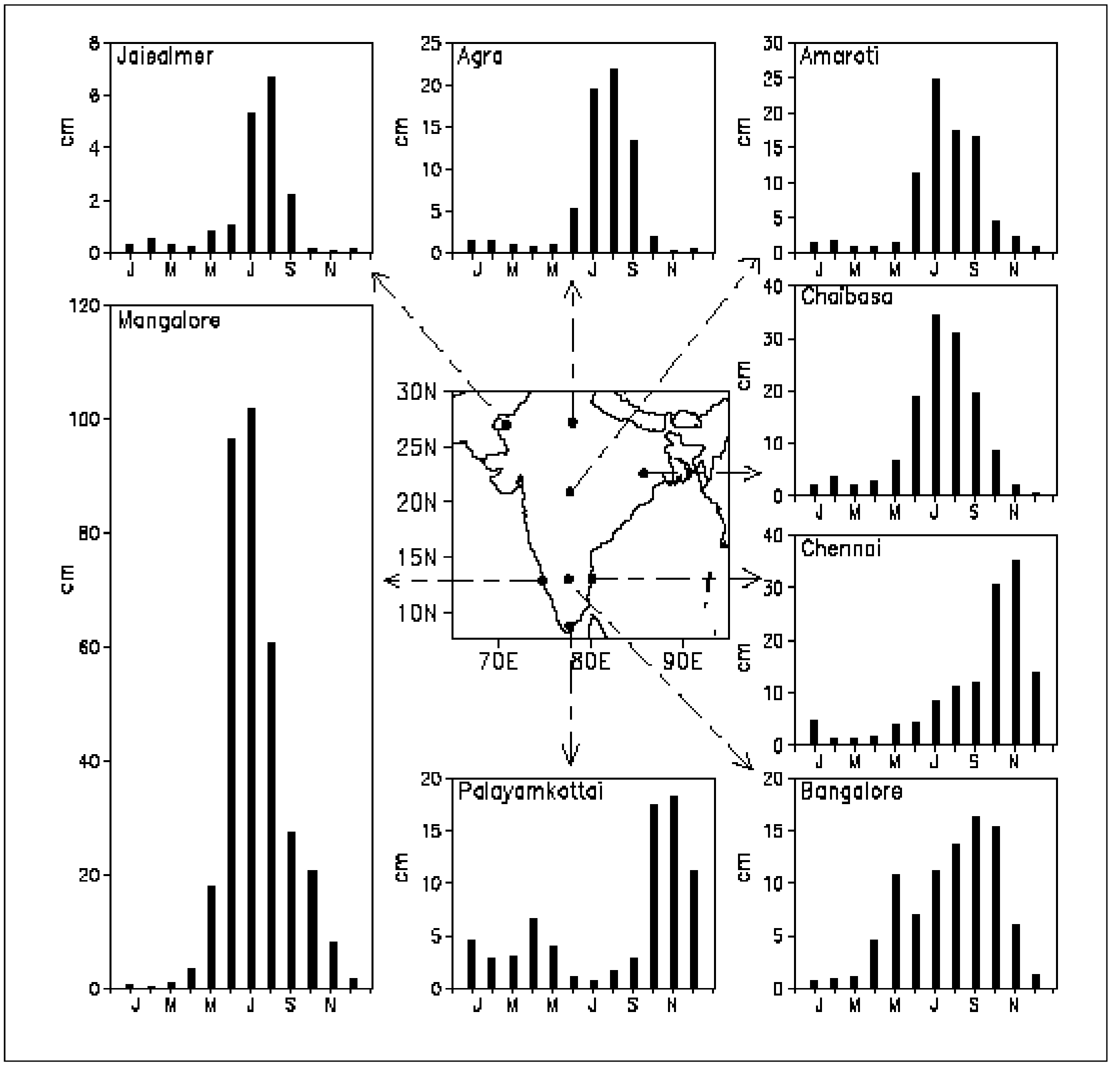


Figure 1 Average monthly rainfall in cm at some stations.

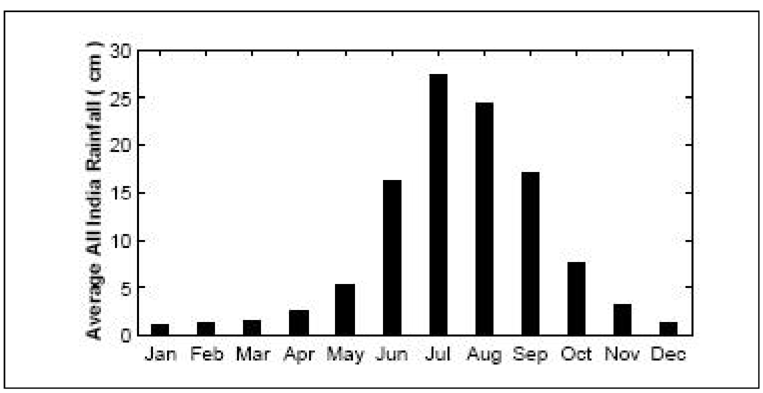


Figure 2. Average monthly all-India rainfall (cm).

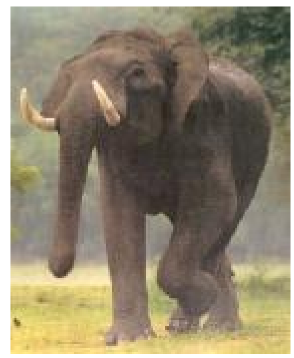
Box 1.

A

B

The life cycles of the flora and fauna are tuned to this rhythmic variation of their environment. At the height of the long dry season, many trees burst forth into bloom, as their seeds must be ripe and ready to sprout with the arrival of the rains (e.g. the flame of the forest (*Butea monosperma*), and the Indian laburnum: *Figures* A,B). As the dry season drags on, the lakes begin to dry and fish become easy picking for the pelicans (*Figure* C). When the monsoon sets in, their chicks fly away and the Pelicans close shop. The spectacular dance of the peacock characterizes the monsoon season. Peafowl breed at the height of the monsoon, feeding on the reptiles that thrive during the rains. As the monsoon season draws to a close, elephants begin to head back to the rain forests (*Figure* D) of the Sahyadris, which they had left for the deciduous forests just before the onset of the monsoon. The seasonal cycle in the life around us owes its existence to the monsoon.

C



D

rainfall and its variability. For example, a major event involving the Prime Minister was organized by ONGC on 23 June 2006. It had to be cancelled due to heavy rains (12.4 cm in 24 hours from 8.30 am on 23 June according to IMD) and it has been reported that there was a loss of Rs. 5 crores! It is seen from *Figure* 1, that the average rainfall for June in Mangalore is almost 100 cm. Analysis of the daily rainfall data available at India Meteorological Department shows that in the second half of June, the chance of getting on a single day, rainfall of 10 cm or more, is 7%. In fact, compared to any fortnight in the summer monsoon season, the chance of getting 10cm or more is the highest in the second half of June. It drops to 3% and 1% in the two halves of August and even further in September. Although the chance of occurrence of heavy rainfall is in itself not very high, since the loss involved in cancellation of the ONGC event due to the occurrence of 'the raging monsoon' is high, it is unwise to schedule such events in this period. Planning such an event during this period, rather than a few weeks later, makes sense only if the expected benefit of the earlier date far outweighs this large expected loss. It appears that we do not use the available extensive knowledge of rainfall variability for assessing the expected costs/risks due to weather and arriving at appropriate decisions.

The direction of the surface wind over the monsoonal region comprising the Indian subcontinent and the ocean surrounding it, changes from being from the southwest during the summer monsoon (June–September) to blowing from the northeast during October–December (*Figure* 3). In fact, the commonly used terms viz. 'southwest monsoon season' for June–September and the 'northeast monsoon season' for October–December refer to the direction from which the surface wind blows in that season. Associating the seasons with wind direction leads to the popular belief (which is totally wrong but often reinforced in schools) that the clouds that give us rain are brought by these winds and hence come from different directions in the two seasons. We shall see in the next article of the series that, in fact, the system responsible for the rainfall is the same in the southwest and northeast monsoon seasons. The change in the wind patterns occurs because this system (and the associated low pressure belt) is located over the peninsula and adjoining seas in the northeast monsoon season and over the plains north of Mumbai in the southwest monsoon season.

Seasonal variation of the temperature, pressure and rainfall associated with the monsoon is evident not only on the large scale but also for sub-regions of the country and even individual stations (e.g. *Figure* 4 from the observations on the roof of our Centre at the Institute from January 2003 onwards). It is seen from *Figure* 4 that within the rainy season, there are wet spells of a few days separated by spells with little or no rainfall. Even though the average monthly rainfall for October is only 15 cm, the rainfall in a wet spell can be over 10 cm.

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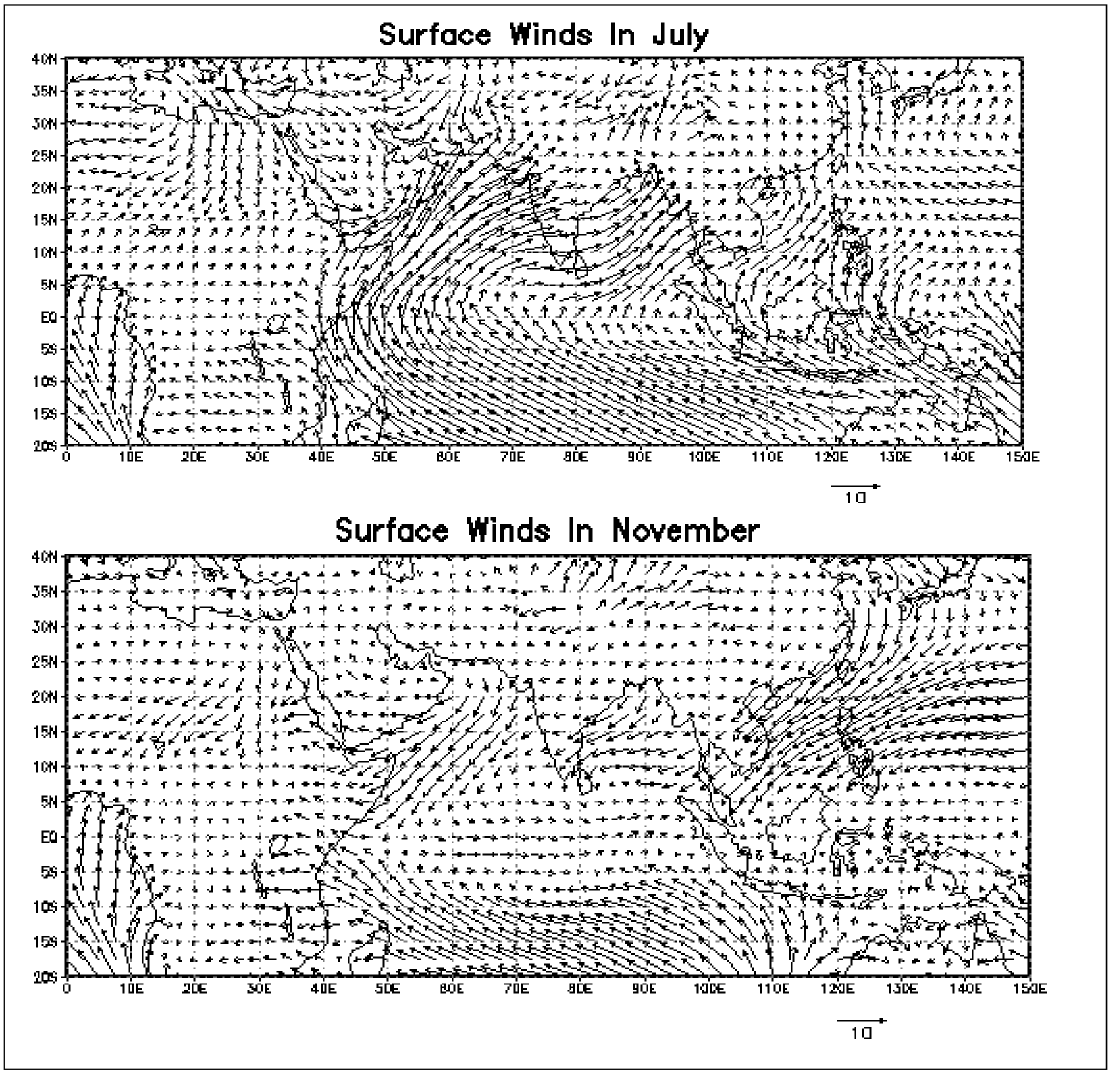

Since the average rainfall over the Indian region is by and large restricted to the summer monsoon season (*Figure* 2), there is a large impact of the variation of the summer monsoon on the agriculture and economy of the country. Naturally, the summer monsoon is the focus of most of the studies of the Indian Monsoon. In the next section, I consider year-to-year variation of the observed all-India summer monsoon rainfall and its impact. The spatial variation of the rainfall over the country is discussed in Section 3 and the rainfall variation within the season in Section 4.

Figure 3. Average surface winds in July and November.

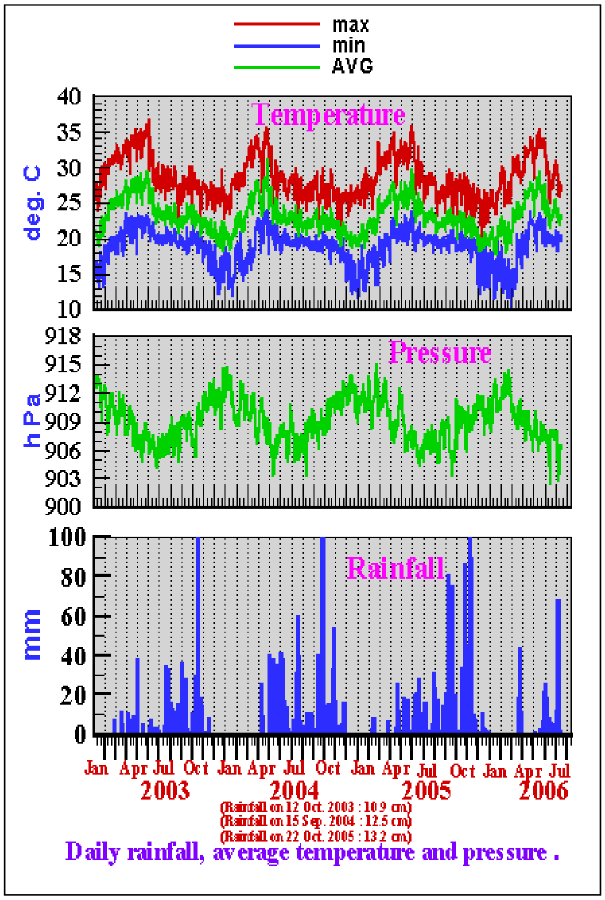

Figure 4. Variation of the temperature (maximum, minimum), surface pressure and rainfall on the roof of CAOS, IISc.

2. Inter-Annual Variation of All-India Summer Monsoon Rainfall

The inter-annual (year-to-year) variation of the all-India average summer monsoon rainfall (henceforth ISMR), can be readily derived from the data available from the website of the Indian Institute of Tropical Meteorology, Pune (www.tropmet.res.in). The long term mean of ISMR is about 85.4 cm and the standard deviation is only 10 % of the mean. Thus when we consider the Indian region as a whole, the summer monsoon is rather dependable. From 1872 to date, it has never been less than 70% and never more than 120 % of the average rainfall. Meteorologists refer to the difference between the observed value of any variable for a specific period (such as a month or season), and the average for the period as the 'anomaly'. Years in which the anomaly of ISMR is negative (i.e. the rainfall is lower than the average), and the magnitude of the anomaly larger than one standard deviation (i.e. 10 % of the average) are called droughts. The opposite extreme, i.e. excess rainfall is said to have occurred when the summer monsoon rainfall is above average and the magnitude of the anomaly is larger than 10 % of the average.

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The variation of the anomaly of ISMR for 1872-2004 is shown in *Figure* 5, in which the droughts and excess rainfall years have been indicated. This interannual variation of the summer monsoon rainfall over the country as a whole, has always had a significant impact on the agricultural production and hence the economy of the region. Over fifty years ago, the Indian economy was described as a gamble on the monsoon rains. Despite the rapid growth of the population since then, the phenomenal

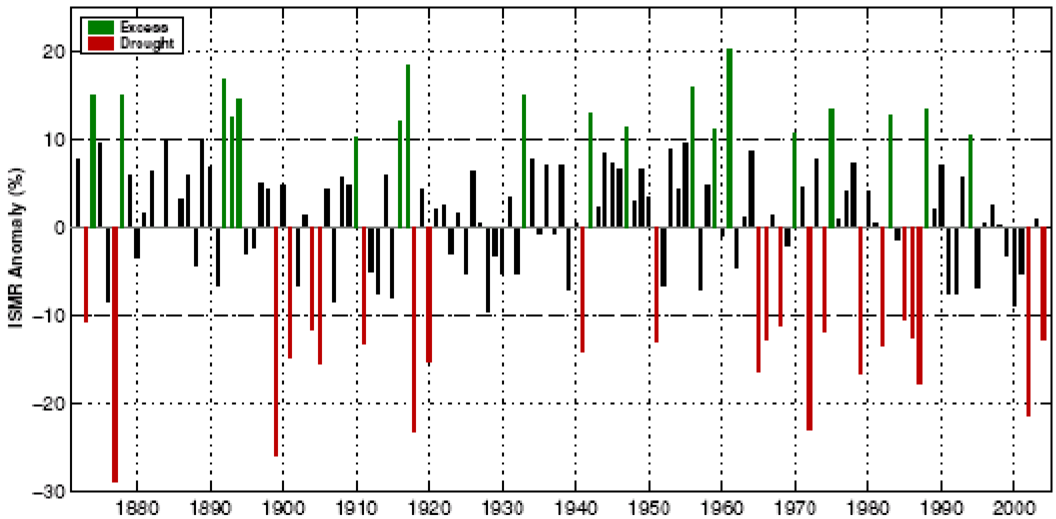

Figure 5. Variation of the anomaly (difference between the actual and the average) of the all-India summer monsoon rainfall (ISMR) from 1872-2004 .

increase in the agricultural production during the green revolution (*Figure* 6) ensured stability of per capita food-grain availability. However, it is seen from *Figure* 6, that the vagaries of the monsoon, particularly the droughts, continue to have a major impact on the total food-grain production even today, because a large part of the agricultural land is still rain-fed.

It is seen from *Figure* 5 that the frequency of droughts has changed considerably over the decadal time-scale. There were a large number of droughts during 1899–1920 and again during 1965–87; and relatively few in the interim. Whether we are entering another epoch since 2002 with high frequency of droughts remains to be seen. In fact one of the major challenges is the prediction of the summer monsoon rainfall and particularly of extremes, i.e. droughts or excess rainfall seasons. The need for prediction of the summer monsoon rainfall has been acutely felt by successive governments particularly in the wake of severe droughts, since the 1880s. Since then, efforts have been made by the official agency, India Meteorological Department, to predict the monsoon on the basis of the observed relationship of the monsoon rainfall with various features of the land/atmosphere/ocean in the season/s prior to the monsoon. Forecasts during the initial years were subjective and qualitative. It was Sir Gilbert

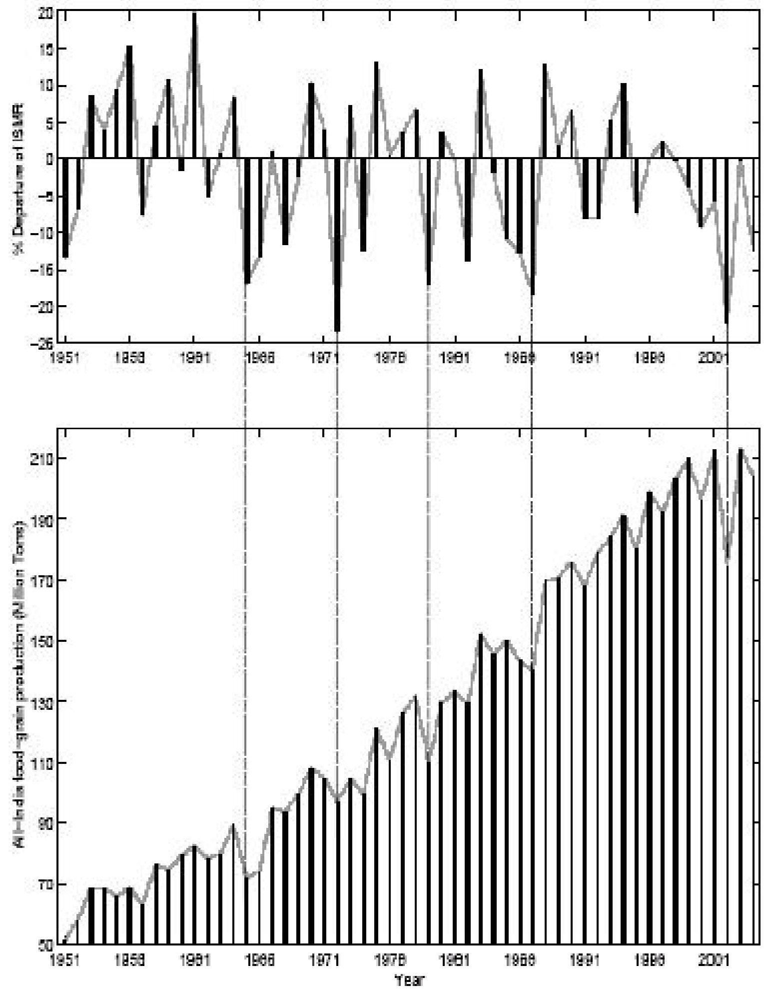

Figure 6. Variation of the all-India summer monsoon rainfall anomaly (as % of average) and the all-India food-grain production (million tons).

Walker who for the first time introduced an objective technique based on correlation and regression analysis to develop a statistical model for prediction in 1909. Sustained efforts at improving the statistical models by changing the predictors have been made for several decades, beginning with Walker himself. However, a recent study shows that the skill of these statistical models has not improved. Thus, while the contribution of Sir Gilbert Walker's discovery of the Southern Oscillation to the present day understanding of tropical variability (see Article-in-a-Box, p.3) is monumental, it appears that following in his footsteps and continuing to use the kind of statistical models he developed for monsoon forecasting has been far from successful.

The last three decades have witnessed enormous advances in atmospheric science and in the development of complex models of the atmosphere or the coupled ocean-atmosphere system based on laws of physics. Over the last decade, with development of models incorporating deeper understanding of the physics brought about partly because of continuous observations of and over critical oceanic regions, it has become possible to make reasonable predictions for the southern oscillation. However, despite these advances, prediction of the Indian summer monsoon rainfall remains a challenge even today. But we do expect major improvement in forecast skill in the next decade because of the rapid progress since the 1980s in understanding the nature of interannual variation of the monsoon and its links with phenomena over the Pacific and the equatorial Indian Ocean.

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3. Spatial Variation of the Rainfall over the Indian Region

Consider first the spatial variation of the mean June–September rainfall over the Indian region (*Figure* 7). We see that there is high rainfall (more than 200cm) along the west coast, over the Western Ghats and in the northeastern region which also has high mountains. The major rain belt during the summer monsoon extends northwestward from Orissa, to Rajasthan in the monsoon zone which is also shown in *Figure* 7. The year-to-year fluctuations of all-India rainfall arise primarily from the fluctuations of rainfall in the monsoon zone (*Figure* 8).

The all-India average rainfall is one measure of the monsoon. However, the variation of the seasonal rainfall is not coherent over the entire country. Generally, in normal years (i.e. with the magnitude of the ISMR anomaly<10% of the average) some regions experience above average rainfall, others suffer from deficit. During droughts, the rainfall over the vast majority of the subdivisions is deficit. This is illustrated in *Figure* 9 in which normalized anomalies of the summer monsoon rainfall for the

Figure 7. Average June–September rainfall in cm ; red curves bound the monsoon zone.

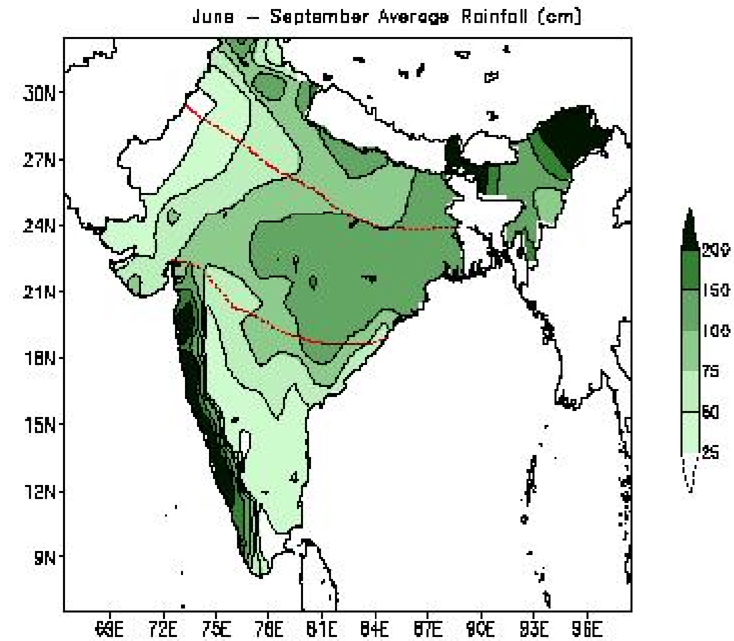
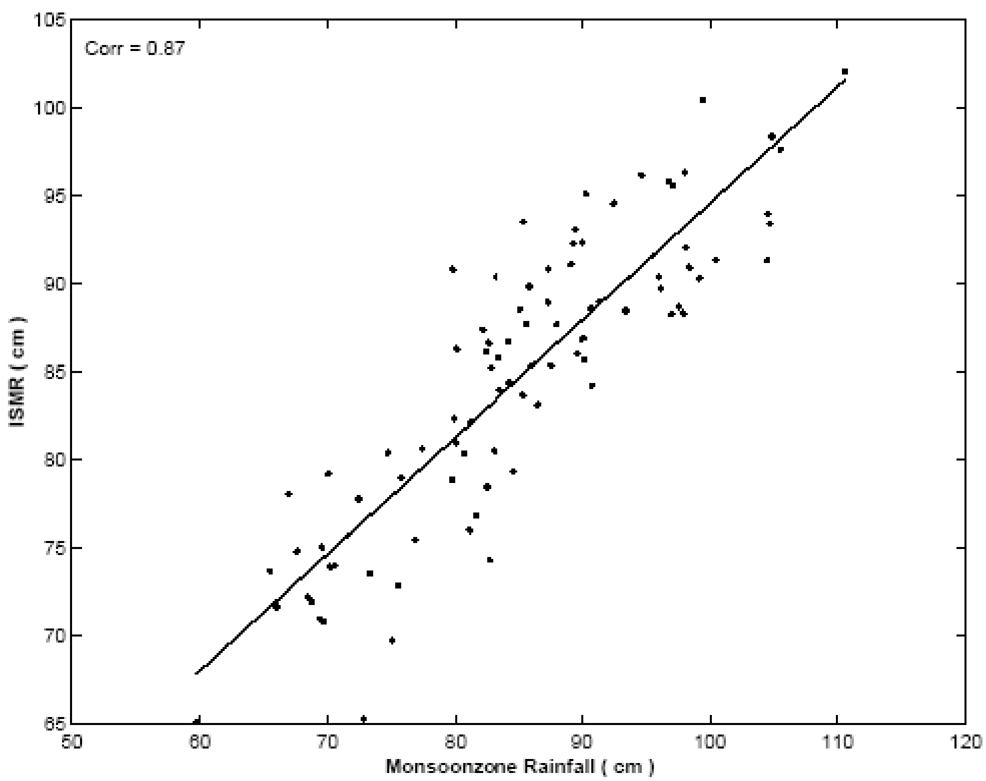


Figure 8. ISMR versus June–September rainfall over the monsoon zone.



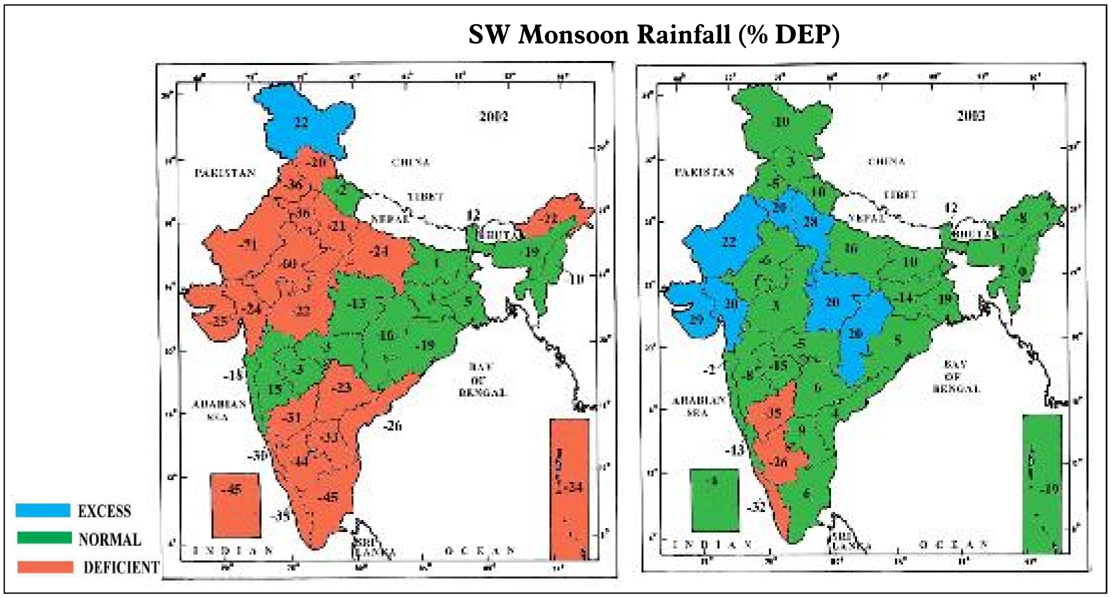


Figure 9. June–September rainfall anomaly patterns for 2002,2003: the anomaly of each meteorological sub-division is expressed as percentage of the average rainfall of that subdivision.

meteorological subdivisions of the country for the drought of 2002 and the 2003 normal monsoon season are shown.

So, if there is reliable prediction of extremes of ISMR (droughts or excess monsoon seasons), we could at least make an educated guess about the expected anomaly patterns on the sub divisional scale. While we expect some progress in the ability to predict ISMR in the near future, prediction at smaller spatial scales is far more difficult.

4. Variation over Sub-Seasonal Timescales

So far we have considered the variation of the total rainfall received in the summer monsoon season. However, for well over a century it has been known that the rainfall over the Indian monsoon zone fluctuates between active and weak spells. Blanford, who published an extremely thought-provoking account of the "Rainfall of India' in 1886, was the first to describe this sub seasonal variation between contrasting phases which he called "height of rains" and "intervals of drought". Blanford's 'intervals of drought' are prolonged dry spells which occur in some years and are called breaks by monsoon meteorologists.

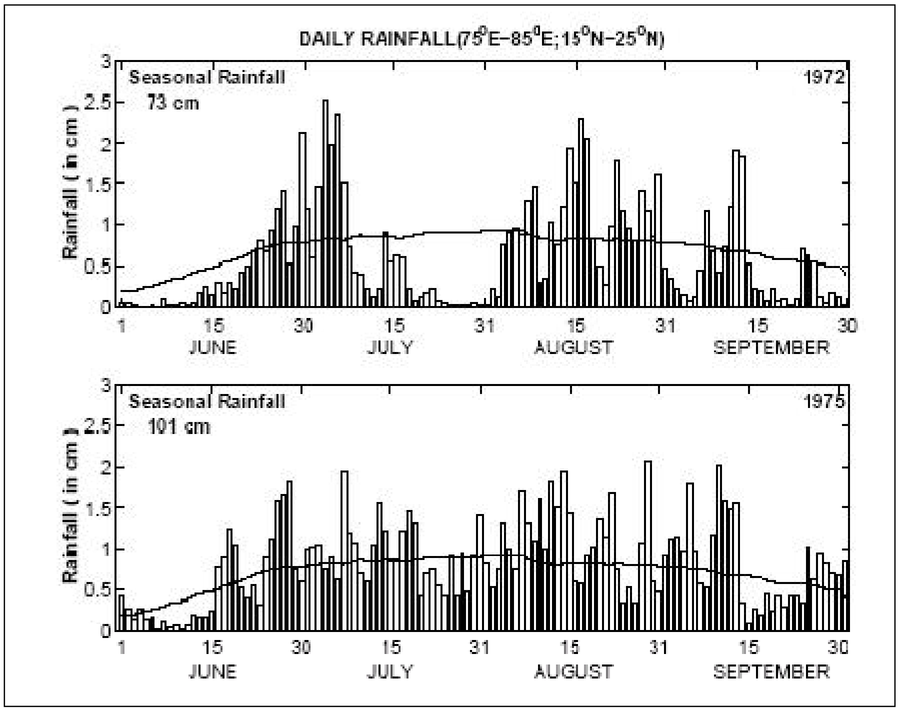


Figure 10. Variation of daily rainfall over central India during June–September for the drought of 1972 and the excess rainfall season of 1975. The long term average rainfall is shown as a continuous curve.

The daily variation of the rainfall over the central part of the monsoon zone during the poor monsoon of 1972 and bountiful monsoon of 1975 is depicted in *Figure* 10. The major difference between the daily rainfall in the monsoon seasons of the two years is seen to be the occurrence of such a break in 1972, suggesting that the deficit of ISMR in 1972 is linked to this break. A prolonged break in July 2002 led to an unprecedented deficit of 49% in the all-India average rainfall in July. Thus the fluctuations in rainfall over the monsoon zone on the sub-seasonal scale are linked to and could determine the inter-annual variation of ISMR. This is not surprising since the ISMR is the integral of the rainfall over these time-scales. However, while breaks occur in several drought years, there have been droughts, such as the one in 1987, during which there were no breaks.

Prolonged dry spells or breaks have a very large impact on agriculture. Prediction of when the break will end and rainfall revive is very important for farmers.

Concluding Remarks

Any theory of the monsoon has to explain the nature of the spatial variation of (i) the seasonality of rainfall (*Figure* 1) as well of (ii) the rainfall received in the summer monsoon (*Figure* 10). Even more importantly, the mechanisms responsible for the variation of the monsoon in terms of local feedback as well as links to systems outside the Indian monsoon region have to be unravelled. In the following articles of the series, we shall see that the theory of the monsoon as a gigantic sea breeze, taught to us as a part of geography at the high school and college level, cannot explain the observed space-time variation of the monsoon rainfall. We will see that it is more appropriate to attribute the mon-soon to the visit onto the subcontinent of a planetary scale system observed over the other tropical regions as well. We will consider what makes possible the organization of the clouds that give us rainfall in synoptic scale systems (like lows, depressions and cyclones) as well as the planetary scale system associated with large scale rainfall on the Indian monsoon zone. We will also elucidate the important role of instabilities in these systems which makes the problem of predicting the rainfall on different time scales far more difficult than, for example, prediction of the orbits of the planets.

Suggested Reading

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