The Indian Monsoon

3. Physics of the Monsoon

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Keywords
Monsoon, land-sea breeze, tropical circulation, seasonality of wind and rain.

We, in the monsoonal regions of the world are concerned about the variation of rainfall in space and time[1] and a major aim of monsoon meteorology is to predict these variations. Understanding the basic system responsible for the monsoon and the factors that lead to its variation is a prerequisite for developing models to generate these predictions. In this article, I discuss the basic system responsible for the monsoon – the wind and the rains.

Introduction

The word 'monsoon' is derived from the Arabic word '*mausam*' for season and the distinguishing attribute of the monsoonal regions of the world is considered to be the seasonal reversal in the direction of the wind[1]. For the hundreds of millions inhabiting the monsoonal regions of the world such as ours, seasonality of rainfall (*Figure* 1) is a far more important attribute of the monsoon than the seasonal reversal of winds, and in common parlance, the word monsoon is used for the rainfall in the rainy season. In this article, I discuss the basic system responsible for the monsoon – the wind and the rains.

Clouds can get generated only when the moist air near the surface of the earth is lifted up to a level at which it can get saturated and water vapour in the air begins to condense[2]. Thus vertical ascent of moist air near the surface is a necessary (but not sufficient) condition for clouds and hence rainfall. The basic source of energy for atmospheric circulation is the radiation from the sun. Since the atmosphere is almost transparent to the incoming radiation, it gets absorbed primarily at the surface of the earth, be it land or ocean. The atmospheric circulation is therefore a

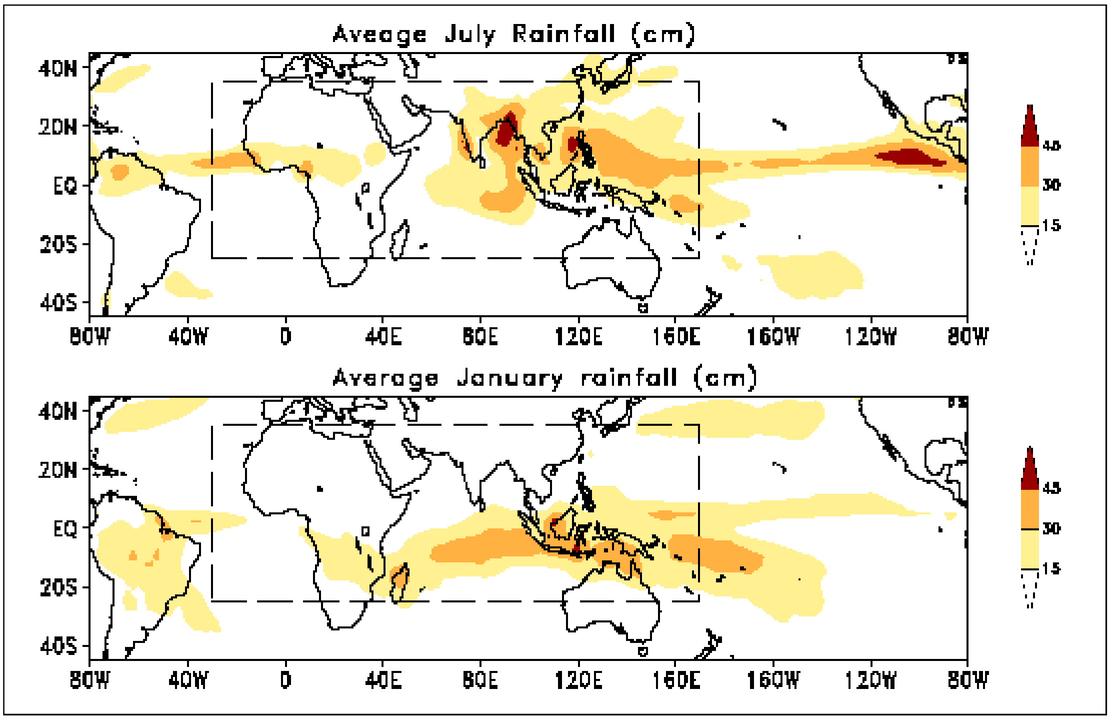


Figure 1. Observed average rainfall in January and July. The box indicates the monsoonal region as defined by Ramage 1971 [1].

response of the atmosphere to heating from below. The heating at the surface of the earth is not uniform but varies with the latitude because of the variation of the incoming radiation. Over the same latitudinal belt, it varies between land and ocean because the heat capacity of the land is much smaller than that of the ocean. The variation of heating at the surface leads to a circulation with ascent over the region of maximum heating. The two major hypotheses for the basic system responsible for the monsoon differ in what is considered to be the most important factor for generating the variation of surface heating and hence ascent of surface air. According to the first hypothesis, the primary cause of the monsoon is the differential heating between the continental and the oceanic regions and the basic system is a gigantic land-sea breeze. According to the second hypothesis, the critical force is the latitudinal variation of the heating at the surface, induced by that of the radiation from the sun. The monsoon is considered to be a manifestation of the seasonal variation of the resulting circulation and rainfall in response to the seasonal variation of the incoming radiation. Before considering each of these hypotheses

[1] Part 1. Variations in Space and Time, *Resonance*, Vol. 11, No. 8, 2006.

[2] Part 2. How do we get Rain? *Resonance*, Vol. 11, No. 11, 2006.

in the light of the observations about the monsoon and its variability, it is necessary to understand the nature of the response of the tropical atmosphere to heating from the surface which varies in space.

Response of a Tropical Atmosphere to Heating from Below

From school geography lessons, we know that seasons arise because the earth's axis (around which it rotates with a period of one day) has a tilt relative to the ecliptic.

From school geography lessons, we know that seasons arise because the earth's axis (around which it rotates with a period of one day) has a tilt relative to the ecliptic (orbital plane of the earth around the sun) of 23.45°. The latitude at which the sun is overhead varies with season from that of the Tropic of Cancer (23.45° N) on 22 June, the northern summer solstice, to the Tropic of Capricorn (23.45° S) on 22 December, the northern winter solstice. The net radiation (i.e. the difference between the absorbed solar radiation and the emitted terrestrial radiation) at the top of the atmosphere is maximum over a belt around 20°S during the northern winter (December–February), 20°N during the northern summer (June–August) and over the equator for the annual average.

Consider first an idealized case in which we assume that there is no variation in the radiation with season, i.e. the sun is assumed to be always overhead over some latitude, which we take to be the equator (corresponding to the annual average heat source). We further assume that conditions at the surface of the earth do not vary with longitude and so axisymmetric flow (i.e. in which the winds do not vary with longitude) is a possible solution. If in addition, we ignore the rotation of the earth, the problem becomes the classic Benard convection problem (or the so-called porridge problem) of a fluid heated from below. The nature of the response of the fluid depends upon the value of the non-dimensional Raleigh number (Ra), which is a measure of the forcing by the imposed temperature gradient *vis-á-vis* the viscosity and conductivity of the fluid. When the viscous effects dominate (as for a thick '*sambar*' or porridge), the Ra number is small and there is no convection; the *sambar* gets burnt over the hot part of the

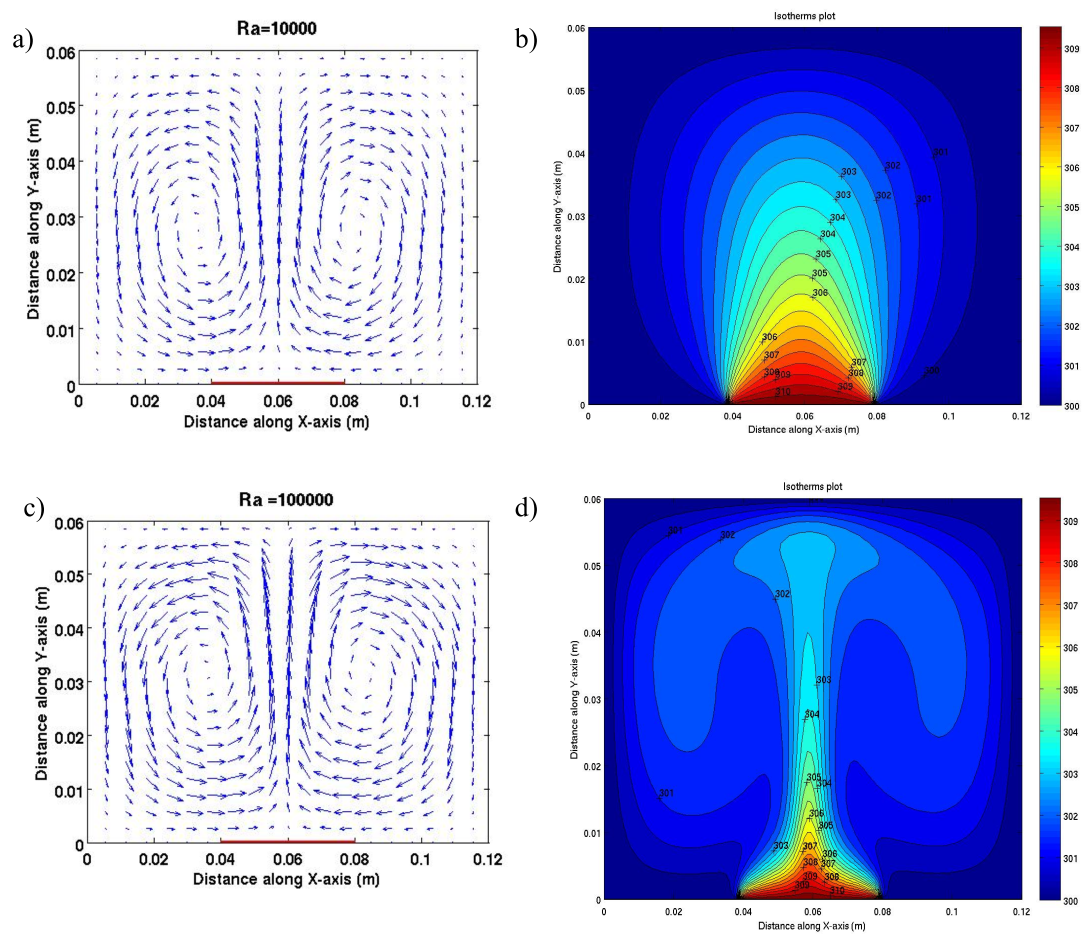


Figure 2. Solution of the Benard convection problem with a part of the bottom plate (shown as red) maintained at 310K while the rest of the bottom plate and the lid and side walls are at 300K. Circulation and temperature for
Ra = 10,000 (a,b);
Ra = 100,000 (c,d).
(Courtesy: M Chandra Mouli, Mechanical Engineering, IISc, Bangalore.)

bottom plate. As the Ra number increases the fluid begins to convect. The solution of the governing equations for the flow of a fluid driven by heating of a part of the bottom plate of the container (assuming that a part of the bottom boundary is at 310° K while the rest of that boundary, the two side walls as well as the lid are at 300° K) is shown for two cases with differing values of the Raleigh number in *Figure* 2. The convection is characterized by the fluid rising above the heated region and sinking elsewhere. The circulation is completed by the fluid converging to the low pressure over the heated region at lower levels and diverging at the higher levels. Note that for very large Ra the rising zone is much narrower than the region over which the fluid sinks.

When we consider the response of the real atmosphere, we need to incorporate two important additional factors. Firstly, the variation of the temperature with height of the atmosphere is such that it is stable with respect to a vertical displacement of a parcel of dry air, i.e., it is stably stratified[2]. Secondly, the rotation of the earth becomes important when we consider circulation on the large scale. Schneider and Lindzen's [2] solution for such an atmosphere driven by the variation of the surface temperature with latitude indicates that the circulation (with rising above the hot region and sinking elsewhere) extends only over the lowest 2–3 km and not throughout the troposphere as suggested by *Figure* 2. Such a low pressure region associated with a shallow circulation is called a 'heat low' by meteorologists. A heat low is a characteristic of deserts such as the Thar or Sahara over which the hot air ascends only in a shallow layer near the surface (about 3 km or less). Above this level, over the heat low, there is descent of air driven by the radiative cooling (which has to be balanced by the heat released due to adiabatic compression of the descending air)[2]. This descending air precludes the genesis of deep clouds and there is no rainfall.

In fact, the circulation extends throughout the troposphere only when the air is moist (as in reality) and the ascent is strong enough to lift the surface air to the level at which condensation begins. Consider the case of an ocean covered earth, i.e., an aqua-planet for which the entire surface is a source of water vapour for generating clouds and rain. We assume that the sea surface temperature (SST) is maximum at the equator and decreases with latitude in either hemisphere. This would lead to a low pressure belt around the equator with winds near the surface blowing towards this trough from both the hemispheres. Air would rise in the trough over the equatorial region. If there is enough moisture in this air, and the ascent is strong enough, the conditional instability of the tropical atmosphere[2] will be tapped and this will result in deep convective clouds and rainfall over the trough zone. This tropical cell known as the Hadley Cell, is schematically shown in *Figure* 3. The zone of ascent of the Hadley Cell,

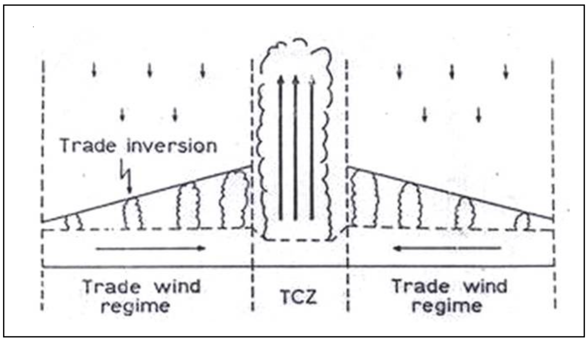


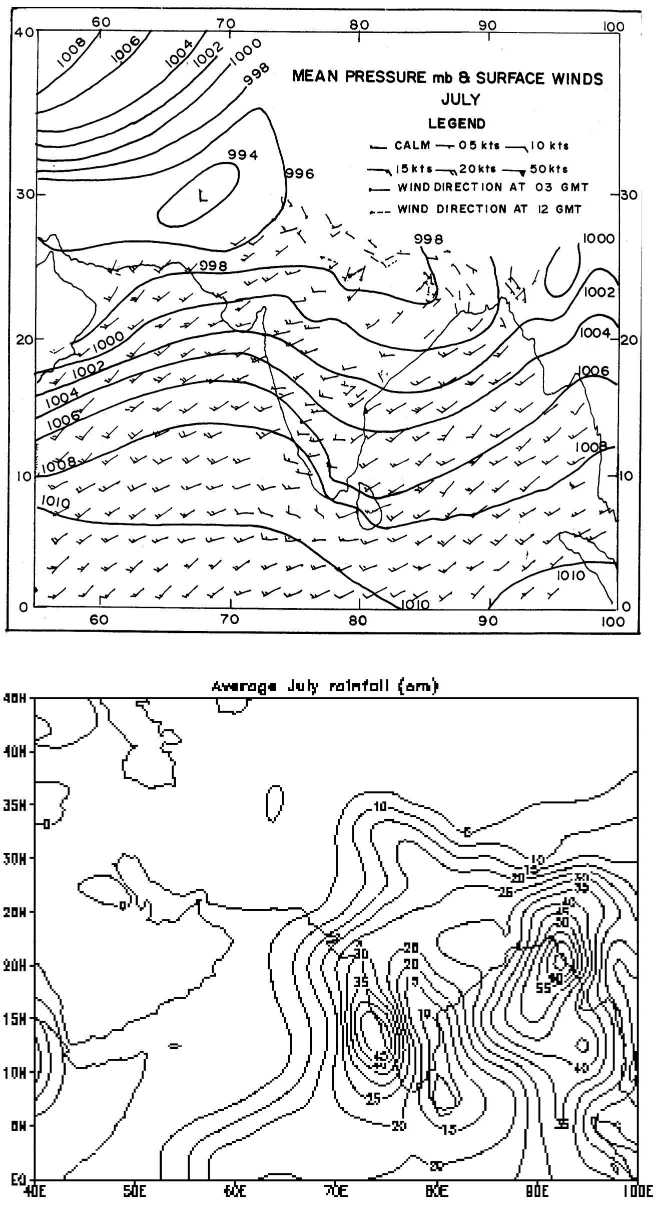
Figure 3. Schematic view of the axisymmetric (i.e. average over longitudes) tropical circulation:Hadley Cell.

characterized by deep convective clouds, has been called the equatorial trough by Riehl [3] who made fundamental contributions to our understanding of tropical deep convection. Charney [4], who first pointed out the critical role of the positive feedback between the strong convergence of air in the lower layers of the atmosphere on the large scale and intense clouding and rainfall associated with the strong ascent over the zone, uses the more common term 'the Inter Tropical Convergence Zone (ITCZ)'. The major rain belt in the tropics is associated with the ITCZ or equatorial trough. In this idealized case we expect a ribbon of deep clouds girdling the earth over the equatorial regions.

In reality, we are not on an aqua-planet and there is a large variation in the nature of the surface of the earth with longitude, with continents and oceans occurring side by side in the same latitudinal belt. Thus, although the incident radiation is the same, the conditions at the surface which drive the atmospheric circulation vary with longitude. In this situation, the response of a tropical atmosphere to heating from the lower boundary is either (i) ascent throughout the troposphere i.e. of the ITCZ type or (ii) heat low type circulation associated with ascent restricted to the lower 2–3 km.

In fact, heat lows and equatorial troughs (or the ITCZ) together comprise a continuous low pressure belt at the surface [1]. This is also clearly seen in the surface wind and pressure pattern for July over the Indian region (*Figure* 4). The well-marked low over the northwestern region is a heat low, which together with the low

Figure 4.
a) Average pressure (shown as contours of equal pressure i.e. isobars) and winds (the speed is indicated by the number of notches at the head of the vectors and the direction is from this end) at the surface in July.
b) Average rainfall in July (in cm).



pressure belt extending westward from the head of the Bay of Bengal (which is associated with organized convection and rainfall, *Figure* 4b) makes up the surface trough zone over the Indian region. Although heat lows also play an important role in determining the direction of the surface wind, most of the variability

(60%) of the tropical circulation, and convergence comes from the space time variation of the ITCZ [5].

So far we have ignored the seasonal variation of the radiation arising from the variation of the latitude at which the sun is overhead. Since the distinguishing attribute of the monsoon is the seasonality of the wind and the rain, the response of the atmosphere to variation of the pattern of heating of the bottom boundary with time associated with the seasonal variation of the radiation has to be considered. I consider next the first hypothesis for the monsoon as a gigantic land-sea breeze occurring in response to the differential heating of land and ocean in the summer hemisphere.

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Monsoon – A Gigantic Land-Sea Breeze?

Over three hundred years ago, in 1686, Edmund Halley (better known for the comet named after him) published a paper entitled "An historical account of the trade-winds and monsoons observable in the seas between and near the tropics with an attempt to assign the physical cause of the said winds" in which he suggested that the primary cause of the monsoon was the differential heating between ocean and land. For the same amount of radiation incident on the surface of land and ocean, the surface of the land gets much hotter than that of the ocean because land has a much smaller heat capacity than the ocean. Such a heating of the land relative to the surrounding sea would lead to rising of the air over the hot land and sinking over the cooler sea. The associated circulation at the surface would be a breeze from the sea to the land (called the land-sea breeze) since the atmospheric pressure over the heated land surface would be lower. At night, when land cools more rapidly, the sea is warmer and the breeze is in the reverse direction, i.e., from the land to the sea. Halley and many scientists after him considered the monsoon to be a gigantic land-sea breeze in which the ascent of air (and hence clouds and rainfall) over the heated land is generated by the land-ocean temperature contrast. In 1735 Hadley modified the theory to incorporate the impact of the Coriolis force arising from the rotation of the earth, which is important for the spatial scales of thousands of kilometers characterizing the monsoon circulation[1].

Can the monsoon be considered to be a gigantic land-sea breeze? The major implication of such a hypothesis is that the intensity of the monsoon (in particular the associated rainfall) has to be directly related to the land-ocean temperature contrast. However, the observations of the space-time variations of the monsoon over the Indian region are not consistent with this expectation. As pointed out by Simpson [6] *"I believe very few educated people would have any difficulties in giving an answer to the question- what is the cause of the monsoon? They would refer to the high temperature over the land compared with that over the surrounding seas; would speak of ascending currents of air causing an indraft of sea-air towards the interior of the country. It is only when one points out that India is much hotter in May before the monsoon sets in than in July when it is at its height – or draws attention to the fact that the hottest part of India – the northwest gets no rain at all during the monsoon – or shows by statistics that the average temperature is much greater in years of bad rains than in years of good rains, that they begin to doubt whether they know the real cause of the monsoon."*

Subsequent studies have clearly shown that the land surface temperature is higher when there is less rainfall during the summer monsoon and lower when the rainfall is higher [7]. This is clearly brought out in *Figure* 5 in which the patterns for the anomalies (defined as the difference between the actual and average value) of rainfall and surface temperature for the drought monsoon season of 2002 are shown. This is consistent with our experience in the rainy season, that days without rain are hotter than rainy days. Clearly, rather than the land surface temperature determining the amount of rainfall via the impact on the difference between land and ocean temperature, the land temperature is determined by the rainfall (or lack thereof).

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Thus, the observations suggest that the land surface temperature varies in response to the variation in rainfall and it is not appropri-

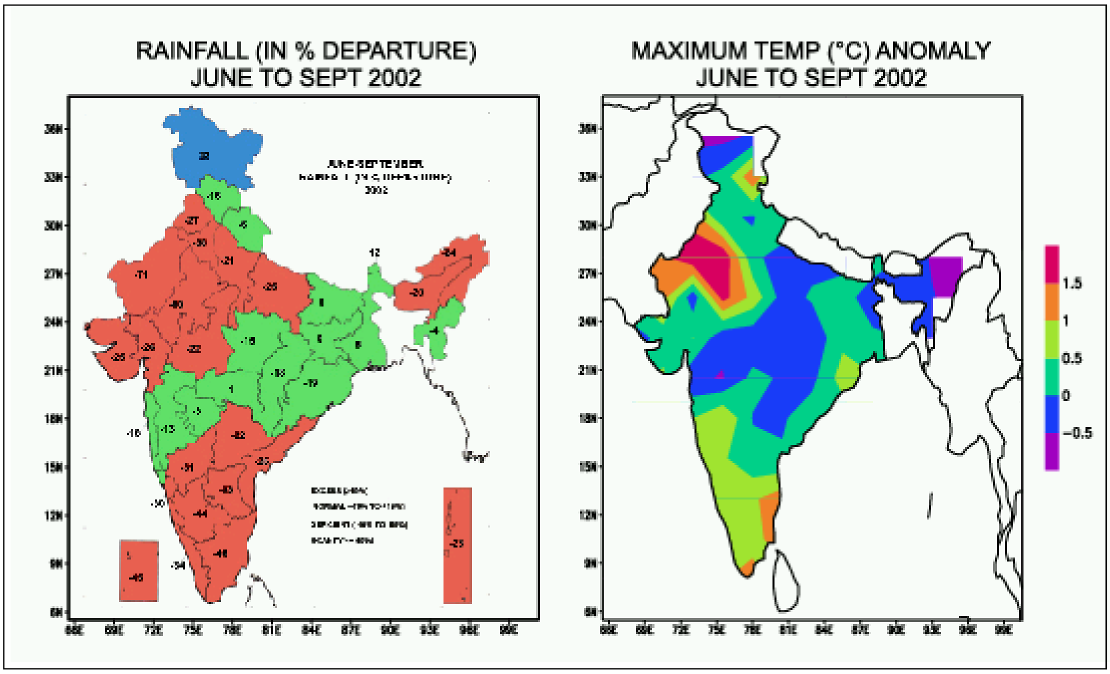

Figure 5. Rainfall anomaly expressed as a percentage of the average rainfall (left) and anomaly of maximum temperature in °C (right) for the summer monsoon (June–September) of 2002.

ate to consider land-ocean temperature contrast as a cause of the monsoon rains. In other words the observations are not consistent with the land-sea breeze hypothesis.

Monsoon: Seasonal Migration of the Major Rain Belt?

It should be noted that an important characteristic of the land-sea breeze hypothesis is that it associates the monsoon with a system special to the monsoonal region. On the other hand, according to the alternative hypothesis, the basic system responsible for the monsoon rainfall is the same as that which is associated with large-scale rainfall over other (non-monsoonal) regions of the tropics. The monsoon is considered to be associated with the seasonal migration of the major tropical rain belt (associated with the ITCZ or equatorial trough) in response to the seasonal variation of the incident solar radiation. The monsoonal regions are characterized by a larger amplitude of the seasonal variation than that of the other tropical regions.

We can now consider the response to seasonal variation of the

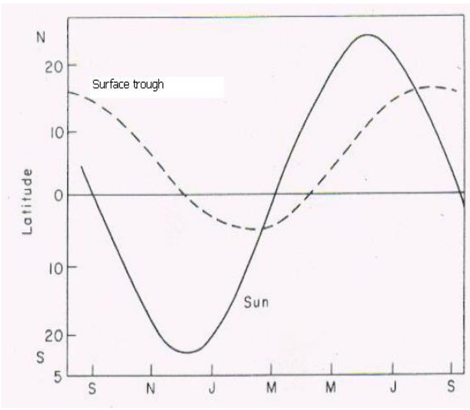

Figure 6. Variation of the latitude of the surface pressure trough (averaged over all longitudes) and the latitude at which the sun is overhead with time; the months are indicated on the x-axis.

radiation from the sun. We expect the maximum heating at the surface and hence the equatorial trough (ascending limb of the Hadley Cell) to be located around 20 N in the northern summer, and around 20 S in the southern summer. The variation of the average location of the surface trough (when averaged over all longitudes) and the zenithal position of the sun with time is shown in *Figure* 6. It is seen that the surface trough migrates with season in response to the seasonal variation in the sun's zenith angle, albeit with a lag of about two months. Also, the amplitude of the seasonal variation of the latitudinal location of the (longitudinally averaged) surface trough is smaller.

If indeed the seasonal migration of the ITCZ were as expected from the zonal average (i.e. average across all the longitudes) we would see seasonal reversal of winds over a large belt across the tropics. However, while the observed amplitude of the seasonal migration of the surface trough is very large over the Asian longitudes, there is hardly any change with season over some oceanic regions such as the east Pacific (*Figure* 7a). *The regions over which the amplitude of the seasonal variation of the trough is large, are the monsoonal regions.* Why is the amplitude of seasonal migration larger over the monsoonal regions than the tropical oceans? This is because, while over the continental regions the heating from the surface tends to be maximum at the latitude at which the net radiation is maximum, the surface temperature of the oceans (*Figure* 7b) is determined not only by the net radiation but also by the winds because they drive the ocean circulation. These non-monsoonal regions arise because despite the seasonal variation in net radiation, the location of the maximum sea surface temperature of these oceanic regions does not vary with season.

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Evidence for the validity of the second hypothesis, i.e., that the monsoon is a manifestation of the seasonal migration of the ITCZ

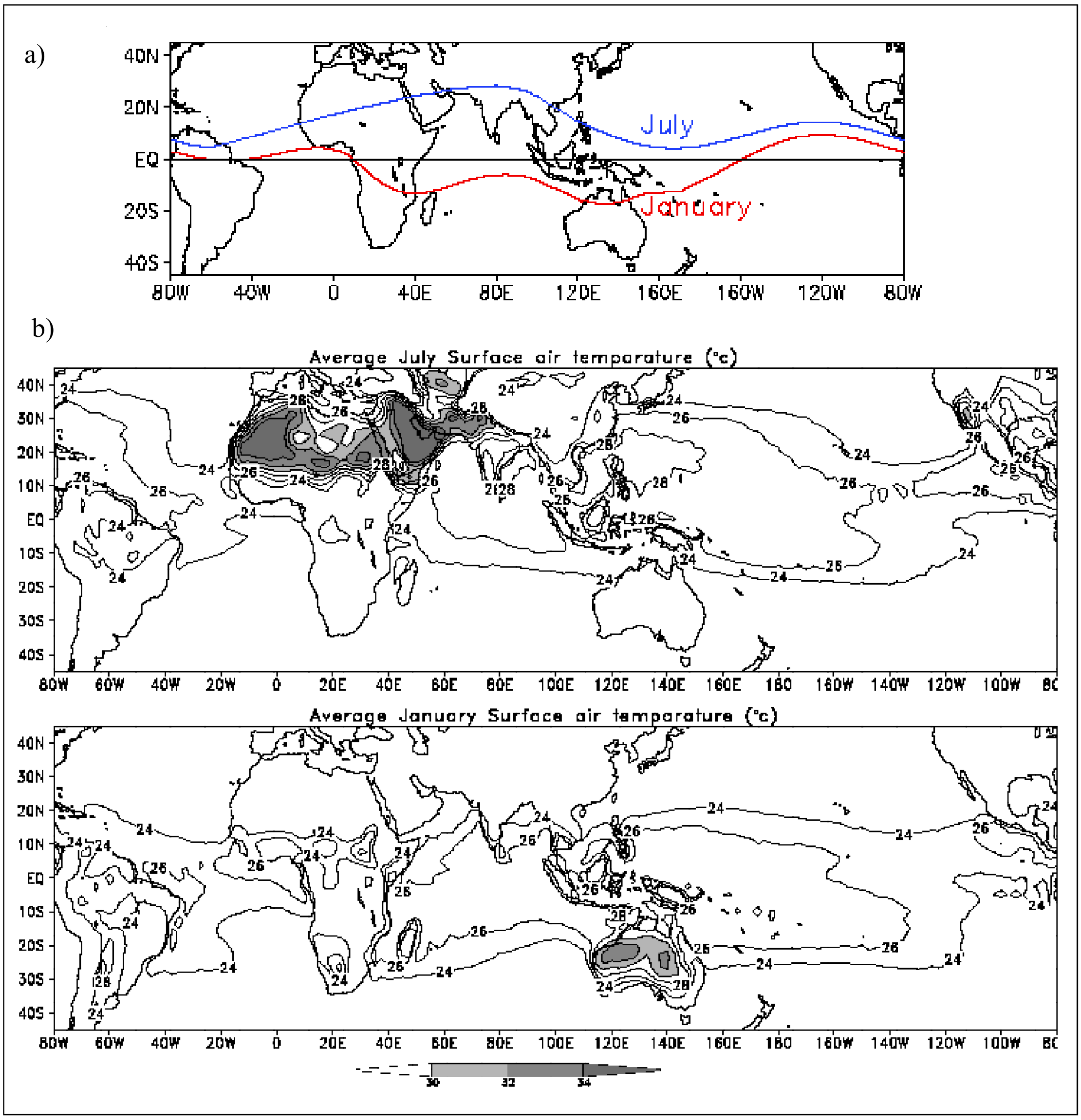

Figure 7.

a) The location of the average surface trough in July and January.

b) Variation of the average surface air temperature in January and July.

was first provided by a study of the daily satellite imagery over the Indian longitudes by Sikka and Gadgil [8]. They showed that (i) the cloud band over the Indian subcontinent on an active monsoon day is strikingly similar to that characterizing the ITCZ over other parts of the tropics and (ii) dynamically the system has all the important characteristics of the ITCZ [3]. In particular it was demonstrated that the monsoonal cloud band had the critical characteristics required for tapping the conditional instability of the tropical atmosphere and generating deep clouding on the planetary scale associated with the ITCZ, i.e., intense cyclonic vorticity above the boundary layer and low level convergence in the boundary layer. The large-scale rainfall over the Indian monsoon zone is directly related to the cyclonic vorticity above the boundary layer [9]. These observations lend support to the second hypothesis which considers the monsoon as a seasonal migration of the ITCZ**.** The variation of the rainfall associated with the monsoon is a manifestation of the space-time variation of the ITCZ.

Note that during the summer monsoon, the surface trough over the Indian region extends northwestward from the head of the Bay of Bengal to the low (994 hpa) around 30°N 70°E (*Figure* 4a). The eastern part of this trough is associated with a ITCZ while over the northwestern region there is a heat low. Unraveling the factors that determine the transition from a heat low type circulation in space and time, is a problem of great relevance to the Indian monsoon. Before the onset of the monsoon, the Indian monsoon zone (the Indian region north of Mumbai which is the core region for monsoon rainfall) is characterized by the presence of a heat low. At the end of the onset phase, a tropical convergence zone gets established over the region. During long intense mid-seasonal dry spells, a heat trough gets established over the Indian monsoon zone. Revival from such breaks again involves a transition from a heat trough to a moist convective regime characterizing an ITCZ. On the seasonal scale, the boundary between the heat low regions over the northwestern part of India and the moist convective regions over the eastern part of the monsoon zone also exhibit significant variation from year to year. In poor monsoon years the boundary between the moist convective regime and the heat low retreats eastward and large negative anomalies appear over the western part of the monsoon zone.

Simulation of the average rainfall associated with the Indian summer monsoon as well as its variation from year to year has remained a challenge despite the rapid development of complex dynamical models of the atmosphere in the last two decades. The results of an international intercomparison experiment with 20 state-of-the-art models showed that while some models get the rain belt over Indian region (although to the south of the observed in some cases), one class of models (e.g. UGAMP model in *Figure* 8) simulates a heat trough over the Indian region with the rain belt situated over the warm equatorial Indian Ocean to the south of India [10]. The factors/ processes that govern the transition from a heat trough to the moist convective regime (ITCZ) in the models are yet to be completely understood.

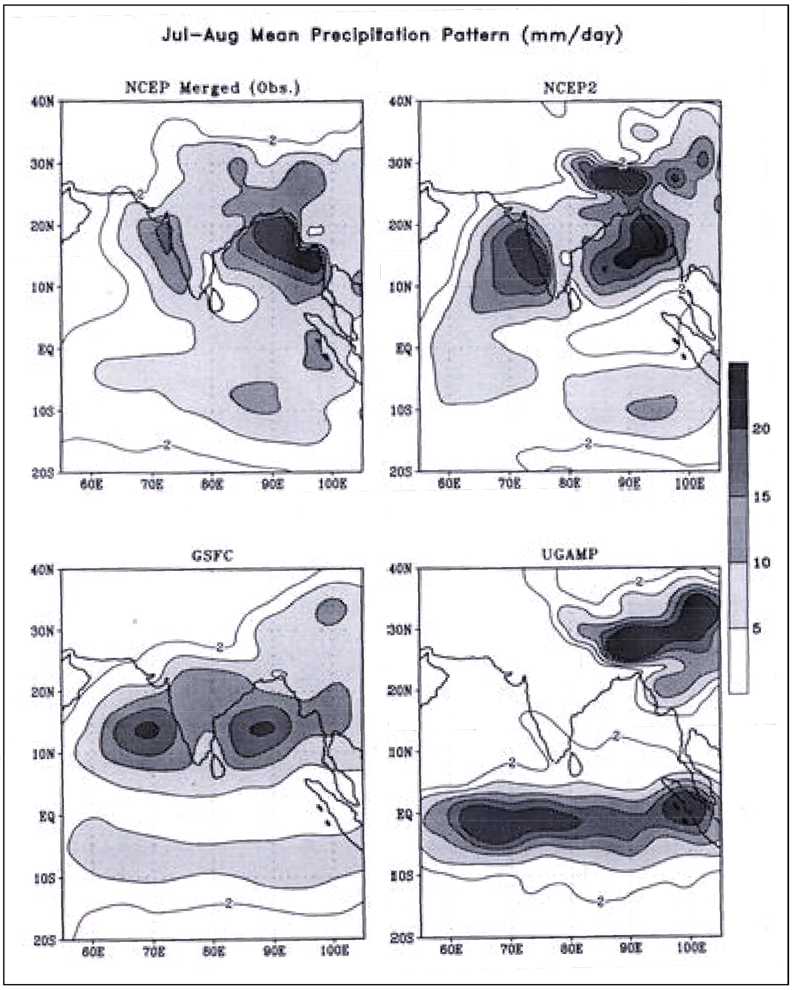

Figure 8. Observed (top left) and simulated July–August average rainfall (mm/day) for three typical models; note particularly the simulation by the UGAMP model.

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Seasonality of Winds and the Monsoon Seasons over the Indian Region

Consider the seasonality of the winds associated with the seasonal migration of the surface trough in response to the seasonal variation in the radiation from the sun. The low pressure belt is over the latitude at which the surface heating is maximum, which includes the heated monsoonal regions in the summer hemisphere. The winds at the surface are determined by the pressure gradient. So far we have considered only the two-dimensional

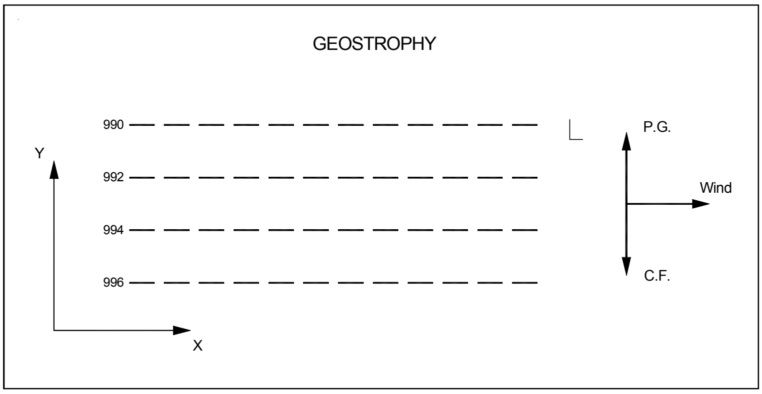

Figure 9. Schematic of geostrophic flow. The x-axis is east-west wtih increasing x corresponding to increasing longitude. The y-axis is south to north, with increasing y corresponding to the increase in latitude in the northern hemisphere. The dashed lines are contours of equal pressure (with the pressure in hpa indicated for each). The geostrophic wind resulting from a balance between the Coriolis force and the pressure gradient is shown to the right.

cell in the plane of latitude versus height and seen that the wind near the surface is towards the low pressure region and ascent occurs over this region (*Figure* 3). However, the components in the third dimension (i.e. along altitude circles at the same height) are also important because in the dynamics of scales such as the entire tropical belt, the Coriolis force arising from the rotation of the earth plays an important role. In fact, at levels above ~1 km from the surface, where friction becomes unimportant, the pressure gradient is balanced by the Coriolis force. The resulting flow (called geostrophic flow illustrated in *Figure* 9) is along the lines of equal pressure rather than down the pressure gradient as in non-rotating systems. In the layer near the surface, where friction is important, there is also a component down the pressure gradient (i.e. from high pressure to low pressure).

In the northern summer, if the equatorial trough or ITCZ is located around 25N, the geostrophic wind over the region south of the trough will be from the west. At levels below ~ 1 km in the atmosphere, friction becomes important and there is a component of flow down the pressure gradient. This implies that the surface wind over a large part of India, and the Arabian Sea as well as the Bay of Bengal is from the southwest (*Figure* 10a). Following the summer monsoon when the trough zone retreats to the south of the Indian subcontinent and a large part of these Indian seas, the region comes under the sway of the wind from the northeast (*Figure* 10b).

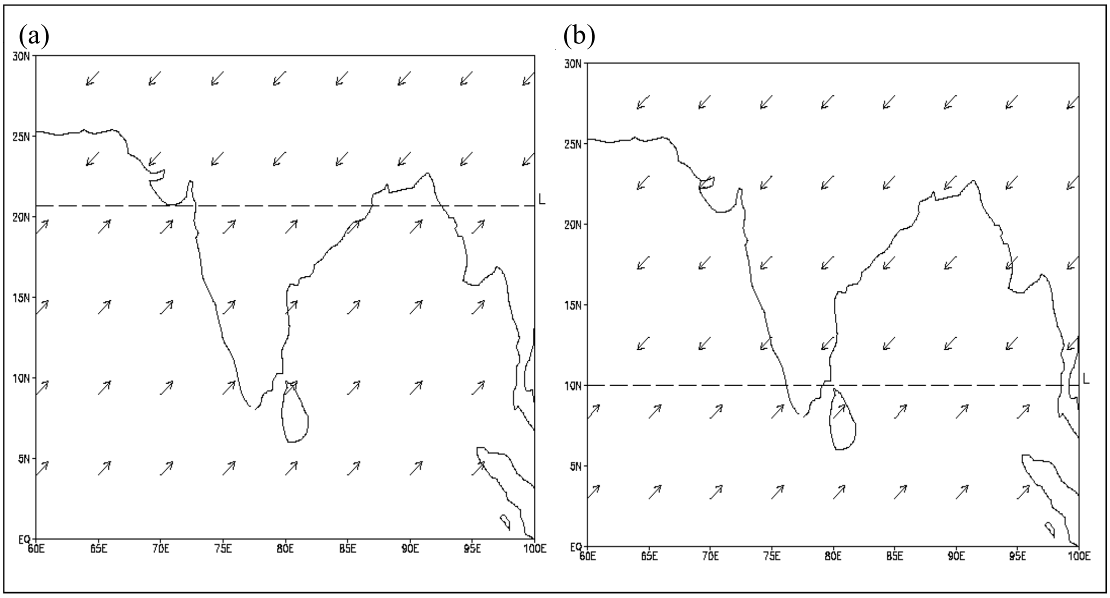

Figure 10. Schematic of the surface winds for (a) summer monsoon and (b) October–December seasons. Idealized situation in which the pressure varies only with latitude. The dashed line is the location of the minimum pressure, i.e., the trough. The ascending limb of the Hadley cell or the TCZ would be located in the low pressure belt around the trough. The winds in the surface layer have a geostrophic component (from east to west as in Figure 8) as well as a component from high pressure to low pressure which is from the south over the region south of the trough.

The summer monsoon season has been called the *southwest monsoon* based on the direction of the surface wind in the region south of the trough zone. However, it is important to note that in the same season over the region to the north of the trough zone, the geostrophic flow will be from the east and surface wind will be from the northeast. At the end of the summer monsoon, during October–December, the ITCZ retreats to the south and the surface wind is from the northeast over a large part of the Indian subcontinent and the surrounding seas and the season is called the *northeast monsoon* season. These names give the impression that we get rainfall from systems coming from different directions or, in some sense, from different kinds of systems or in the two seasons, although the system that gives us rainfall is the same in both the seasons viz. the ITCZ. Clearly it would be better to use the terminology summer monsoon for the June–September season and post-monsoon (or a more appropriate name which needs to be coined) for the October–December season.

Concluding Remarks

In this article I have tried to elucidate what I believe is the basic physics of the monsoon. In the next article I shall discuss the simulation of the Indian monsoon by complex models of the atmosphere based on the laws of physics and what we know about the physics of the variability of the monsoon.

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