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THE INDIAN MONSOON: RECENT INVESTIGATIONS

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Introduction

Various issues relating to the Indian monsoon have been a subject of intensive scientific investigation ever since the last quarter of the 17th century when the English scientist Edmund Halley postulated that the Indian monsoon was the outcome of the differential heating of land and oceanic areas, resulting in convectional uplift of moist air. This basic concept of the convectional system resulting from differential heating is, with some modifications, still accepted. However, scientists have made an extensive study of various aspects of the monsoon and its relationship with other weather phenomena. They have aimed particularly at predicting the monsoon with adequate accuracy and sufficiently in advance, so that steps may be taken to control the damage done by the erratic behaviour of the monsoon which has often caused devastating floods in one part of the country while severe drought brought death and disaster in another. A glaring example is provided by the year 1972 which saw the havoc caused by the floods in the states of Uttar Pradesh, Bihar, West Bengal and Kerala, while, ironically enough, some other parts constituting about 47 per cent of the country suffered from terrible droughts resulting in a loss of about one-third of the total food production. The impact of the monsoon on Indian economy necessitates an in depth study of its ramifications. Research, made possible by means now made available by modern technology has provided some insights into the mysteries of the complex phenomenon. A startling example is that of the relationship seen between the far off apparently unconnected phenomena- that of the Indian monsoon and El Nino and La Nina effects along the western coast of South America. An increased understanding of the role of Tibetan Plateau in the monsoon system and the influence of snowfall in Tibet are other interesting examples. Studies have also been made of rainfall over long term periods in the past and on the basis of cyclical variations in the past, predictions have been made about future. However, in view of the vastness of the country, spatial variation in monsoon rainfall and the extreme complexity of the monsoon system comprising a number of factors, dependable forecasts are not possible at present.

Monsoon: Meaning and Explanation

The term monsoon is derived from the Arabic word *Mausin* meaning season. The monsoon wind system is so named because of its seasonal change of direction. There is a reversal of the direction of the wind to the extent of 120° to 180° over a very large area of the world. The monsoon type wind blows from one direction in summer and from the opposite direction in winter. The reversal of direction in the Indian subcontinent is complete to the extent of 180° as a result of the following three factors: (a) land/ sea distribution; (b) latitudinal position and (c) the presence of hills and mountains at places most conducive to a complete change of direction.

Monsoon: The Basic Concept of the Convectional System

As stated above, the monsoon is a convection system resulting from the seasonal heating and cooling of land and sea surfaces. This is the original basic concept of the system advanced by Edmund Halley (O'Hare, 1997). It constitutes the traditional theory about the origin of the monsoon and is also known as the 'thermal concept.' Water has a higher specific heat than land, i.e. it needs relatively more heat than dry land to raise its temperature to the same extent. Moreover, as a liquid, it is better able to dispose heat absorbed by it. These two facts result in a reversal of direction of the monsoon with the change in the season from summer to winter.

Monsoon and Lower Tropospheric Air Flows in Summer and Spring

The sequence of lower tropospheric air phenomena in summer and spring is as given below: (a) As a result of the differential heating of land and oceanic areas as explained above, the annual cycle of surface heating for land surface in summer and spring in north west India is ampler than over oceanic surface in the Arabian Sea (Indian Ocean), (b) The air over the mass of land, being in contact with the land surface, gets heated, expands and ascends, thereby creating a depression. On the other hand, the air over the colder Indian Ocean absorbs less solar energy from the water surface below it and, being much cooler sinks and creates an anticyclone over the ocean. (c)The expanded warm dry air over land is of greater height and weight than the sinking compressed cold dry air mass over the ocean. The pressure of the former at a height of about 6 to 7 km from the surface is therefore, relatively high. Thus, over land the pressure is low near the surface and comparatively high at an elevation of say 6 to 7 kilometres. Conversely, over the ocean the pressure is high at the surface level and comparatively low at an elevation of 6 to 7 kilometres. To sum up, there is (i) over land a depression surmounted by an anticyclone at an elevation of about 6 to 7 km; and (ii) over the ocean, a high surmounted by a depression at an elevation of about 6 to 7 km. Pressure gradients inevitably lead to the flows of air and as air always flows from high pressure to low pressure areas, it has two parallel horizontal flows - one of cooler denser air on the surface from ocean towards the land and the other - a reverse flow - at about 6 to 7 km above the surface, from land to ocean. A circuit is thus completed and the so-called thermal direct cell is created. The pressure gradient at the elevation is stronger than the gradient at the surface. The air flowing from ocean to land sinks and lifts up the warmer air over land. Conversely, the air aloft at an elevation of 6 to 7 km flows from the land to the ocean. The circulation of air is named lower tropospheric circulation because it occurs in the lower part (6 to 7 km above the earth) of the 14 km deep troposphere.

Monsoon and Lower Troposheric Air Flows in Winter

A description has been given above of the low-level tropospheric thermal cell in spring and summer in the northern hemisphere. In winter there is a complete reversal of this situation. A strong high pressure cell develops at the land surface over north-west India and a low pressure is formed over the warmer ocean surface of the Indian Ocean. The land surface has an anticyclone surmounted by a depression at a relatively low elevation of about 3 km and the ocean surface has over it a depression surmounted by an anticyclone at an elevation of about 3 km. The back flow of air in winter is at an elevation of 3 km above the surface as compared with 6 to 7 km in spring and summer. The Figs 1 and 2 show the lower tropospheric flows of winds in winter and summer.

The lower tropospheric summer air flow from the Indian Ocean (Arabian Sea) towards north-west India, as described above, is that of rainy summer monsoon, while the lower tropospheric winter air flow in the opposite direction from north-west India to the ocean is that of dry winter monsoon winds over India.

Summer Monsoon Winds and Coriolis Force

Halley described the rainy summer monsoon as southerlies and the dry winter monsoon as northerlies (O'Hare, 1997). They blew, according to his account to and fro, between the Indian Ocean (south of Equator) and the north west of India. One omission on the part of Halley was that he did not take into account, the Coriolis force resulting from the rotation of the earth, which affects the direction of winds. George Hadley was the first scientist to apply the Coriolis principle to explain the deflection of the winds (Lutgens & Tarbuck, 2007). At all levels in the atmosphere the Coriolis force deflects winds to the right in the northern hemisphere and to the left in the southern hemisphere, so that the 'southerlies' while moving northward in the southern hemisphere, are deflected to the left, and become south-easterly trade winds. Later when they cross the equator, they are deflected to their right as south-westerlies. (Figs. 1 and 2)

South Westerly Monsoon and their Branches

As mentioned above, the south-easterly trade winds of the southern hemisphere after crossing the equator are deflected to the right and are termed south westerlies. Arabian Sea

Patterns of Surface Monsoon Winds in January

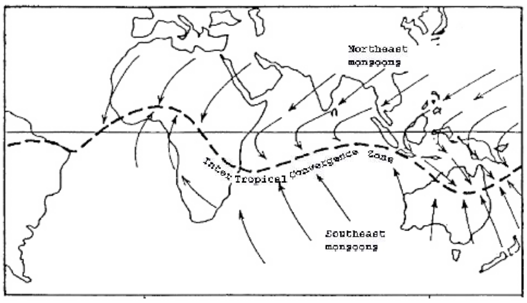

Fig. 1

Source: Adapted from O'Hare,G.(1997):"The Indian Monsoon Part 1", Geography, vol.82(3), July, 1997, p.223.

Patterns of Surface Monsoon Winds in july

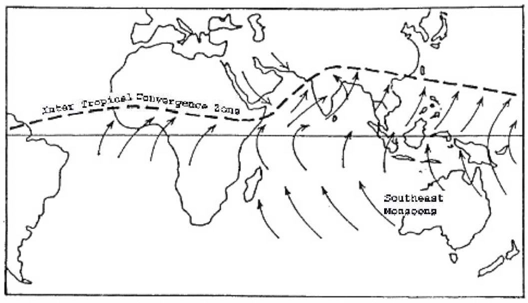

Fig. 2

Source: Adapted from O'Hare.G.(1997):"The Indian Monsoon Part 1", Geography, vol.82(3), July, 1997, p.223.

Branch and the Bay of Bengal Branch are the two main branches of south westerlies.

(a) Arabian Sea Branch

In India one of the branches of the westerlies, rising from the Arabian sea, strikes the Western Ghats and then crosses the Deccan. But a weak current of this branch of the westerlies flows towards north-west India to Rajasthan and reaches Punjab. This branch of the south westerlies is known as the Arabian Sea Branch.

(b) The Bay of Bengal Branches

The other branch of south westerlies, having its origin in the Arabian Sea flows round the southern tip of India and Sri Lanka and then moves north to the Bay of Bengal. This branch is named the Bay of Bengal Branch. It gets divided into two different currents: (i) one of the currents moves to the Gangetic Delta and then northward to Assam; (ii) The other current takes a turn to the west around the eastern end of the trough which takes shape in summer in northern India. It then moves on west-north-westward along the Gangetic plain towards the Punjab. Here it meets in weak current of the Arabian Sea Branch which had strayed northwards as stated above.

Winter Monsoon Winds and Coriolis Force

The Coriolis force applies also to the winter monsoons. Winter monsoon winds as moving over India from north to south, are deflected to the right as north easterly trade winds in the northern hemisphere and later, after crossing the equator are deflected in the southern hemisphere to the left in accordance with the Coriolis principle, as north westerly trade winds.

Dynamics of the Indian Monsoon

As stated above, the basic concept of differential seasonal heating and cooling of land and sea surfaces, formed the basis of the origin of the monsoon. But it called for a modification, which was the result of intensive investigations by American meteorologists. They investigated the factors other than the differential heating and cooling of land and sea surfaces, which were responsible for the terrific force of the summer monsoon. It was discovered that powerful forces driving the thermal monsoon were (i) latent heat release and (ii) shifting Inter Tropical Convergence Zone (ITCZ).

(i) Latent Heat Release

In the middle of the nineteenth century, particular emphasis was placed on the latent heat release concept. Warm air from the southern subtropical Indian Ocean moves over the warm ocean in summer. Water evaporating from the ocean surface gets converted into water vapour in the air but its temperature remains unchanged. The energy consumed to convert liquid water into the gaseous form is latent or hidden within the vapour. It is this tremendous amount of energy, carried by moist air which contributes richly to the power of the monsoon. The latent heat of evaporation is released back to the atmosphere and converted into sensible or detectable heat when water vapour condenses to form clouds. The latent heat released by the ascending warm air on condensation of water vapour makes the air warmer, more unstable and therefore buoyant. It accounts for further ascent followed by cooling, condensation and further release of heat. Due to latent heat release, a stronger upper air pressure gradient is created, resulting in higher and more powerful monsoon. This effect is the strongest when the temperature of the sea surface is at its highest in the late summer.

(ii) Shifting Inter Tropical Convergence Zone (ITCZ)

Still another source of the power of the monsoon was discovered by U.S. meteorologists in 1950's. They discovered that the power of the monsoon was due not so much to the land/sea temperature contrast as explained above but to the shifting of the Monsoon Trough (MT) (the low-pressure region of the summer monsoon over northern India is known as monsoon trough) and the resulting annual migration of pressure belts and winds on the globe. It is found that the change in the position of the sun relative to earth as a result of the earth's rotation and revolution, all the wind belts in the northern hemisphere are shifted northward in summer and southward in winter. In January, in the northern hemisphere, the I.T.C.Z (Inter Tropical Convergence Zone- the zone where the tropical winds converge) is situated at about 10° south over the Indian Ocean. In July, on the other hand, it shifts northward upto 25° north over the Indian subcontinent. Thus, ITCZ does not fall exactly along the equator throughout the year but shifts northwards and southwards. This is because the earth rotates round its axis and the earth's axis makes an angle of not 90° but about 66 1/20 with the earth's equator. Corresponding to the position of the ITCZ, the low-pressure region of the summer monsoon over northern India is known as monsoon trough. The Monsoon Trough (MT) is situated along the Gangetic Valley from Bengal in the east to the Punjab in the northwest. The convergence of trade winds at the monsoon trough gives power to the monsoon in summer in the northern hemisphere and to winter monsoon over the southern Indian Ocean in winter. Halley, in his analysis of the Indian monsoon, did not take into account the impact of the shifting ITCZ and based his explanation only on the contrasting temperature between land and sea. As a result of later investigations, his analysis of the monsoon stood modified.

Monsoon and Upper Atmospheric Circulation

So far the three forces viz. (i) the impact of the Coriolis force; (ii) the contribution of the latent heat released on the cooling and condensation of water vapour and (iii) the impact of shifting ITCZ to provide power to Monsoon winds, have been analysed to understand the complexities of the Indian Monsoon.

The picture, however, was still incomplete and failed to explain fully the terrific power of the monsoon. With improved technology, data relating to the pressure and wind currents in the higher layers of troposphere came to be available in the early 1930s. Working on the data supplied by German meteorologists and realizing the importance of upper atmospheric circulation in the monsoon system, Rhiel (1954) in his book *Tropical Meteorology* discussed that the pattern of the march of the Indian monsoon depended more on the change in the upper atmospheric circulation than on the depression over the north western India-Pakistan. Upper tropospheric air circulation data, inaccessible to earlier scientists, can now be secured to enable the climatologists to understand the seasonal cycles of the Indian monsoon. Brief details of the upper air circulation follow :

(i) In the months of December to February very cold air blows over the north pole. As this air sinks to the surface, it creates: (a) high pressure at the surface; but (b) low pressure in the middle and upper troposphere.

(ii) Low pressure in the middle and upper troposphere coupled with the effect of earth's rotation from the west to the east, results in a belt of upper tropospheric winds moving anti-clockwise round the globe. These winds are known as the upper westerlies. The existence of upper westerlies as well as upper easterlies was first discovered by American pilots flying over India towards Japan during World War II. The upper air over India was noted to be marked by

Air Circulation in Winter

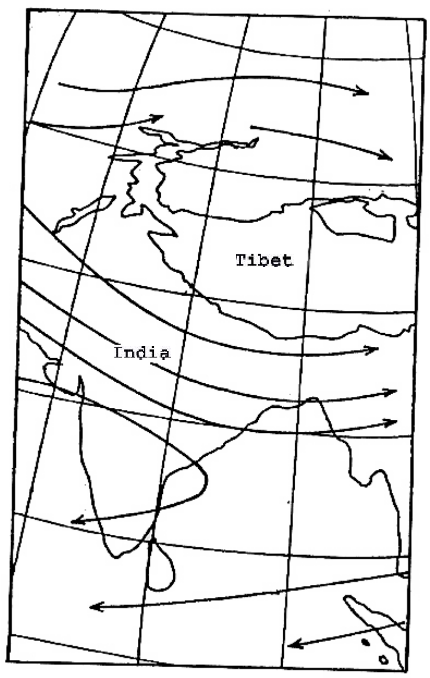

Fig. 3

Source: Adapted from Agnado Edward & Burt, James E (1999): Understanding Weather and climate, Prentice Hall, Upper Saddle River, New Jersey, p.209

strong jet streams of air. In the north over the Himalayas it was a westerly current and over southern India it was an easterly current. For the benefits of pilots information about these strong jet streams was incorporated in the Meteorological Atlas for Airmen.

(iii) The upper westerlies in the region 30°-40° north are divided into two parts when they strike the high mass of the Tibetan Plateau: (a) the northern current of the upper westerlies moves north of the plateau; and (b) the southern current, which is stronger than the northern current flows south of the plateau and over northern India (Figs. 3 and 4).

iv) The strong southern current of the upper westerlies moving at an elevation of 5-10 km above the earth's surface produces a strong air descent on its northern flank. This is due to a very strong jet stream at its centre which is known as subtropical westerly jet.

(v) Simultaneously with this southern current of the upper westerlies, there is, over northern India, the lower tropospheric monsoon air at about 3-4 km high above the earth's surface and flowing from land to ocean. The upper westerlies surmount this land—to—sea circulation of dry north-east monsoon. Together with their 'jet' mentioned above, the subsiding westerlies make a descent of 10 km. Thus a 10 km high jet-induced monsoon circulation is established between northern India and southern Indian ocean. The dry north easterly monsoons are thus strengthened and broadened.

Air Circulation in Summer

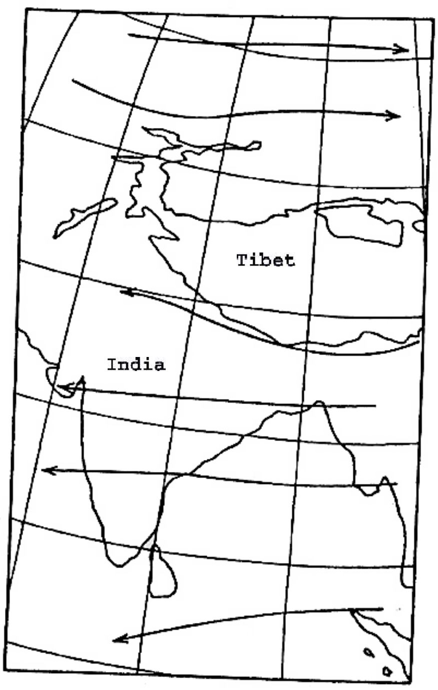

Fig. 4

Source: Adapted from Agnado Edward & Burt, James E (1999): Understanding Weather and climate, Prentice Hall, Upper Saddle River, New Jersey, p.209

Monsoon and Upper Westerlies

In the months of April and May, north-west India develops a depression caused by the ascent of air due to heating. South westerly monsoons from the Arabian Sea make their way to the depression in the north-west, moving at an elevation of 6 to 7 km above the surface. Simultaneously the upper tropospheric low, over the north pole begins to weaken resulting in the slackening of the upper westerlies. However, the upper westerly jet can still prevent the rise of surface air. As the air is prevented from rising, the progress of summer monsoon is checked and retarded. Consequently in April and May, south-westerly air stream rising from the Arabian Sea as outlined above, is relatively weak.

Monsoon and Upper Easterlies

Early in summer, south westerlies begin to grow weaker born over the Tibetan Plateau, as outlined below (Fig. 4):

a The intensity of solar insolation in summer warms the air over the Plateau. Warm air ascends to high elevation in the atmosphere.

b In addition to it, the condensation of water vapour in the ascending air over northern India releases lots of latent energy over the southern flanks of the Plateau, imparting more heat to middle and upper troposphere.

c The air in the upper troposphere over Tibet in early June, being warmer than the air at similar altitudes over the equator in the south, develops an anticyclone, corresponding to a tropospheric trough over the equator. This is because of the high pressures at a given level in the troposphere for a hot, moist air column.

d A north-south air flow is generated as air inevitably flows from a high pressure to a low pressure area.

e This northerly air jet, acted upon by the Coriolis force, is deflected to the right and becomes an upper tropospheric easterly jet.

f The upper tropospheric easterly jet crosses India and the Arabian Sea and heads towards east Africa.

As already stated above, early in June the weakening westerly jet moves to the north of Tibet. At about 15° north, at an elevation of 10-15 km; the easterly jet described above meets the weakened westerly jet. The westerly jet finally disappears from India. The easterly jet now plays an important role during the period of summer. It spreads over a wide area in India at high elevation in the atmosphere and on its northern flank, encourages the ascent of surface air. The surface air from northern India which is heated by solar insolation in summer is drawn up to a height of 10-15 km to meet the easterly jet and to form 14-15 km deep strong summer monsoon. The jet draws also the moist wind from the surface of the Indian Ocean, south of the equator, over India. In this, it is aided by a low-level jet stream known as the Somali jet. The Somali jet takes shape in the region of strong south west winds at the lower level at an elevation of about 1.5 km. The low-level south-west monsoon is strengthened in full measure by the easterly jet. The suddenness with which the dying westerlies are replaced by the strong easterlies after the collision of the two results in a 'burst' of the monsoon over India and heavy rains. Moving south towards the equator, the easterly jet gradually begins to weaken till around the end of September and the beginning of October, the retreat of the strong summer monsoon begins. In the meantime, the summer heat being over, in the low that was formed over north-west India, the ascent of warm air stops. The upper westerlies return to the scene and once again the air circulation typical of winter as described above, takes , over, thus completing the cycle.

Sometimes the cycle is broken in summer and contrary to normal conditions the extreme north and the extreme south of India experience rainfall. The phenomenon is known as 'break' monsoon and has an impact on agriculture. For fairly long periods, sometimes lasting several weeks, low pressure and rising air currents are caused by (i) the weakening of the upper easterly jet and its movement southwards; and (ii) the migration of ITCZ towards the north resulting in a change in the position of the overhead sun. Under the conditions, much of the Indian subcontinent (other than the extreme north and the extreme south) experiences less rainfall because of the rising surface pressure and subsiding air over central and north India.

Seasonal and Spatial Variations of Indian Monsoon and their Causes

Over 80 per cent of the total rainfall of India comes from the summer south-west monsoon winds. Consequently, the mean annual rainfall distribution and the seasonal mean rainfall distribution follow more or less the same pattern. The duration of the rainy season is different in different parts of the country. Generally, the period from June to September is looked upon as the rainy season. But there are many places in northwest India where the rain falls for no more than two months while there are places in southern India where the rains last for full six months. However, in the central part of India, the rainy season does last four months i.e. June to September.

Orographic factor is important in rainfall of India. The altitude of a surface is the most important factor to determine the amount of rainfall it receives. For example, mountainous areas of the Western Ghats of southern India and the north eastern mountainous region of Khasi Hills of Meghalaya are the recipients of very high rainfall of over 250 cm per annum. Areas at a lower elevation, such as the Thar Desert in north-west, on the other hand, receives an average rainfall of less than 20 cm per annum.

Location of tropical cyclones is another important factor which causes most of the total rainfall in the year. Many rice-producing low-lying plains of northern India owe their rainfall to these regional tropical cyclones which are situated within south-west monsoon flows. These rain-producing cyclones are mostly weak lows or at best moderately strong ones. Sometimes, although relatively rare, there are severe cyclones causing large scale devastation. One such cyclone struck and ravaged Orissa in the later part of 1999. Such cyclones cause intense rainfall and take a huge toll of life and property. Rainfall caused by such severe cyclones is not taken into account in calculating the aggregate rainfall, although they substantially alter the regional rainfall distribution in the country.

Besides the orographic factor and the tropical cyclones, there are various other causes of spatial variations in rainfall. They include (i) monsoon 'break' mentioned above, that often occur in central and northern India; (ii) failure of monsoons and; (iii) unexpectedly early or late beginning or cessation of monsoons. These factors which may lead to serious droughts and famines, are considered to be the outcome of the position of the easterly jet in the upper troposphere and variations in the ITCZ shift described above.

Variations in Annual Rainfall in India

Data relating to the annual rainfall over various areas in the country since 1870 reveal some other significant features.

a) Absence of a Regular Trend

Average rainfall varies from year to year but there is little evidence of a regular trend in successive years of rise or decline in average rainfall. Large areas described as 'arid' and 'semi-arid' are situated in the north western part of India. These areas tend to expand further in years of scarce rain; on the other hand in years of heavy rainfall, there is a corresponding tendency of relatively wetter areas to expand.

b) Cycles of Excessive and Deficient Rainfall

Indian Summer Monsoon Rainfall Index (ISMR) from 1871 onwards betrays cycles of 30 year periods of excessive and deficient rainfall alternating with each other, so that the 30 year period (1880-1900) of excessive rains is followed by a 30 year period (1901-1930) of deficient rains. Again the succeeding 30 years (1931-1960) registered heavy rainfall, to be followed by the next 30 years (1961-1990) of deficient rains. The first decade of the next 30 years period (1991-2020) seems to suggest that the pattern is likely to be maintained and the period will see good Indian monsoon.

Indian Monsoon and El Nino Southern Oscillation (ENSO)

El Nino (meaning “the child” after the child Christ) is the name given by local residents to a warm current that flows in the ocean from north to south along the coast of Ecuador and Peru (Fig.5) This warm current usually appears in the Christmas season for a

El Nino, La Nina & Ocean Surface Temperature Conditions

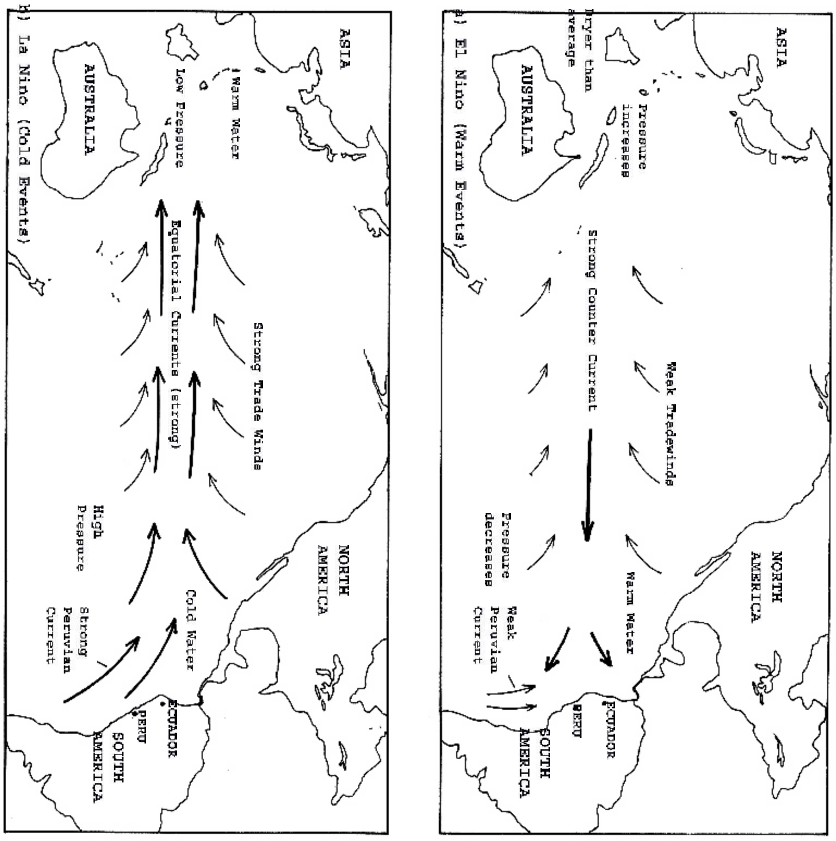

Fig. 5

Source: Adapted from Lungens Frederick K. and Tarbuck Edward J. (2007): The Atmosphere, New Jersey, P.220

El Nino, La Nina & Ocean Surface Pressure & Tropospheric Pressure Conditions

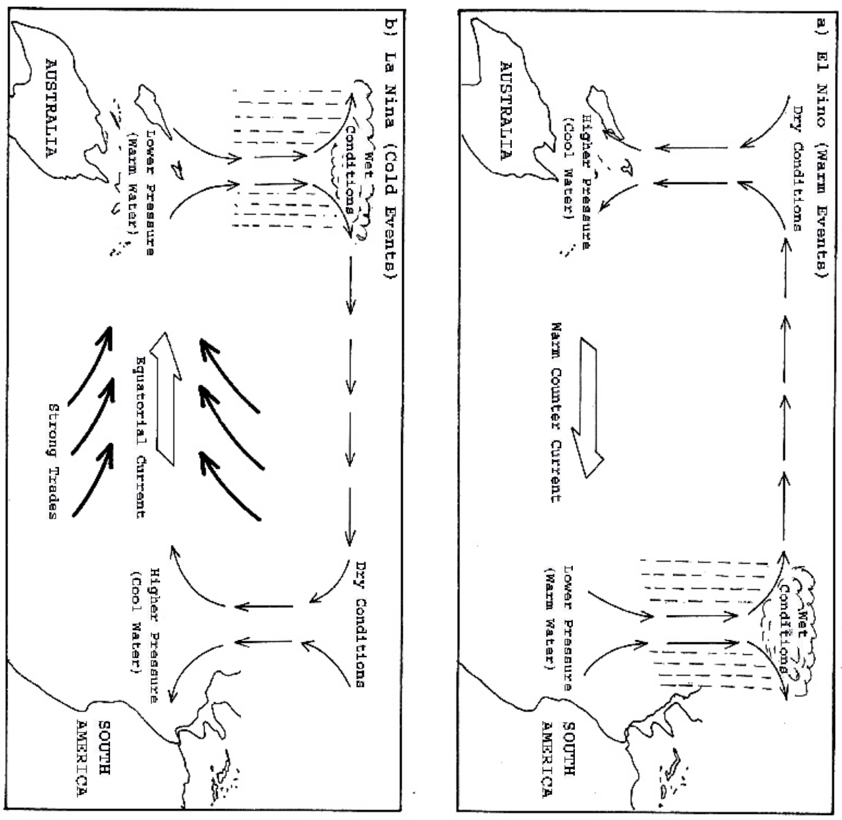

Fig. 6

Source: Adapted from Lungens Frederick K. and Trabuck Edward J, (2007): The Atmosphere, New Jersey, P.221

few weeks (and that is why the local residents connect it with Christmas and the child Christ). This warm current, when it flows, takes the place of the normal cold current flowing towards the equator along the coast.

After a few weeks, El Nino, the warm current, once again gives way to the cold Peruvian flow. However, at regular intervals of 3 to 7 years, El Nino is exceptionally strong and replaces the normally cold waters with warm equatorial waters. Scientists use the term El Nino for these episodes of ocean-warming affecting the eastern tropical Pacific.

It is notable that these are not merely local phenomena but affect extreme weather changes at distant places in various parts of the world, creating havoc through floods and rain at some places and droughts at others. El Nino phenomena are extraordinarily strong at irregular intervals of 3 to 7 years. When a major El Nino event comes to an end, there are pressure differences created between eastern and western Pacific every 3 to 7 years. This phenomenon is known as El Nino Southern Oscillation (ENSO). ENSO brings about a dramatic change in the surface temperature and pressure of the Pacific Ocean. Trade winds change direction and even diminish. In the end, the pressure difference between the two regions swings back in the opposite direction. The seasaw pattern, thus, formed between the eastern and western Pacific is called El Nino Southern Oscillation (ENSO). La Nina is the opposite of El Nino and is now regarded as an important atmospheric phenomenon in its own right. El Nino begins with increase of temperature and decrease of surface pressure in the south eastern pacific and a decrease in temperature and an increase in the surface pressure in the western Pacific. La Nina is the opposite.

ENSO is, thus, the name given to the periodic oscillations occurring on a very wide scale in the ocean atmosphere circulation in the Pacific basin. Researches over the last few decades have shown that there is a close relationship between El Nino (warm surface ocean temperatures and low surface air pressure taking place off the coasts of Peru and Ecuador in Eastern Pacific and near Tahiti in Central Pacific) on the one hand and the development of the Indian Monsoon, on the other.

The changes in the pacific take place in about January to April in any one year. While the crucial months for the development of the monsoon in India every year are April and May. The changes in the Pacific are marked by a falling surface air pressure and the consequent strong upper tropospheric high pressure, which is in contrast with the normal depression (low pressure system) (Fig.6).

On the other hand, during La Ninas (cold events) surface waters in the Pacific grow cold below normal, resulting in a strong surface anticyclone and a deep low pressure circulation in the upper troposphere. The warm El Nino and the cold La Nina events in Pacific Basin have remarkable "teleconnections" with immediately adjacent regions bringing about the onset and development of the Indian Monsoon and have been the subjects of study by various researchers ever since 1924 when Sir Gilbert Walker (Walker, 1924) first discovered the connection. Between 1871 and 1990, most of the 27 warm phase (El Ninos) events correspond to poor monsoons and low rainfall and only four (1884, 1887, 1914 and 1953) out of 27 El Nino years had good monsoons and excess rainfall. On the other hand, among the 23 cold phase (La Nina) events during the same period, 21 had good monsoons when two La Nina years (1920 and 1966) were affected by droughts (Kripalani and Kulkarni, 1997)

The events have also been studied in the context of 'epochal variability'. Epochs 1900-30 and 1960-90 were characterized by below normal rainfall. The worst drought situations prevailed over India in the El Nino years of 1899, 1918, 1972 and 1987. Three of these four years fall within the epochs of 1900-30 and 1960-90, while one (1899) falls on the border of them. As contrasted with this, strong El Nino years (1884, 1891, 1941, 1951 and 1957) were marked by lesser drought conditions and they occurred in the epochs 1870-90 and 1930-60. A different explanation is offered in respect of the long El Nino Event of 1991-94 when there was no serious failure of monsoon and crop. This may be attributed to the epochal trend which is moving from dry period (1961-90) towards an expected wetter epoch (1990-2020). Drought situations have, however, been experienced by India even in non-El Nino years e.g. in 1873, 1901, 1904, 1913, 1915, 1920, 1974, 1979 and floods in the absence of La Nina e.g. in 1874, 1893, 1910, 1917 and 1961 (Kripalani and Kulkarni, 1997). This highlights the importance of influences other than ENSO. Accurate monsoon forecasts cannot be made solely on the basis of ENSO events though the relationship between ENSO and the monsoons cannot be denied.

Indian Monsoon and their Forecast

As a result of vigorous investigations in the field, the basic facts relating to the monsoon and the factors which have an impact on them are fairly well known. However, they present a highly complicated picture of the system with interacting forces, so that the possibility of accurate forecasts still eludes the meteorologists. The target of forecasting them a full year or even a couple of months in advance is still to be achieved.

'Parametric and Power Regression Model' was devised by Indian Meteorological Department in 1988 for forecasting monsoons. This model is scientific and detailed information of rainfall and ground and satellite data have been used to predict monsoons. Sixteen weather parameters (carrying equal weightage to all the parameters) on global, regional and local levels have been considered in this model. Out of these sixteen parameters, six are dependent on temperature, three on wind patterns, five on atmospheric pressure and two are related to snow-cover. To a large extent, the periods of droughts and floods have been predicted correctly by the model.

Conclusion

Traditional monsoon theory, as envisaged by Halley in 1686, is still substantially correct. According to it, the Indian monsoon is basically a product of differential land and sea heating. The concept of the role of released latent heat in strengthening the monsoon as analysed by mid 19th century meteorologists is fully acknowledged by present day meteorologists. The impact of Coriolis effect on the pattern of monsoon as enunciated by Hadley in the 18th century is also accepted by the modern meteorologists. Surface south westerlies blow from ocean to land in summer and surface north easterlies blow from land to ocean in winter. The discovery of the migration of ITCZ to the north and the south in different periods of the year and the effect of these shifts on the Indian monsoon pattern serve to endorse the basic traditional monsoon theory. However, the traditional monsoon theory took into consideration circulation of air only in the lower atmosphere. Data relating to the upper atmosphere being inaccessible to the meteorologists in the past, they had only a partial view of the monsoon system. The traditional theory failed to envisage the global sweep of the system as it is understood today. Mysteries have been brought to light by modern research connecting e.g., the lower tropospheric circulation, the upper tropospheric circulation, the role of the Tibetan Plateau in the pattern of the Indian monsoon. The cycle of the early summer monsoon, winter and summer monsoons and the break monsoon is better understood today as a result of a better understanding of the contribution of air flows in the upper atmosphere, though the full mysteries of the monsoon system are still to be discovered. Upper tropospheric winds moving anticlockwise around the north pole during the period December to February (upper westerlies) get split into two branches. One branch of the current travels north of the Tibetan Plateau. The second branch is the southern branch, having a strong jet stream (known as subtropical westerly jet) at an elevation of 5-10 km above the earth's surface, brings about descent of air on its northern flank. The strong winter monsoon blows over northern India as a land to ocean flow on the surface. Simultaneously the upper westerlies at an elevation of 5-10 km flow across northern India. Winter monsoon over northern India, thus, becomes 10 km deep. It flows between northern India and the southern Indian Ocean. The dry north easterly winds of the winter monsoon are strengthened by the westerly jet. Upper tropospheric easterlies serve to encourage strong air ascent over India thereby strengthening the lower tropospheric south west summer monsoon. Upper tropospheric anticyclone is formed over the Tibetan Plateau as a result *inter alia* of solar insolation in summer. The anticyclone gives rise to upper tropospheric easterlies which replace the weakening upper tropospheric westerlies over northern India resulting in the bursts of the summer south west monsoon. Heavy rainfall follows. Monsoon 'break' air flow is caused by the occasional weakening of the upper tropospheric easterlies and their replacement by upper tropospheric westerlies. There are wide seasonal and spatial variations in the amount of rainfall in India. Rainfall does not depict a regular trend toward rise or decline from year to year. El Nino effect is a harbinger of poor and La Nina effect that of good monsoon in India. Accurate weather forecast still eludes meteorologists.

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