Indian Monsoon: Origin and Mechanism

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ABSTRACT *Climate is the most important element of the physical environment which affects the economic, social and cultural activities of human beings. In Indian context, the monsoon has its bearing on the economic activities, way of living, food preferences and even on the behavioural responses. Despite lot of scientific and technological advancement our dependence on monsoon has not been averted. Indian budget is still considered as a gamble on monsoon. The objectives of the present paper are – (i) to highlight the significance of Indian monsoon; (ii) to identify the main characteristics of monsoon; (iii) to describe the distribution of monsoon climate areas; (iv) to discuss origin and mechanism of Indian monsoon; (v) to identify the main factors responsible for monsoon origin and mechanism, and (vi) to explain traditional to modern perspectives regarding monsoon.*

Keywords: *Monsoon, Reversal, Uncertain, Irregular and Prediction.*

India is situated in the tropical and subtropical zones. About half of the area of the country extends to north of the Tropic of Cancer. Northern part of the country experience not only sub-tropical but even some temperate weather phenomena, especially during winter. In terms of overall climatic conditions, however, the country is more of a tropical land as tropical weather conditions cover most of the country in almost all seasons. Climate conditions in India are affected the most by tropical monsoon. It is only during the winter season and that too in only in the northern parts of the country that sub-tropical or temperate climatic phenomenon and their influences are experienced. India is par excellence a tropical monsoon country.

Due to the overwhelming influence of the tropical monsoon on Indian climate, India is called a tropical country. Agriculture is the mainstay of a large majority of Indians and agriculture here being rain dependent, the monsoon becomes extremely important in India. Agriculture sector employs 56.7 per cent of the total work force and has a share of about 16 per cent in the Gross Domestic Production (GDP). Besides agriculture is a source of raw material for industrial production and serves as a huge market for the industrial products and service sector. About 68.8 per cent population of India still resides in rural areas. Failure or success of monsoon determines agricultural production in the country. Besides the people engaged in farming occupation even those engaged in trade and commerce and allied occupations are affected by the success or failure of monsoon. Agriculture being the source of raw material for a number of industries, industrial production is also affected by monsoon. Agricultural production determines the purchasing power of a large population thereby affecting the trade and commerce. Due to its great importance in national economy monsoon it is often called the 'Real Finance Minister of India'.

A good monsoon is considered a boon while a weak monsoon or failure thereof is considered a curse. While failure or delay in the onset of the southwest monsoon lead to drought conditions in the country, too high an intensity of monsoon and the resultant rainfall causes floods in many parts. Both these situations are adverse in an agricultural country. Drought prone areas of India have

very high rates of suicides by farmers. The uncertain and irregular monsoon results into great loss of life and property. Of the country's total rainfall, about 75 per cent is received during the south west monsoon season from June to September, 13 per cent comes in the post monsoon season, 10 per cent in the pre-monsoon season and the remaining 2 per cent in the winter season. Monsoon rainfall is torrential in nature. It is stated that it pours, it never rains in India. Much of the rainfall is received in 3 summer monsoon months. Even in this season the actual rainy days are 40 – 45 only. The heavy downpour in this season is associated with floods and associated losses.At the same point of time some areas face deficiency of rainfall or drought conditions. Therefore, monsoon management is pre condition to sustainable development of India.

Monsoon is a wind system of the tropical regions under which the direction of the winds is reversed seasonally and it results in summer rainfall and dry winters. There are three characteristics of monsoon:

(i) An approximately 180º change in the direction of winds between summer and winter. According to Nieuwolt (1977), the word monsoon is used only for wind system where the seasonal reversal is pronounced and exceeds a minimum number of degrees (120 degrees).

(ii) Rainy summer and dry winter.

(iii) A tropical phenomenon

These three conditions are considered the identifying features of monsoon system. Under this system the winds blow from ocean to the continent during summer season and from continent to the ocean during winter. Hence there is an approximately complete reversal of wind direction. The winds in summer season coming from the ocean carry moisture and therefore cause rain. In winter blowing from land towards ocean, they do not carry moisture, so there is no rain on the continent. Such a seasonal reversal of wind direction occurs in some other regions also, for example in the areas of Mediterranean type regions. However it results in winter rains in thoseareas. The term monsoon is thus applied to such reversal of wind direction only if it occurs in the tropical region. Thus a rainfall regime, with wet summers and dry winters is characteristic of the areas experiencing monsoon climate.

Although the monsoon in its entirety is an annual phenomenon, covering both winter and summer seasons, in India the term is more often used with respect to the summer monsoon or the southwest monsoon. In common parlance in India monsoon implies the onset of the southeast monsoon (winds blowing from the India Ocean to Indian subcontinent) in the beginning of the summer season so that the months from June to Mid-September are rainy. The southwest monsoon winds are replaced October onwards by the northeast monsoon blowing from the continental area towards the sea to the south. Hence the winter season remains by and large dry. The only exceptions to this dry winter are provided by occurrence of some rainfall during the winter months in the northwestern parts of the country provided by the westerly depressions and in Tamil Nadu provided by the northeast monsoon. The westerly depressions that influence the climate of northern parts of India are typically subtropical or temperate phenomena.

Monsoon: Origin and Mechanism

The term monsoon has been derived from the Arabic word *mousim* or the Malayan word *monsin* which mean season. Monsoon is characterised by a seasonal reversal of wind direction. They flow from sea to land during the summer and from land to sea during the winter. The Asiatic seasonal wind reversal is

notable for its immense extent and the penetration of its influence. According to A.A. Rama Sastry, "Monsoons are large scale seasonal wind systems flowing over vast areas of the globe, persistently in the same direction, only to be reversed with the change of season." The seasonal reversal of winds has been identified as the most characteristic feature by all scholars explaining monsoons. This was specifically highlighted by scholar Conrad. He concluded that, "a true thermal monsoon demands a complete reversal of winds that is an angle of about 180º between the dominant winds at extreme seasons." According to Chang-Chia-Cheng, "Monsoon is a flow pattern of the general atmospheric circulation over a wide geographical area, in which there is a clearly dominant wind in one direction, but this direction is reversed (or almost reversed) from winter to summer and summer to winter.

P.A. Menon in his work 'Our Weather' (1993) emphasised that, the main criterion used in demarcating monsoon areas is the reversal of wind systems between summer and winter. However, this seasonal reversal of winds is very rhythmic and not a sudden process. Therefore, it is often stated that rhythm is the key-note of monsoonal climate. In the context of monsoon winds, C.S.Ramage (1971) identified the following four main features of monsoon winds:

(i) The prevailing wind direction should shift by at least 120º between January and July.

(ii) The average frequency of prevailing wind directions in January and July should exceed 40 per cent.

(iii) The mean resultant wind velocity in at least one of the months should exceed 3 m/s.

(iv) There should be less than one cyclone-anticyclone alternation every two years, in either month, over a five degree latitude/longitude grid.

On the basis of above criteria he identified the area of the monsoon region as a rectangle roughly extending from 35º N to 25º S latitudes and 30º W to 173º E longitudes.

Savindra Singh has classified the areas of monsoon climate into the following categories:

(i) True Monsoon Areas: include India, Myanmar, Pakistan, Bangladesh, Thailand, Combodia, Laos, Vietnam, southern China, Philippines and northern coastal areas of Australia.

(ii) Areas of monsoonal tendencies or pseudo-monsoons: are found along the south-west coast of Africa including the coasts of Guinea, Sierra Leone, Liberia and Ivory Coast; eastern Africa and western Madagascar.

(iii) Areas of monsoon effects: include the north-west coast of Latin America e.g. east Venezuela, Guyana, Surinam, French Guyana and north-eat Brazil. Besides, Puerto Rico and Dominican Republic in the Caribbean Island also enjoy mild monsoonal effect.

(iv) Areas of modified monsoon: are found in parts of Central America and south-east USA.

In the present paper the focus is on the true monsoon areas. These are the areas where all main criteria or characteristics of monsoon are well established. Within Asiatic Monsoon the special focus is on Indian monsoon. Monsoon is a complex climatic phenomenon. According to Barry and Chorley, the Asiatic monsoon regime is a consequence of the interaction of planetary and regional factors, both at the surface and in the upper troposphere. A number of hypotheses have been put forth by scholars to explain the complex phenomenon of monsoon origin and mechanism.

Classical Theory or The Thermal Concept:

Although monsoons are mentioned in old literature like the Rigveda and in the

writings of Buddhist scholars, the credit for first scientific description of monsoon winds goes to the Arab scholars. Al Masudi, the tenth century Arab scholar, provided detailed description of monsoon winds and their seasonal reversal characteristic. In 1554 S.Ali reported the date of onset of monsoons at several places. The thermal origin of monsoons was explained in detail by Sir Edmund Halley in 1686. This is known as the 'classical theory' of origin of Asiatic monsoon. According to this concept monsoons are land and sea breezes on gigantic scale produced by the differential seasonal heating of continental and oceanic areas.

This is the oldest well established view about the origin of monsoon. According to this view monsoon is a result of differential rates of heating and cooling of land and sea. The sun is vertical over the Tropic of Cancer in summer season of northern hemisphere and the Indian landmass at this time gets heated to a greater extent than the neighbouring sea. This leads to formation of low pressure conditions over the Indian subcontinent in comparison to over Indian Ocean. Therefore, thermally induced pressure gradient is produced from ocean towards Indian sub-continent leading to the onset of southwesterly winds blowing from Indian Ocean towards India. These winds, called southwest monsoon, blowing from sea towards land carry a large amount of moisture and cause copious rainfall over the landmass.

The land not only gets heated faster, it also cools faster and to a greater extent in summer than the ocean. Hence the Indian Ocean is warmer than the Indian subcontinent in winter. This causes the pressure gradient to be reversed towards sea. This altered pressure gradient leads to the onset of winds blowing from northeast to southwest, i.e. winds blowing from Indian subcontinent towards Indian Ocean. This wind system is called the northeast monsoon. Since the winds are at this time blowing from land towards sea, they carry little moisture. The winter season over the Indian landmass thus remains largely dry (Fig.1).

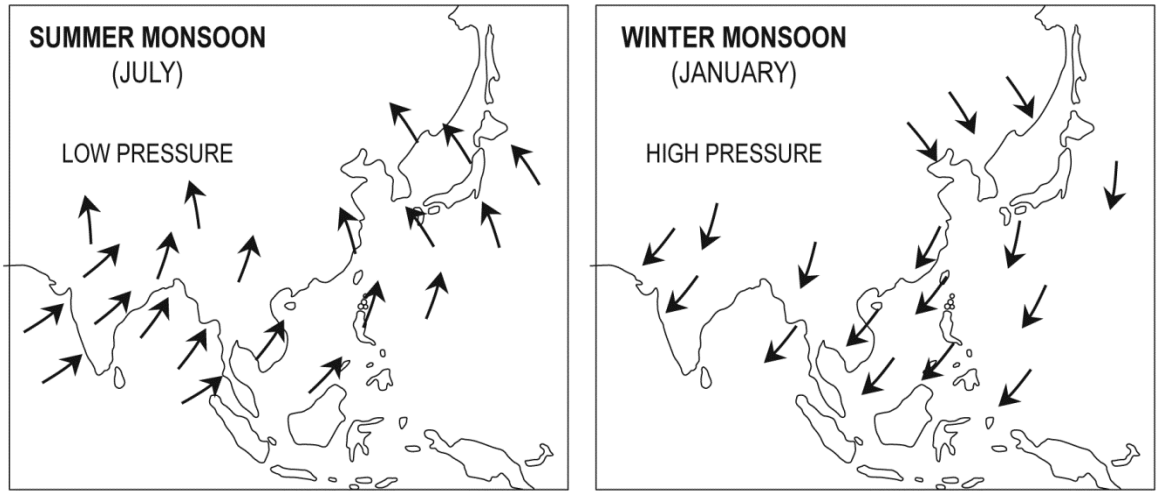

Fig. 1 Monsoon - the Traditional View

The thermal theory of monsoon treats this system as a system of land and sea breezes operating at sub-continental level. The direction of winds reverses seasonally rather than daily, unlike the true local land and sea breeze. The thermal concept of monsoon as proposed by Edmund Halley was supported by a number of scholars like Koeppen (1923), Hann (1932), Angot (1943) and Byers and Miller. They all believe that the, "monsoon

represent simply a land and sea breezes on a large scale, and that the annual period of the monsoon corresponds to the diurnal period of the breezes." Halley's ideas are basically the same as those involved in land and sea breeze except that the reversal is instead of day and night, summer and winter and instead of narrow coastal extent large extents of oceans and continent are involved.

The thermal concept of Halley has been criticised on more than one count by modern climatologists and meteorologists. This concept visualizes monsoon winds as regional surface winds only. It fails to explain the uncertain and irregular character of dynamic monsoon. Modern climatologists express doubt about the thermal origin of low (summer) and high (winter) pressure areas over the land (the Indian sub-continent). According to them the position of low and high pressure areas changes suddenly. These sudden changes are not exclusively related to thermal conditions rather to dynamic factors. According to them the winter high is the outcome of the anticyclonic conditions prevailing over Indian sub-continent due to the presence of southerly westerly jet streams. The summer season low pressure areas are also associated with the cyclonic lows. Further, the modern research works in meteorology have shown that monsoon rainfall is not wholly orographic rather it is an amalgamation of all the three types: orographic, cyclonic and convectional.

Dynamic Concept or Shifting of Inter Tropical Convergence Zone (ITCZ):

This concept was propounded byH. Flohn of German Weather Bureau in 1951. He has suggested that monsoon system experienced in tropical Asia is a result of the seasonal changes in the planetary wind system resulting from the seasonal swing of temperature and pressure belts in this region in association with the changes in overhead position of sun. The planetary winds of tropics are trade winds. In the months of March and September, when sun is overhead in equatorial area low pressure belt is created near equator and north-east trade winds of northern hemisphere and south-east trade winds of southern hemisphere converge in this belt of low pressure. This zone is known as Inter tropical Convergence Zone or ITCZ. The ITCZ is associated with the zone of highest temperature and the lowest pressure. It is due to the low pressure here that the Trade Winds of the northern and the southern hemispheres converge here. When ITCZ is situated close to the equator, the Trade Winds converge near equator. It is also known as the 'doldrums' or calm area. In this equatorial zone the planetary winds are equatorial westerlies.

During summer solstice sun's rays are vertical over the Tropic of Cancer. Therefore, all wind and pressure belts of the globe shift towards the north. At this point of time ITCZ shifts northwards and becomes NITCZ (Northern Inter Tropical Convergence Zone). It extends up to 30º N Latitude in South and South-East Asia. The excessive heating of Indian sub-continent further intensifies this process. According to Flohn, at this point of time the equatorial westerlies of doldrums shift northward and get extended as south-west monsoon winds. Some other scholars consider south-west monsoon winds as an extension of south-east trade winds of southern hemisphere towards NITCZ. They become south-westerly under the influence of coriolis force as they cross equator. NITCZ also result into tropical disturbances which play significant role in surface weather conditions. Heavy rainfall is received during summer season become south-west monsoon winds are on-shore.

During winter season due to southward shifting of ITCZ the pressure and wind belts the planetary system of north-east trade winds gets reestablished over this region. These are called north-east winter monsoons. They prevail over majority area as

off-shore winds. Therefore are generally dry and devoid of rains. But on Tamil Nadu coast they are on-shore and bring precipitation in winter months. The SITCZ (Southern Inter Tropical Convergence Zone) position is associated with north-west monsoon rainy season over northern part of Australia. When the ITCZ shifts towards Tropic of Capricorn in winter, the Trade Winds of northern hemisphere will cross the equator, will be deflected to left hand side and the southern hemisphere tropical zone will experience northwesterly winds. The reversal of wind direction thus occurs in both hemispheres in the tropical zone.

This theory does not negate the effect of the differential heating of land and sea. However, instead of explaining monsoon as an Asian phenomenon, the dynamic theory considers it as a circum-global phenomenon of the tropical zone. The fact that the low pressure area extends over northern India even beyond the Tropic of Cancer is explained by the effect of differential heating of land and sea. On the extensive ocean areas this shift is confined to the tropical zone only. However the reversal of wind direction occurs even over wide oceanic areas away from large landmasses. This dynamic concept also fails to explain the complex monsoon mechanism. The classic concept of Halley and dynamic concept of Flohn fail to explain the intricacies of the monsoons. In both these concepts scholars have ignored the upper atmospheric circulations and teleconnections.

Recent Concepts

Recent concepts of monsoon are based on the generalization that monsoon is the result of the interaction of regional and planetary factors, both at surface and in the upper troposphere. Recent research works and experiments have revealed that there seems to be a link between meteorological events which are separated by long distances. They are known as meteorological teleconnection. Teleconnections are defined as linkages over great distances of atmospheric and oceanic variables. Recent concepts of origin and mechanism of monsoon are based on the findings of research works conducted after 1950 using meteorological data from different places distributed over oceans and continents and upper troposphere. In the last three decades the remotely sensed data in the form of satellite images has provided the spatio-temporal data. Computer based 3-D modeling techniques help in processing this digital data. These recent concepts mainly focus on the role of jet streams and Tibetan plateau and ENSO (El Nino and Southern Oscillation). Gilbert Walker observed teleconnection between ENSO events and the lower than normal monsoon rainfall over South and South-East Asia. The role of jet streams, Tibetan plateau and ENSO is described in the following section:

Upper Air Circulations: M.T.Yin (1949) and P.Koteswaram (1952) have expressed the opinion that mechanism of monsoon depends on the upper air circulation. According to them the upper atmospheric conditions over Tibetan Plateau and positions and intensity of sub tropical westerly jet stream and tropical easterly jet stream play a significant role in the onset, withdrawal and intensity of Indian monsoon (Fig. 2).

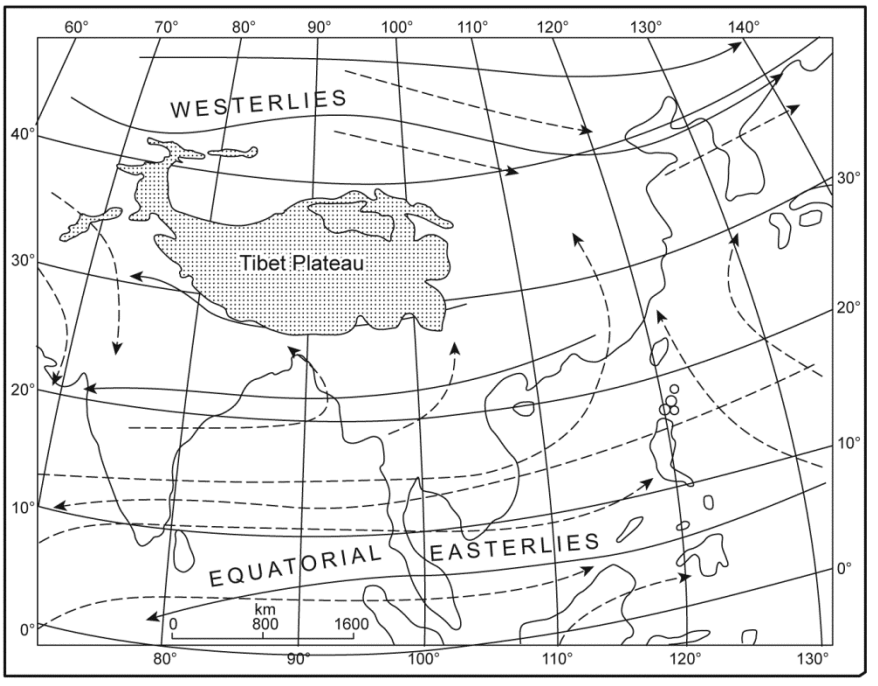

Fig.2 Upper Air Circulation and Monsoon

The sub-tropical westerly jet occupies a position over north India in winter season and the Himalayas and the Tibet plateau lead to bifurcation of this jet stream into two branches. The northern branch occupies a position to the north of the Tibetan Plateau and the southern branch is located over north India to the south of the Himalayas. In the upper troposphere a 'high' pressure system (anticyclonic conditions with clockwise air circulation) develops towards south of southern branch of sub-tropical jet stream over Afghanistan and north-west Pakistan. Consequently, the winds tend to descend over the north-western parts of India, resulting into atmospheric stability and dry conditions. It also contributes in the flow of north east monsoon winds of winter season. The sub-tropical westerly jet streams also help western disturbances to enter the Indian sub-continent and affect its weather. On an average 4-6 disturbances (temperate cyclones) per month pass over northern India between November to April. These disturbances result into snow fall in western Himalaya and rainfall in the Great Plains and provide moisture to rabi season crops.

During the summer season (during months of April, May and June) due to shift in the overhead position of sun, low pressure areas develop at the surface near Peshawar (Pakistan) and north-west India. The winds descending from the upper air high pressure restrict ascend of winds from the surface low pressure. This results into warm and dry weather conditions. This is why the months of April and May (hottest month) are dry inspite of high temperature and evaporation. Contrary to it, upper air low pressure is formed in the eastern Himalayan region due to upper air seasonal easterly jet streams. Due to these conditions the winds coming from southern Myanmar are forced to ascend and produce rainfall in Myanmar, Bangladesh and North East India. The pre-monsoon showers are very common in this part.

After the first week of June the southern branch of sub-tropical westerly jet steam disappears and only northern branch operates to the north of the Tibetan plateau. This results into the development of a dynamic depression over north western part of Indo-Pakistan. As this dynamic depression

gets established over the thermal depression present in this area, burst of monsoon takes place. M.T. Yin (1949), while explaining the origin of monsoon stated that the burst of monsoon depends on upper air circulations. P.Koteswaram (1952) established relationship between upper air circulations and atmospheric conditions over Tibetan plateau. He concluded that the fact that northward movement of the sub-tropical jet stream is the first indication of the onset of monsoon over India. Their ideas were well recognized by Pierre Pedelaborde (1963).

In summer season the Tibetan Plateau gets heated and acts as a high altitude heat source which produces a thermal anti-cyclone over this region (in the upper atmosphere). This anti-cyclone weakens the westerly sub-tropical jet stream south of the Himalayas, and gives rise to the tropical easterly jet stream at 80º E longitude and intensifies the high pressure cell over the Indian Ocean. Thus a surface pressure gradient is produced from the Indian Ocean towards India and it activates south-west monsoon. The seasonal easterly jet stream has its core at a height of about 13 km and it may extend from the southern tip of the peninsula upto 20º N latitude. The periodicshifts of the jet streams are often indicators of the onset and subsequent withdrawal of the monsoon. In fact, northward shifting of subtropical westerly jet stream is the first indication of the onset of the monsoon over Indian sub-continent. The Tibetan Plateau plays the role of a heat engine. The altitude of the plateau ranges between 4000 and 5000 m, and it extends over 4.5 million sq. km area. There is poor vegetation cover and it is surrounded by snow clad mountain ranges. Therefore, it gets heated in summer and is around 2ºC to 3ºC warmer than the air over the adjoining region. When the summer temperature over Tibetan Plateau remains high for a sufficiently long duration, it provides strength to the easterly jet stream and results in heavy rainfall over India. Whenever it remains snow covered for longer duration in summer it results in a poor monsoon.P.Koteswaram (1958), Director General of Indian Observatories, in an international symposium on "The Monsoons of the World" concluded that heating of Tibet plateau was the most important factor in the causation and maintenance of monsoonal circulation over India.

Impact of El Nino and Southern Oscillation (ENSO): El Nino is a temporary warm ocean current which appears off the coast of Peru in December in some years. 'El Nino' in Spanish means the child Christ and it is named so as it appears around Christmas. Sir Gilbert Walker in 1920 noticed that when the pressure was high over equatorial south Indian Ocean, it was low over the equatorial south Pacific and vice-versa. This pressure variation gives rise to circulation along the equator known as Walker Circulation. The pressure variation is stated as Southern Oscillation Index (SOI) and it is measured as difference in pressure between Tahiti (17º45'S, 149º30'W) in French Polynesia, representing the southern Pacific Ocean and Port Darwin (12º30'S, 131ºE), in northern Australia, representing the Indian Ocean. During an El Nino year the SOI Index is negativei.e. pressure at Port Darwin exceeds that at Tahiti. When there is low pressure over the Indian Ocean in winter months, it indicates the chances of the following monsoon being good (Fig. 3).But in an El Nino year the SOI being negative, India receives a lesser amount of rainfall from southwest monsoon.A study of the one hundred years (1870-1970) of the Indian monsoon shows that out of 43 deficient monsoon years, 19 were associated with an El Nino. On the other hand, there were 6 El Nino years which were also years of above average monsoon rainfall. Likewise the analysis of meteorological data from 1972-73 to 2013-14 shows that out of 14 drought years only 9 were El Nino years.

On the other hand, years 1991-92, 1994-95, 1997-98, 2004-05 and 2006-07 were the years of severe drought, without El Nino phenomenon. It means that there is tendency of monsoons being poor in El Nino years but the relationship is not deterministic.

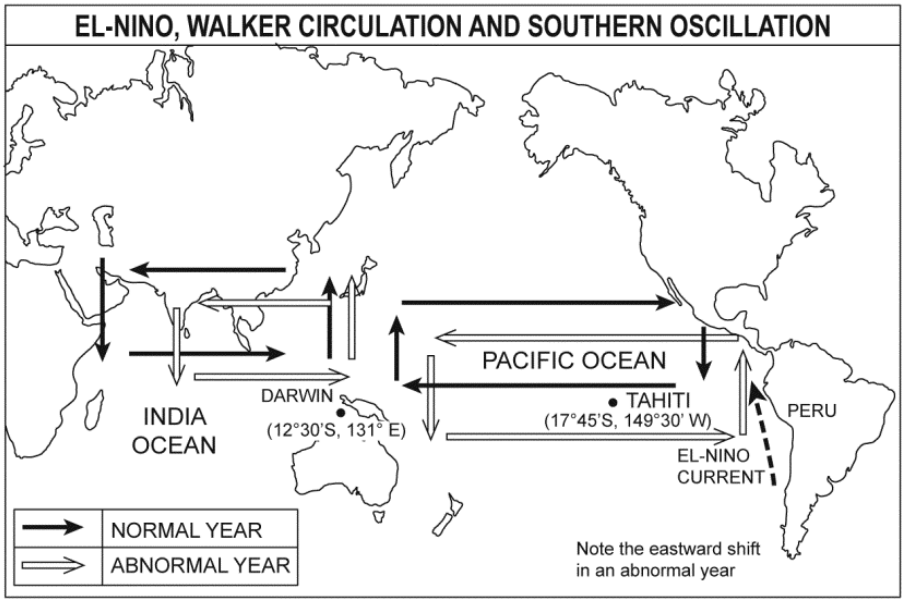

Fig. 3 El Nino and Southern Oscillation

Prediction of Monsoon:

Meteorologists have been trying to identify and understand the role of various factors for a timely prediction of monsoon for long. MONEX (Monsoon Experiment) has been an important effort in this direction. Intensive data was collected to understand the monsoon mechanism under this international experiment taken up in 1979. Subsequently the scientists of Indian Meteorological Department joined an international study programme called TOGA (Tropical Ocean and Global Atmosphere) in 1985. Prediction of monsoon remains a challenge even after these detailed studies of atmospheric and sea surface data.

H.F. Blanford, the first director general of IMD (Indian Meteorological Department) on the basis of amount of snowfall over the Himalayas provided tentative forecast from 1882-85. His generalization was that excessive snowfall over the Himalayan region indicates poor monsoon. Gilbert Walker developed a multiple regression model using 4 parameters to predict monsoon. These parameters were – accumulation of snow in Himalayas at the end of May; pressure in South America during spring; pressure in Mauritius in May and rainfall in Zanzibar in April and May. Later on he added rainfall in Sri Lanka in May and SOI in spring. This way Walker established teleconnections of monsoon. In 1979, scholar V. Thapliyal used the dynamic stochastic transfer model and it improved the accuracy of prediction to about 75 per cent.

Using the data obtained through various studies and digital satellite data, Gowarikeret el (1989 and 1991) proposed a 'power regression model' using 16 parameters, of which 6 are temperature related, 3 are wind related, 5 are pressure related and the remaining 2 are snow related. In 1989, this model was improved by determining a curvilinear relationship among the various predictors. This model has been used with a high degree of accurately for forecasting monsoon rainfall since 1989.

However, it is not a foolproof model. In spite of modifications and revisions this model is still unable to explain satisfactorily the spatio-temporal variations in rainfall.

Conclusion: On the basis of analysis of classical concepts and modern concepts of monsoon origin and mechanism it can be concluded that monsoon is complex and dynamic in nature. Indian monsoon climate is affected by factors such as – latitudinal position (latitude), altitudinal variations (relief), the mountain wall of the north i.e. the Himalayas, distribution of land and sea, distance from sea, jet streams (westerlies and easterlies), tibetan plateau, tropical cyclones and western distrubances, El Nino and Southern Oscillation (ENSO). Over the period of time the prespective regarding monsoon has changed from that of local land and sea breezes to tropical planetary winds and from surface winds to circulations involving upper air conditions. Monsoon climate is basically a sub-system within the global climate system. It means there are teleconnections. Till the time scholars are not able to identify all the elements involved in this mechanism and intensity and dynamics of their roles, correct prediction will remain a challenge even after using super computers and dynamic models. The global climate change has further increased the intensity of this challenge. A high level of accuracy is required in the forecasting and prediction of monsoon in spatio-temporal dimensions to provide stability and sustainability to Indian economy.

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