EFFECT OF LA NIÑA-EL NIÑO ON CLIMATIC FLUCTUATIONS OVER MAJOR HYDRO-ECOZONES ACROSS INDIA

ASHWINI A. RANADE, NITYANAND SINGH and H.N. SINGH
(Ministry of Earth Sciences, Government of India, New Delhi)
Indian Institute of Tropical Meteorology,
Pune, Maharastra, India

ABSTRACT *During boreal summer, the troposphere over southern hemisphere is warming at a faster rate compared to that over northern hemisphere, and the intensity of the general atmospheric as well as the Asian-Indian monsoon circulation shows decreasing trend. Over the equatorial central and eastern Pacific (Niño region), the easterlies are weakening and the SSTs rising, and there is a tendency for occurrence of frequent and intense El Niño than La Niña. Rain-producing weather systems (convergences) are frequent and intense along the western Indian subcontinent, and weaker and infrequent over Indo-Gangetic plains, central India and Bay of Bengal. Consequently, monsoon rainfall is somewhat subdued over Indo-Gangetic plains and central India. The La Niña-El Niño phenomenon provides vital information for extreme rainfall activities across India. To understand effect of the phenomenon on the hydro-ecosystems of the country, difference between La Niña and El Niño years in the parameters of the hydrological wet season (HWS), summer monsoon and wet-dry spells over major/minor/sub-basins have been examined. During El Niño years, climatic condition is considerably adverse over almost the entire hydro-ecosystems across the country compared to that during La Niña years.*

Key words: Hydroecozones; Global warming-cooling; General Atmospheric Circulation Intensity; Asian-Indian summer monsoon circulation Intensity; El Niño-La Niña; Rain-producing systems; Hydrological Wet Season; Onset and Withdrawal of Monsoon; Wet Spells.

INTRODUCTION

Monsoon means many things for India and other countries in the Asia-Pacific region. The monsoon rainfall is the main source of water over most parts of India. This highly space-time variable important living element is available only for four months of the year, June through September. Normally, 2,880 bcm (billion cubic meters) of rainwater is received during monsoon each year – 60% of which evaporates, 10% accumulates on the surface (lakes, reservoirs, ponds and marshlands), 10% percolates to subsurface aquifers and 20% flows into rivers and streams. Major portion of this 40% surplus monsoon rainwater is available in hilly and forested terrain of the West Coast, central India, western Himalaya and eastern Himalaya that constitute 25% area of the country. Contrary to surplus water availability, most of the agricultural and other water-related human activities are spread over dry areas of Indo-Gangetic plains, northwest India and peninsula (excluding the West Coast). The nation must display its enlightened consciousness by effectively utilizing this surplus rainwater for the upliftment of rural masses. During recent global warming, the monsoon activity has been somewhat subdued – monsoon rainfall was less by 2.4% during 1979-2009 compared to the period 1949-1978 (Ranade et al., 2008; Sontakke et al., 2008 a,b). As the monsoon is a thermally driven circulation system, it should intensify during global warming and produce more rains over India. Contrary to this physical understanding, there is a decline in monsoon rainfall over India, particularly over Indo-Gangetic plains and central India though there is some increase in rainfall over northwest India, eastern India and the West Coast.

During boreal (northern hemisphere) summer, a planetary scale atmospheric circulation develops over AfroAsia-IndoPacific region with heating and rising motion (heat lows) over Middle East and China-Mongolia sector, outflows from upper troposphere anticyclone over the THIKHIHILs (Tibetan-Himalaya-Karakoram-Hindukush Highlands), subsidence over eight deep highs across the globe (north pole, south pole, North Pacific, South Pacific, Australian, Mascarene, Azores-Bermuda and Marina) and return flow from lower troposphere of the different highs through a variety of meander courses converging into the heat lows. These moist return flows through different types of convergences (line, circular, meander, eddies, head-on-collision, orographic effect and channelized flow) embedded in large flows produce frequent rains/rainspells over the Asia-Pacific region (Eq.-45°N; 40°-170°E). Seasonally occurring, the entire rain-producing wind-weather system is popularly known as the monsoon (Singh et al., 2010a; Figure 1).

The combined effect of temperature contrast between northern hemisphere and southern hemisphere, between tropics and extra-tropics, between land and sea, between lower and upper troposphere and between the THIKHIHILs and the vast water bodies of the Indian and Pacific Oceans is the main cause of the occurrence of the monsoon. During boreal summer, the temperature (thickness) of the troposphere over the THIKHIHILs is ~10°C (483.8 m) higher (thicker) than that over the whole globe. It is warmer (thicker) compared to the troposphere over the northern hemisphere 6.2°C (284.5m), the southern hemisphere 13.8°C (682.3m), the northern hemisphere extra-tropic 9.4°C (461.2m), the southern hemisphere extra-tropic 22.0°C (1134.5m), the north pole 16.5°C (785.2m), the south pole 41.7°C (2076.0m), the northern tropic 3.0°C (103.9m), the southern tropic 5.9°C (250.6m), the North Pacific High, 5.1°C (204.6m), the South Pacific High 5.1°C (198.9m), the Australian High 4.6°C (167.8m), the Mascarene (southern Indian Ocean) High 5.0°C (178.3m), the Azores (North Atlantic) High 5.2°C (226.0m) and the Marina (South Atlantic) High 6.0°C (243.5m). Presence of hot troposphere over the Middle East is essential condition for the occurrence of the summer circulation. The troposphere over the Middle East can be called Monsoon Hot Tropospheric Tower or simply MHoTT. The temperature and thickness of the MHoTT is highly correlated with the all-India summer monsoon rainfall (1951-2007), 0.51 and 0.59 respectively (Singh et al., 2010b).

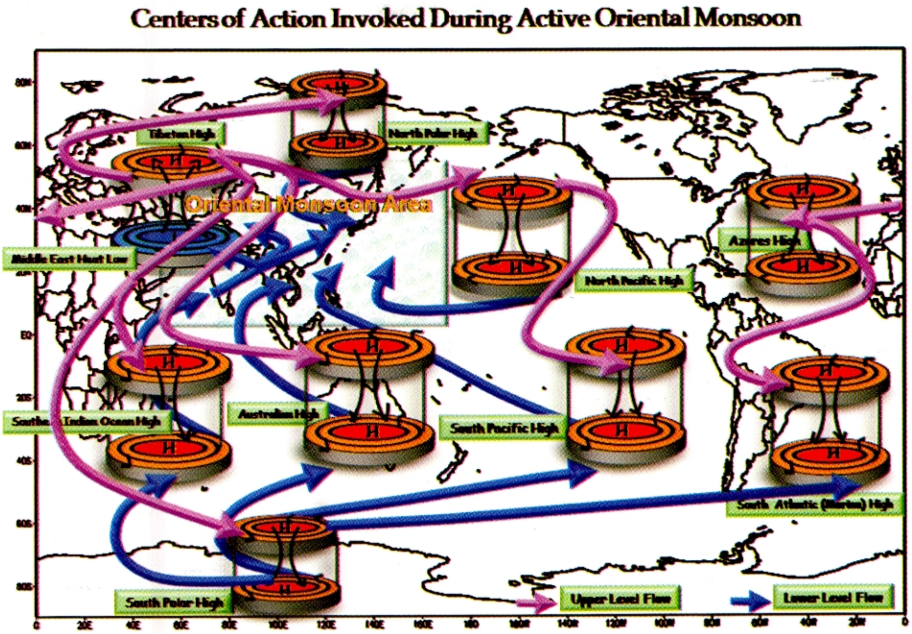

Fig. 1 The Centers of Action (COA) invoked during active Oriental monsoon circulation. Location of the different COAs is approximate attempted to adjust them on small map.

The monsoon is an equatorial-type thermally direct atmospheric circulation, which occurs seasonally around an area in the summer hemisphere where the troposphere temperature exceeds that of the nearest equator by 0.2 times the latitude of the area in degree. The core area should be sufficiently large to experience higher-than-equator temperature for more than 20-40 days. Intensity and geographical location of the different components of the general atmospheric circulation (e.g. polar highs, sub polar lows, temperate westerlies, subtropical highs, tropical easterlies and equatorial lows/convergence zone) show a large seasonality following north-south annual migration of the Sun with a lag of 20-40 days. Even different components show different seasonality over land and ocean and over lower and upper troposphere. The equatorial lows (or the ITCZ) show only a small spatial shift across the equator over the Atlantic and the Pacific oceans but a large shift over continents of Africa, South America, Australia and Asia. Largest pole-ward stretching of the ITCZ occurs in the marine environment between the Afro-Asian landmass on the west and the Indo-Pacific water-body on the east. The maritime environment from equatorial Indian Ocean to western/northwestern North Pacific and eastern flank of the Afro-Asian land mass experience climatic conditions of the equator, the tropic, the sub-tropic and the temperate zones and their interannual and intra-seasonal variability. During each boreal summer, the ITCZ sweeps this part of the globe.

The THIKHIHILs, in the middle of the eastern hemisphere with contiguous landmass on the west and north and water bodies on the east and south, act as elevated heat source during boreal summer. In response to deep tropospheric heating, an inward intense pressure gradient in the lower layers and outward pressure gradient in the upper troposphere develop in and around the THIKHIHILs facilitating unusual lower level convergence, upper level divergence, air-sea interaction and tropical-extratropical interaction. The southeasterly (SE) trades after crossing the equator flow in a meander course via Arabian Sea, Bay of Bengal, Indo-Gangetic Plains and Indo-China peninsula before converging into the convergence zone over northwest India-Pakistan-Afghanistan sector and eastern Tibet-Yangtze River-central China sector. The Coriolis force, orography and diabetic heating affect large-scale monsoon flow. During active phases of the Oriental monsoon circulation, 17 convection-convergence zones develop which produce rainfall. Following factors are responsible for the occurrence of different convergences (accumulation of mass and/or moisture).

- two large-scale flows in opposite direction;
- two large-scale flows in one direction but with different velocity, resulting in development of shear zone;
- between the two subtropical anticyclones;
- formation of trough due to orography;
- presence of low pressure area in the vicinity; and
- effect of Coriolis force.

Western North Pacific Convergence (WNPC)

Outflows from the Australian High (AuH) and the South Pacific High (SPH) after crossing the equator merge together and become southerly-southwesterly flows which converge with an outflow from the North Pacific High (NPH) to form northwest-southeast oriented line converge over the western North Pacific Ocean. If the outflows from the NPH are stronger than the combined outflows from the SPH and the AuH, tropical cyclones form in the WNPC. The cyclones are then steered by the large-scale wind currents with their speed. Most of the rainfalls over the Philippines and tropical western North Pacific are due to this convergence.

East Asian Convergence (EAC)

It is a southwest-northeast oriented line-cum-eddy convergence over the eastern China-Korea-Japan-northwestern North Pacific sector. The convergence develops from combination of warm tropical airflows from the NPH and the southwesterly flows over the Arabian Sea, the Bay of Bengal and the South China Sea, and cold extratropical westerlies over eastern Asia. Sometimes the tropical cyclone which forms in the WNPC and move within it, shifts into the EAC and affect the eastern China, Korea and Japan.

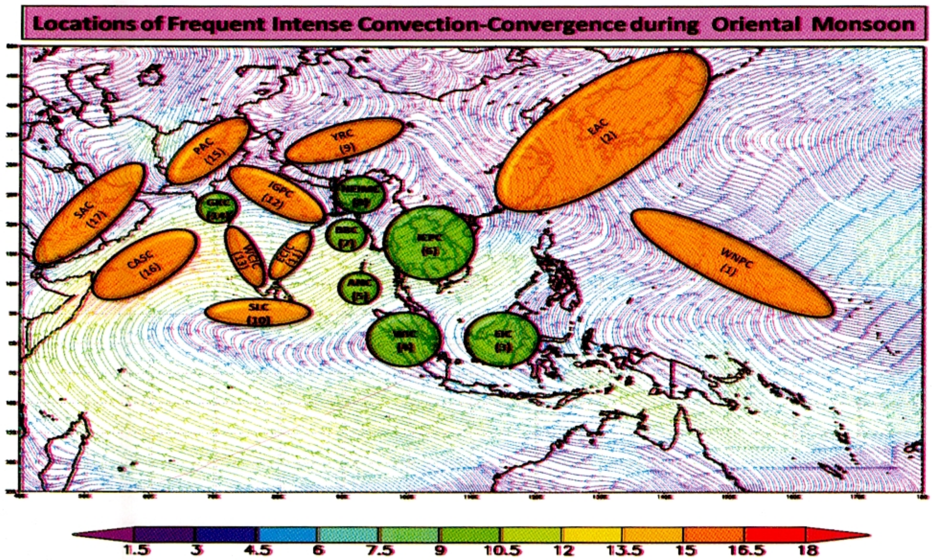

Fig. 2 The 17 major rain-producing weather systems (convergences) in the monsoon Asia region

East Indonesia Convergence (EIC)

It is a circular convergence between cross equatorial flow and the North Pacific easterlies over eastern Indonesia. Depending upon temperature field around equator, the convergence of southeast trades straddle over central and eastern Indonesia. The shape of the convergence varies between circular and elliptical depending upon the equatorial heat source.

West Indonesia Convergence (WIC)

It is often a circular convergence over western Indonesia that straddles around equator.

Andaman and Nicobar (Islands) Convergence (ANC)

A circular convergence develops due to wind shear in the monsoon flow over the Andaman Nicobar Islands. Southwesterly-westerly flows from the Arabian Sea and the southeast trades emanating from the Australian High and crossing the equator (80°-100°E) merge over the southern Bay of Bengal. Whenever the later wind system is stronger than the former, cyclonic shear develops resulting into formation of cyclone which moves first in northwesterly direction and then westerly over Indo-Gangetic plains and central India along with large-scale steering currents.

Indo-China Peninsula Convergence (ICPC)

The main monsoon flow takes a meander over the Indo-China peninsula causing development of a convergence. The returnflows from lower troposphere of the four subtropical highs over the Pacific and the Indian Oceans converge over the South China Sea. Most portion of the total flow find three pathways from here – toward heat low over the Middle East, the Asian continental low over the China-Mongolia sector and northeast around the North Pacific High. Sometimes westward and northward turning of the flow is via a sharp curvature resulting into formation of intense cyclonic circulation. A small portion of the mass-moisture rises under non-hydrostatic condition, which eventually condenses and precipitates.

Bay of Bengal Convergence (BBC)

The southwesterly-southerly monsoon flow over the head Bay of Bengal takes a sharp turn toward west resulting into frequent formation of circular convergences (low, depression, cyclonic storm and severe cyclonic storm). The disturbances travel westward/northwestward under the steering influence of the monsoon flow, and produce ample rainfall along their path over Indo-Gangetic plains and central India.

Northeast India- Myanmar Convergence (NEIMC)

A northwest turn in the monsoon flow and orographic effect causes this convergence over northeast India and Myanmar region. A combined forcing of meander and orographic effect produces frequent convergence and rainfall over the area.

Yangtze River Convergence (YRC)

A line convergence develops over the China's Yangtze River basin due to a direct collision between northwesterly winds and the monsoon flow. In fact it is a front between cold dry continental air from northwest and warm moist marine air from southeast. Sometimes this front produces heavy to very heavy rainfall over the Yangtze River basin.

Sri Lankan Convergence (SLC)

A convergence develops over Sri Lankan area due to formation of trough in the monsoon flow between the Arabian Sea and the Bay of Bengal. With the variation in location and intensity of this trough, the intensity of convergence and rainfall changes over Sri Lanka and extreme south peninsula.

East Coast of India Convergence (ECIC)

This convergence occurs along the East Coast of India when a southwest-northeast oriented trough develops in the westerly monsoon flow after crossing the Western Ghats due to meandering of the flow before converging into the 'heat low'. Intensity of the trough varies depending upon strength of the westerlies and intensity of the heat low. Eastern parts of Indian peninsula receive ample rainfall from this trough.

Indo-Gangetic Plains Convergence (IGPC)

It is a line-cum-eddy convergence over the Indo-Gangetic Plains. The monsoon flow from the Arabian Sea and northwesterly from the Iranian High forms a line convergence over central India, and the eddies form on the left bank of the combined flow over the Indo-Gangetic Plains before converging into the 'heat low'. This is also popularly known as the monsoon trough. Sometimes monsoon depression/cyclone from the Bay of Bengal get aligned into the convergence zone and produce heavy to very intense rainfall over the IGPs and central India.

West Coast of India Convergence (WCIC)

Frequently a trough forms and convergences occur in the monsoon flow along the West Coast due to orographic effect of the Western Ghats. Due to this trough and convergence, the West Coast experiences most intense rainspells compared to other parts of the country.

Gujarat-Kutch Convergence (GKC)

A circular convergence develops at mid-tropospheric level (600-400 hPa) over Gujarat-Kutch region when the heat low over northwest India and monsoon wind over the Arabian Sea are intense. , which gives rise to intense and ample rainfall.

Pakistan-Afghanistan Convergence (PAC)

Similar to the YRC a line convergence develops over Pakistan and Afghanistan border.

Central Arabian Sea Convergence (CASC)

It is a line convergence between northwesterly outflow from the Iranian High and cross equatorial flow from the Mascarene High over the central Arabian Sea.

Saudi Arabia Convergence (SAC)

It is similar to the YRC over Saudi Arabia. Location, shape, size and intensity of different types of rain-producing weather systems vary due to following factors:

- net radiation over the THIKHIHILs and the surrounding Afro-Eurasian land mass;
- the SST conditions of the Indian and Pacific Oceans;
- the speed and depth with which northwesterlies and southwesterlies converge-merge into the ITCZ over the central Arabian Sea and the combined flow approaches the Indian landmass and further over the Bay of Bengal;
- the speed and depth with which the westerlies/southwesterlies from the Arabian Sea, the cross-equatorial flows from the Australian high and the easterlies from equatorial Pacific meet and merge over the southern Bay of Bengal and the Indo-China peninsula;
- branching of the combined flow over the head Bay of Bengal into easterlies blowing over the Indo-Gangetic Plains (IGPs) and southerlies blowing over the Indo-China and eastern China;
- convergence of the easterlies into 'heat low' over the central Middle East and the southerlies into the Asian continental low;
- rising motion from the two lows, divergence from the THIKHIHILs anticyclone, outflows towards east and south and subsidence over the North and South Pacific Oceans and Indian Ocean highs (effective sink due to close, large, deep and warm anticyclone);
- return-flows towards Asian summer monsoon regime; and
- the orographic effect of the West Coast, the central highlands and the THIKHIHILs.

In the investigation, the monsoon will be treated as an active feature as opined by Normand (1953), and the effect of monsoon intensity on easterlies and sea surface temperature (SST) over equatorial Pacific will be examined. The main objectives are:

- To develop suitable index (abstract statistical indicator) for the Asian-Indian summer monsoon circulation intensity;
- To know the effect of the global temperature changes on the Asian-Indian monsoon circulation on the one hand, and the effect of the Asian-Indian monsoon circulation changes on the rainfall over India;
- To understand relationship amongst global temperature, general atmospheric circulation intensity, Asian-Indian summer monsoon circulation intensity, the La Niña- EL Niño and rainfall over India; and
- To find out difference in climatic condition between La Niña and EL Niño years across major hydroecozones of India.

DATA USED

The rainfall data used in this study is obtained from the APHRODITE website and other meteorological parameters from the NCEP-NCAR website.

THE ASIAN SUMMER-INDIAN SUMMER MONSOON CIRCULATION INTENSITY INDEX (AISMCII)

After carefully examining geometry of 3-D structure of the Asian monsoon circulation, an index (statistical indicator) has been developed by suitably aggregating eight upper troposphere – lower troposphere thickness gradients to quantify the intensity of the circulation system as follows:

$$AISMCII_j = \frac{1}{8}\sum_{i=1}^{8}\left[\overline{\overline{UTT}}_{mon,j}^{ME} - \overline{\overline{LTT}}_{mon,j}^{DH_i}\right], \text{j} = 1, 2........ 61 \text{ (years)}$$

where,

$\overline{\overline{UTT}}_{mon,j}^{ME}$ – normalized value (actual minus respective mean divided by respective standard deviation) of monsoon period geopotential thickness of upper troposphere over the Middle East; and

$\overline{\overline{LTT}}_{mon,j}^{DH_i}$ - normalized monsoon period geopotential thickness of lower troposphere over the eight deep highs (DH_i, i= 1, 2....8)

Declining trend in the AISMCII is evident, particularly with the start of global warming since 1979 (Fig. 3). Possible cause of the diminuendo phase in the monsoon circulation has been investigated in this study. The AISMCII shows significant correlation with chosen parameters from the nodal points of the Asian summer monsoon circulation, e.g.

- The upper troposphere thickness over the THIKHIHILs:
  0.50
- The geopotential thickness between 850 hPa and 150 hPa
- over the Indo-Gangetic Plains:
  0.39
- The low level zonal (1000-850 hPa) wind central Arabian Sea:
  0.49
- The shear in zonal wind over Arabian Sea, Indian south peninsula
- and Bay of Bengal (U_{850}-U_{200}):
  0.75
- Low level meridional wind Myanmar over Indo-China peninsula :
  0.39

- Precipitable water over central Bay of Bengal (PW) :
  0.38
- Tropopause zonal wind over Korea-Japan-North Pacific Sector:
  -0.37
- Tropopause zonal wind over Arabian Sea, Indian
- south peninsula and Bay of Bengal:
  -0.68
- Kinetic energy of monsoon flow over Arabian Sea
- (Webster and Yang, 1992):
  0.68
- Meridional monsoon index (Goswami et al, 1999)
  0.57
- Indian monsoon index (Wang et al, 2001)
  0.66

The above CCs are significant at 5% level and above. Hence, the AISMCII provides representation of the Asian summer monsoon circulation. The AISMCII shows correlation of 0.59 with the Monsoon-Asia monsoon rainfall series, 0.61 with India and almost negligible with other countries. For the four monsoon months, the CC between the AISMCII and the all-India rainfall is: June 0.52, July 0.41, August 0.44 and September 0.63. It is seen often that the representation of the simple intensity index reduces as the size and complexity of the atmospheric circulation system increases. Decrease in monsoon rainfall over India is due to decrease in the intensity of the Asian summer monsoon circulation. Due to lower troposphere warming, there is a westward shift in location of the heat low over the Middle East and the monsoon winds over the Arabian Sea are converging into the heat low via the West Coast of India rather than taking a larger meander course via Bay of Bengal and Indo-Gangetic plains. In this situation, the convergences as WCIC, GKC and PAC are stronger while IGPC, ECIC, BCC and ANC weaker. Changes in the strength of other convergences are yet to be determined.

Similar to the AISMCII, we have developed the general atmospheric circulation intensity index (GACII) also by calculating difference in the summer (June-September) geopotential thickness difference between upper troposphere over extratropical northern hemisphere (north of 25°N) and lower troposphere over extratropical southern hemisphere (south of 25°S). The fluctuation of the GACII also shows sharp decreasing trend (Figure 3), which is because of asymmetric rise in the tropospheric temperature over the two hemispheres – the southern hemisphere is warming at a faster than the northern. Based on data of 1949-2009, the CC between AISMCII and GACII is 0.8, which is highly significant (at 0.01% level). The monthly AISMCII and the GACII for the monsoon period also show sharp falling trend; the CC between the two indexes is: June 0.65, July 0.74, August 0.77 and September 0.68. Hence, the monsoon circulation is weaker because of the weaker general atmospheric circulation. The cause of asymmetric rising trend in the two hemispheres is being investigated.

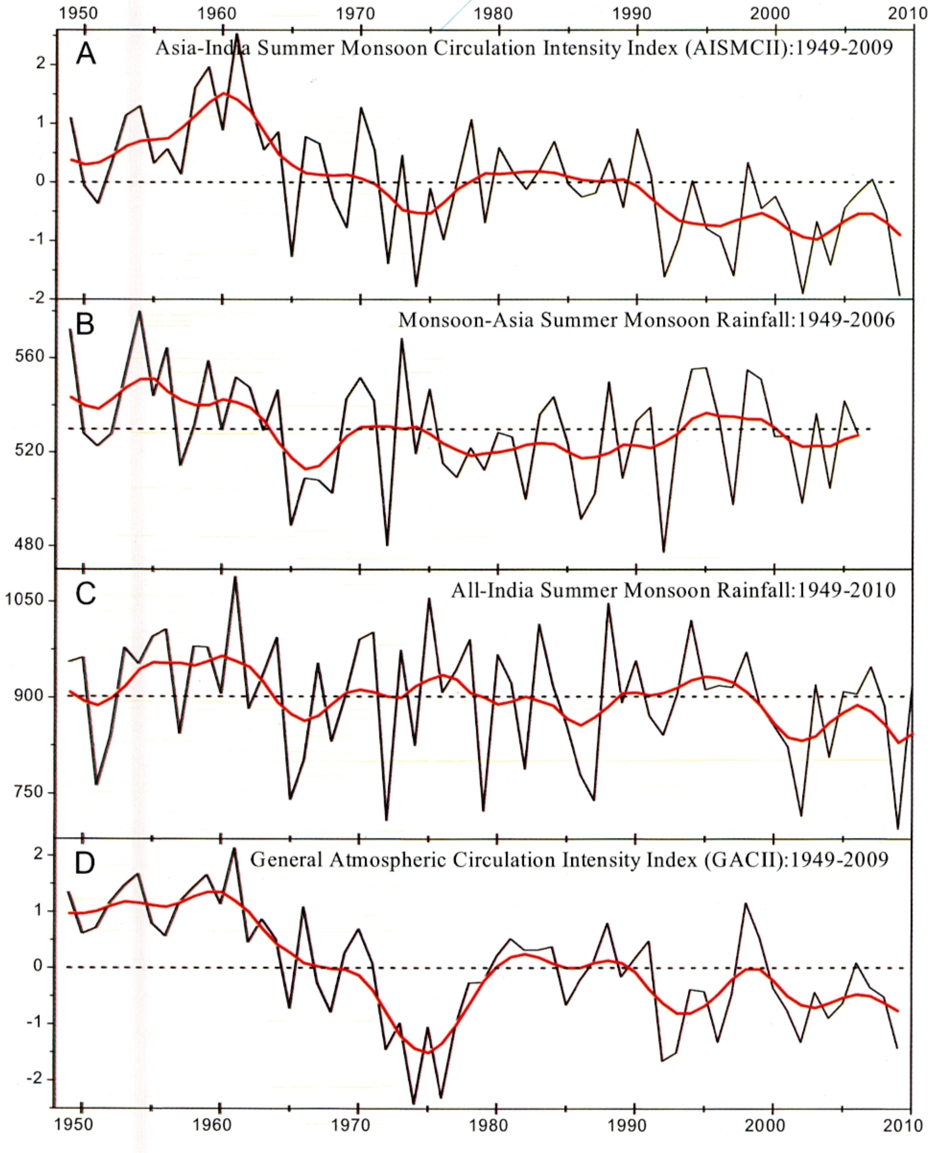

Fig. 3 Actual (thin curve) and 9-point Gaussian low pass filtered (thick curve) time series of the AISMCII (A), the monsoon-Asia summer monsoon rainfall in mm (B), all-India summer monsoon rainfall in mm (C) and the GACII (D).

Each of the six monthly GACII of the boreal summer (April through September) shows monotonic decreasing trend. There exists a strong persistence in the boreal summer monthly GACII; the average CC for lag1 (Apr-May, May-Jun, Jun-July, July-Aug and Aug-Sep) is 0.79, lag2 (Apr-Jun, May-July, Jun-Aug and July-Sep) 0.84, lag3 (Apr-July, May-Aug and Jun-Sep) 0.81, lag4 (Apr-Aug and May-Sep) 0.82 and lag5 (Apr-Sep) 0.82. For austral summer, October through March, the GACII is defined as the difference in the geopotential thickness between upper troposphere over extratropical southern hemisphere and lower troposphere over extratropical northern hemisphere. The monthly (October through March) GACII shows sharp increasing trend with a strong persistence (average CC for lag 1-to-5 is 0.88, 0.69, 0.60, 0.53 and 0.49), which means during austral summer also the southern hemisphere is warming at a faster rate compared to its northern counter part.

SUMMER MONSOON AS AN ACTIVE FEATURE AND EL NIÑO-LA NIÑA PASSIVE

In the year 1891, Señor Dr. Luis Carranza reported a counter-current that occasionally flowed from north to south between the ports of Paita and Pacasmayo. Professor Wyrtki provided one of the first indications that the interannual appearance of exceptionally warm surface waters off the coast of Peru is a consequence of change in the circulation of the entire ocean basin in response to changes in the surface winds that drive the ocean. Sir James Lighthill (1969) calculated that the time it takes the ocean to adjust to a change in the winds should decrease rapidly with decreasing latitude. El Niño is also an example of the rapid response of the equatorial oceans to changing winds. Walker (1924) knew that interannual pressure fluctuations over the Indian Ocean and eastern Tropical Pacific are out of phase (Southern Oscillation): "When pressure is high in the Pacific Ocean it tends to be low in the Indian Ocean from Africa to Australia." Bjerknes (1969) postulated that the El Niño is that phase of the Southern Oscillation when the trade winds are weak and when pressure is low over the eastern and high over the western tropical Pacific. He proposed a physical relation between the interannual oceanographic and meteorological variations in the tropical Pacific. He explained how dry air sinks over the cold water of the eastern tropical Pacific and flows westward along the equator as part of the trade winds. The air warms and moistens as it moves over the progressively warmer water until it reaches the western tropical Pacific, where it rises in towering rainclouds. Return flow in the upper troposphere closes this Walker Circulation. The cold water off Peru and the warm water in the western tropical Pacific – are necessary for the atmospheric pressure gradients that drive the Walker Circulation. He organized the intertwined elements of the Southern Oscillation, El Niño, and large-scale air-sea interactions into a new conceptual framework supported by plausible dynamic and thermodynamic reasoning.

Occurrence of alternating SST polarity between eastern and western equatorial Pacific is the cause of occurrence of El Niño – La Niña in the Pacific basin (Wyrtki, 1982 & 1985). The cycle is a manifestation of complex interaction between random atmospheric processes and deterministic oceanic processes. During prolonged atmospheric circulation with normal strength over the tropics, the trade winds push warm water toward west and cause it to accumulate in the western Pacific. The east-west Walker circulation dominates the atmospheric situation. The region in and around Indonesia experiences low-level convergence, large scale rising motion and convective activities resulting in heavy rainfalls. The north-south Hadley circulation weakens which implies a weak vorticity transport from the tropics to the subtropics resulting in a weakening of the subtropical high-pressure system. The trade winds relax and an El Niño event is triggered. The convective activities shift eastward over South America giving massive rains and floods over there. The Walker circulation weakens and a warm current flows along Peru-Ecuador Coast. Southern Oscillation is not confined to tropical and subtropical latitudes but is closely linked to mid-latitude systems and long waves in the westerlies (Trenberth, 1976). Meehl (1994) provided an explanation for variability of the dynamically coupled climate system that connects different regions of the planet earth. Anomalous tropical Indian Ocean SST during the northern winter intensifies the mid-latitude circulation pattern and enhances the land-sea (or meridional tropospheric) temperature contrast, which are favorable conditions for strong Asian monsoon during the following summer. The Indonesian region experiences cooler SSTs with weaker Australian monsoon, the western Pacific with warmer SSTs and strong convective activities and the East African region strong rainfall activities. During and after the Asian summer monsoon, the tropical Indian Ocean SST changes from warmer to cooler conditions due to strong cross-equatorial flow along Somali coast and associated upwelling, the cooler SST of the Indonesian region changes to warmer SST due to lesser convective activities and greater insolation, and the land-sea temperature contrast decreases due to increase in soil moisture over the Indian region. In the following winter, conditions similar to the preceding winter will be observed but with sign reversed resulting into a weaker Asian monsoon in the following summer.

Intensity of the Asian summer monsoon and the near-equatorial Walker circulation is at a quadrature (Webster and Yang, 1992). During spring and summer, the summer monsoon dominates the Walker circulation and during autumn and winter, the Walker circulation is strongest. The tropical-extratropical interactions through the northern winter northeast monsoon circulation play an important role in the ENSO-monsoon mechanism (Tomita and Yasunari, 1996). When the Indian summer monsoon is weaker, convective activity around the Indonesian maritime continent and the Walker are also weak. Westerly wind anomalies over the tropical central western Pacific causing excitation of El Niño like situation. Positive SST anomalies develop in the central and eastern tropical Pacific during northern summer through winter. Modulated SLP anomalies form large positive anomaly over the central North Pacific. The atmospheric circulation associated with this anomaly weakens the NEWM, which causes the positive SST anomaly around the SCS due to increased insolation. In the following spring and summer, the seasonal convective activity around the maritime continents intensifies around the SCS that contributes to stronger Indian summer monsoon. The Walker circulation intensifies triggering the La Niña like phenomenon. The La Niña phase persists to the next northern spring with similar seasonal processes but with the reversed signs of the anomaly patterns and eventually completes the cycle of the biennial oscillation of the ENSO-monsoon system.

The correlation of the AISMCII with the low layer zonal wind (1000, 925, 850 and 700 hPa mean) and SST (sea surface temperature) over the Niño3 (5°S-5°N; 150°W-90°W), the Niño4 (5°S-5°N; 160°E-150°E) and the Niño3.4 (5°S-5°N; 170°W-120°W) regions is highly significant (5% level and above). The CC with the low-level zonal wind is: Niño3 -0.71, Niño4-0.38 and Niño3.4 -0.66; and with the SST Niño3 -0.47, Niño4 -0.38 and Niño3.4 -0.43. That is higher the upper troposphere and lower troposphere thickness gradient from the THIKHIHILs to the eight deep highs, stronger the easterlies and lower the SST over the Niño. Hence, the monsoon as an active system is affecting the wind and SST over the equatorial Pacific Ocean not the other way round. The CC between zonal wind and SST is Niño3 0.48, Niño4 0.82 and Niño3.4 0.68. An appreciable similar correlation is seen amongst the GACII and the Niño regions SST and u-wind and on monthly scale through the year. This corroborates the proposition of Sir Charles Normand that '*the Indian monsoon therefore stands out as an active, not a passive feature in world weather, more efficient as a broadcasting tool than as an event to be forecast*' (Normand, 1953). Important to note that over the Niño region the easterlies have weakened from -10m/sec to -7m/sec (3m/sec) during 1949-2009 while the SST rose 26.75°C to 27.25°C (0.5°C). We understand the monsoon-El Niño-La Niña relationship as: i. *cooler northern upper troposphere* – weaker THIKHIHILs anticyclone, outflows from the anticyclone, subsidence over the deep highs and easterlies over equatorial central Pacific, and warmer SST over Niño3, Niño4 and Niño3.4 regions (El Niño); and ii. *warmer northern upper troposphere* – stronger THIKHIHILs anticyclone, outflows from the anticyclone, subsidence over the deep highs and easterlies over equatorial central Pacific, and cooler SST over the Niño regions (La Niña). However, it seems the La Niña is an accumulated result of few strong monsoons and the El Niño that of weak monsoons.

EFFECT OF LA NIÑA AND EL NIÑO ON CLIMATIC CONDITION OF THE MAJOR RIVER BASINS

To understand relative effect of the La Niña against El Niño on the hydroecosystems across the country, we calculated difference between 12 La Niña years (1954, 1955, 1956, 1964, 1971, 1973, 1974, 1975, 1985, 1988, 1999 and 2000) mean and 12 El Niño years (1957, 1965, 1969, 1972, 1982, 1987, 1991, 1992, 1997, 2002, 2004 and 2006) mean in starting date, ending date, duration and total rainfall of the hydrological wet season (HWS) over the 12 major basins; and in onset date, withdrawal date and duration of the summer monsoon, and start of the first wet spell, end of the last wet spell and number, total duration and total rainfall of the wet spells over the 19 hydroecozones.

Hydrological Wet Season (HWS)

Annual weather cycle across the country can be broadly divided into two periods, dry and wet. The summer monsoon is the main rainy season over major parts of the country. However, some areas receive rainfall during winter (JF), pre-monsoon (MAM) and post-monsoon (OND) also. Irrespective of the weather systems that produced the rainfall, a hydrological wet season (HWS) is defined as '*a continuous period with monthly rainfall greater than 50mm*', and its characteristics are documented for the 11 major basins, 36 minor basins, the West Coast Drainage System (WCDS) and the whole country (Ranade et al., 2008). In the first month of the continuous period with monthly rainfall greater than 50mm, the starting date of the HWS is determined by linear interpolation up to which, from the beginning of the month, 50mm rainfall is expected. In addition, the ending date is determined in the last month of the period so that between linearly interpolated date and end of the month 50mm rainfall is expected to occur.

Starting Date

Normally, the HWS starts the earliest over the Surma basin (17 March) followed by Brahmaputra minor basin (27 March). Over Dhansiri, the season starts by 4 April, Tista 14 April and Mahananda 24 April. By 30 April, the West Coast Drainage System (WCDS) starts getting thunderstorm-associated rainfall due to strengthening of moist westerlies over the Arabian Sea and heating of the Indian subcontinent from enhanced seasonal solar insolation. As the season advances thunderstorm rainfall activities spread over larger spatial domain, in both the east and the south- the season starts simultaneously (4 May) over Damodar (eastern India) and Cauvery (south peninsula). Due to moist air incursion from the Bay of Bengal over eastern India, spreading of rainfall activities continues over Kasai and Suvarnarekha (12 May), Kosi (20 May), Brahmaputra (21 May) and Gandak (31 May). The Tungabhadra in the central peninsula starts experiencing rainfall as the season advances over Gandak (Bihar State). Over these basins, the pre-monsoon rainfall is considerable and reliable and gives rise to early start and longer duration of the HWS in continuation with the monsoon rainfall. By 31May, the Chenab also starts getting considerable precipitation from western disturbances and the wet season over the basin starts before the arrival of the southwest monsoon currents. Over Palar & Ponnaiyar river systems, the mean starting date is 3 July, Penner 21 July and Vaigai 14 August. Compared to the El Niño year, during the La Niña year the average starting date is about 8 days earlier over Indus, Ganga, Godavari, Sabarmati, Mahi, Narmada, Tapi, Mahanadi, Cauvery and the WCDS. However, the monsoon onset is not affected over Brahmaputra and Krishna basins.

Ending Date

End of the HWS from the country is gradual and well organized compared to the starting date. Normally the process starts from northwest and ends from southeast. The season ends by 23 August from western Rajasthan and by 31 August from the Luni basin. It ends between 1 and 15 September from Chenab, Beas, Sutluz, Yamuna, Chambal, Sabarmati and Mahi; between 16 and 30 September from Gomati, Ramganga, Ghaghara, Sind, Betwa, Ken Tons, Narmada, Tapi, Wardha, Penganga and Bhima; between 1 and 31 October from Gandak, Kosi, Tista, Mahananda, Brahmaputra minor, Dhansiri, Surma, Damodar, Kasai, Suvarnarekha, Brahmani, Mahanadi, Wainganga, Indravati, Godavari minor, Krishna and Tungabhadra; between 1 November to 30 November from Penner, Cauvery and West Coast; and between 1 and 10 December from Palar & Ponnaiyar and Vaigai. The spatial pattern of the mean ending date is in close agreement with normal withdrawal dates of the southwest monsoon. In comparison to the El Niño year during the La Niña year, the HWS ending date is 13 days later over Indus, Ganga, Brahmaputra, Godavari, Sabarmati, Mahi, Narmada, Tapi and Mahanadi basins. However, the ending date is earlier by 18 days over the Cauvery basin and the WCDS, no change over the Krishna basin.

Duration

Over the Indo-Gangetic plains and central India, the mean duration of the wet season varies from 60 days (Luni) to 117 days (Son). The West Coast, south peninsula and Indravati, Mahanadi, Brahmani, Suvarnarekha, Kasai, Damodar, Kosi, Gandak, Mahananda, Tista, Brahmaputra, Dhansiri and Surma basins experience longer duration of wet season due to considerable and reliable rainfall in the post-monsoon period (October-December). In the northeast, the mean duration varies from 185 days (Tista) to 224 days (Surma). Over the basins in eastern parts, the duration varies from 124 days (Gandak) to 171 days (Mahananda); over Mahanadi, Indravati and Krishna basins from 129 to 137 days; over Tungabhadra and Cauvery basins from 141 to 192 days; over Penner, Palar & Ponnaiyar and Vaigai basins from 118 days to 163 days; and over minor basins of the Indus system from 68 days (Satluz) to 107 days (Chenab). Over the nine major basins, Indus, Ganga, Brahmaputra, Godavari, Sabarmati, Mahi, Narmada, Tapi and Mahanadi, the average difference in the duration of the HWS between the La Niña and the El Niño years is about 19 days. However, the duration is shorter by 4 days over Cauvery and the WCDS, and no change over the Krishna basin.

The Total Rainfall

The mean HWS rainfall is lowest (487.7mm) over the Luni basin and highest (3279.9mm) over the Tista basin. During the La Niña year, the HWS rainfall is normally higher by 198.8mm across the major basins compared to the El Niño year.

EFFECT OF LA NIÑA AND EL NIÑO ON CLIMATIC CONDITION OF THE HYDROECOZONES

Division of the Country into 19 Hydroecozones

In the past, due to large geographical area (~3.3 million km^2), the country was divided into certain zones/subdivisions/subregions for different purposes, agriculture, hydrology, ecology, daily weather forecast, long range rainfall prediction, monitoring rainfall variations etc (Sontakke and Singh, 2008 a&b and references therein). The classification done for a particular purpose was not found suitable for another. A new division of the country has been done here for understanding climatic change in onset and withdrawal of monsoon and features of wet and dry spells. Following physico-hydro-climatic factors qualitatively, the country has been divided into 19 hydroecozones (Singh and Ranade, 2010a).

- Topographic features;
- Spatial pattern of the mean annual/summer monsoon rainfall;
- Monsoonal rain-producing weather systems
- Physiographic characteristics, coast, plateau, plains, valley, desert, etc. (NATMO, 1986);
- Drainage pattern (NATMO, 1996);
- Normal onset and withdrawal dates of southwest monsoon across the country (IMD, 1943); and
- Daily rainfall data available as 1-degree raster.

Based on topographic considerations the country is divided into seven zones e.g. West Coast, Central Highlands, Eastern Himalaya-North Eastern Range (northeast India or NEI; HEZ18), Western Himalaya-Punjab Plains (extreme northern India or ENI; HEZ19), peninsula (excluding the West Coast), Indo-Gangetic Plains (IGPs) and northwest dry province. Considering monsoonal rain-producing weather systems and annual/monsoon rainfall, the peninsula is again divided into central peninsula and east coast; and the West Coast into extreme southwest peninsula (ESWP; HEZ1), southern central West Coast (SCWC; HEZ 3), northern central West Coast (NCWC; HEZ 5) and northern West Coast (NWC; HEZ 8). By incorporating physiographic features the IGPs are further divided into three hydroecozones, eastern IGP (EIGP; HEZ14), central IGP (CIGP; HEZ17) and western IGP (WIGP; HEZ16); central highlands into western central India (WCI; HEZ12) and eastern central India (ECI; HEZ13) and northwestern India into two hydroecozones, northern northwest India (NNWI; HEZ15) and southern northwest India (SNWI; HEZ11). Inclusion of drainage pattern as a factor in the classification, the central peninsula and east coast are divided into six hydroecozones, extreme southeast peninsula (ESEP; HEZ 2), central southeast peninsula (CSEP; HEZ 4), southern central peninsula (SCP; HEZ6), central east coast (CEC; HEZ7), northern central peninsula (NCP; HEZ 9) and northern east coast (NEC; HEZ10). Daily rainfall data is available as 1-degree raster therefore; rectangular boxes are drawn to arrive at final classification of 19 hydroecozones. While drawing boundaries it is checked that, the monsoon advanced northward with a distinct onset date from one subregion to another, and withdrew distinctly southward (Figure 4).

ONSET AND WITHDRAWAL DATES OF THE SUMMER MONSOON

The onset of the summer monsoon over extreme southwest peninsula (Kerala State) occurs around 1 June and it takes about 40 days to cover the whole country. The circulation system remains largely stationary for 65 days (10 July-12 September), it starts withdrawing from extreme northwest around 13-17 September and the process is completed from extreme south peninsula around 18-22 October (Figure 4).

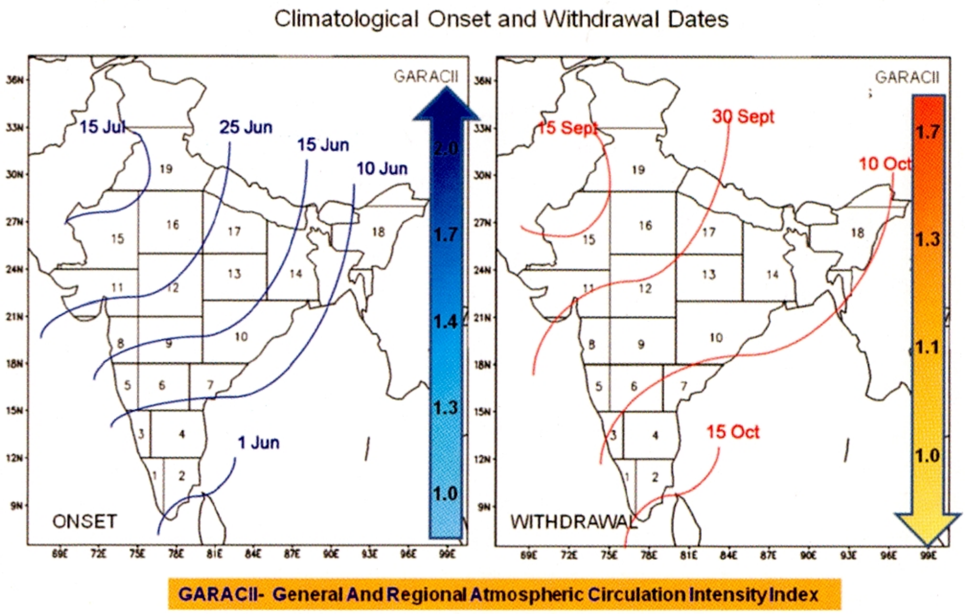

Fig. 4 Geographical location of the 19 hydroecozones. The blue isolines indicate climatological onset date (a), and red withdrawal date (b). The figure inside the arrows is the GARACII (**G**eneral **a**nd **R**egional **A**tmospheric **C**irculation **I**ntensity **I**ndex) values at the time of respective onset and withdrawal dates (Singh and Ranade, 2010b).

Definition of Onset over a Subregion

Starting from 1 April when 30-day running mean of the hydrometeorological condition and atmospheric circulation intensity exceed their thresholds, the 30th day of the latest 30-day period is treated as the onset date (Singh and Ranade, 2010b).

Definition of Withdrawal over a Subregion

After the onset when 30-day running mean of the hydrometeorological condition and atmospheric and regional circulation intensity fall below their thresholds, in the middle of the two thresholds achieved, the 1st day of the latest 30-day running period is the withdrawal date.

The average difference between La Niña and El Niño years in the monsoon parameters over the 19 HEZs is, onset 5 days earlier, withdrawal 7 days later and duration 12 days longer.

Wet Spells

The wet (dry) spell over a hydroecozone has been identified by applying an objective criterion '*a continuous period with daily rainfall equal to or greater than (less than) daily mean monsoon rainfall (DMMR) over the area of interest*' (Singh and Ranade, 2010a). Normally, the extreme southeast peninsula (HEZ 2) experiences the largest number (11) of WSs. The number decreases along the East Coast to seven over eastern Indo-Gangetic plains (EIGP or HEZ14), then decreases to four over northwestern India (HEZs 11 and 15; Figure 5). Total duration of the WSs follows the similar pattern and decreases from 101 days (SR2) to 29 days (HEZ15). Total rainfall due to WSs is, however, highest along the West Coast with 1290-2130mm, followed by northeast India with 1262mm, and lowest over northwestern India with 284mm.

Over the remaining areas, the total rainfall varies from 495mm to 900mm following annual rainfall pattern with low values over the central peninsula (HEZ9 and HEZ6) and high values elsewhere. Features of individual WSs are different along the West Coast. Duration varies from 10-12 days, rainfall amount from 263-327mm and rainfall intensity from 29-37mm/day; over other parts, the duration varies from 7-10 days, rainfall amount from 70-159 mm and rainfall intensity from 8-18mm/day.

Normally the first WS starts on 19 March over the HEZ2, followed by 23 April over the HEZ18, 3 May over the HEZ4, 16 May over the HEZ19, 21 May over the HEZ1, 23 May over the HEZ7 and 30 May over the HEZ6. Over the peninsula, the northeast India and extreme northern India, thunderstorms associated with the first WS starts 11 to 55 days earlier than the onset of the monsoon. Most parts of the country experience the first WS between 2 June and 23 June i.e., about 5 days earlier than the monsoon onset. Over the HEZ15, the first WS starts on 22 June, 16 days earlier (8 July) than the monsoon onset. The SD of the start of the first WS is 8-11 days (smallest) over central and northern West Coast and 31-35 days over the southeast peninsula and 30-53 days over the extreme north/northwest

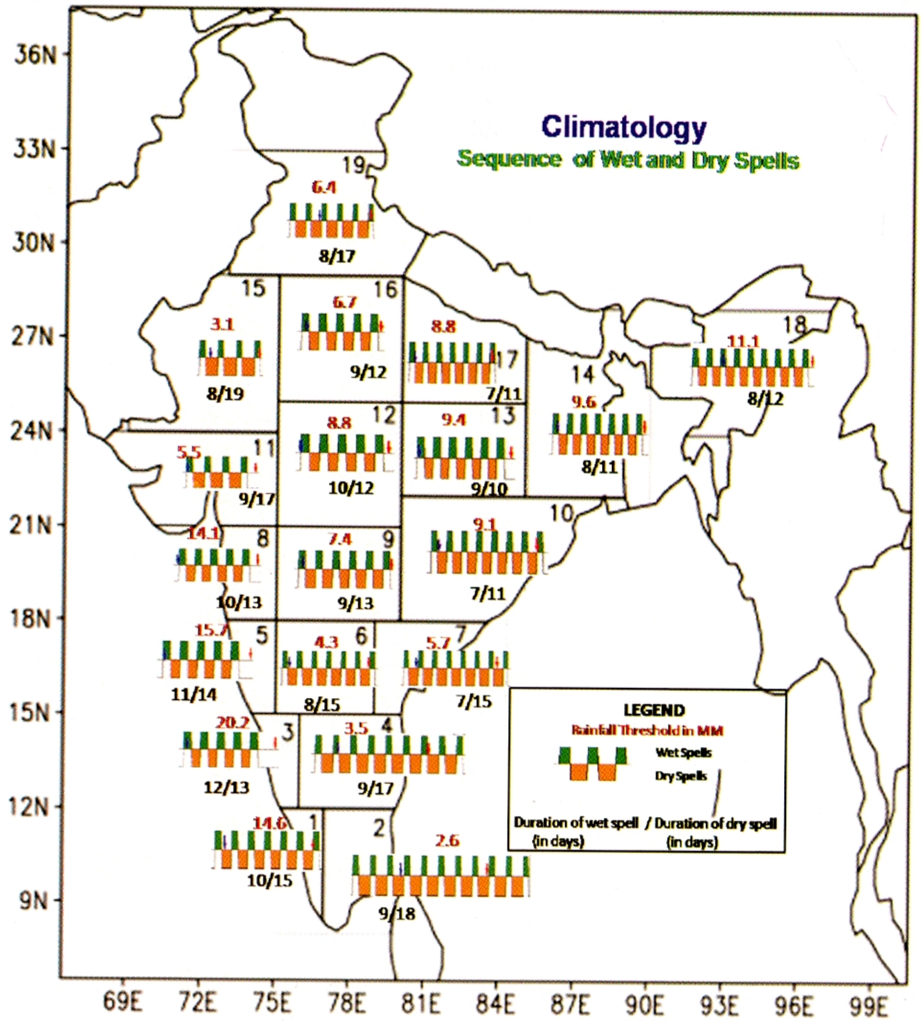

Fig. 5 The 19 hydroecozones (HEZs) of India for the purpose of present study. Rainfall threshold for identification of wet and dry spells, climatology of sequence of wet and dry spells, duration of wet and dry spells and normal onset (blue arrow) and withdrawal (red arrow) dates of the summer monsoon are shown on the wet-dry spell gratis of each of the HEZ (Singh and Ranade, 2010a).

The cessation process of the last WS starts from the HEZ15 on 12 September, the date progressively shifts towards the east, southeast and south and ends on 16 December from the HEZ2. In general, over most regions, the last WS ends ~9 days earlier than the withdrawal of the monsoon. However, from the northeast, east coast and southeast peninsula the last WS ends after the monsoon withdrawal: 4 days later from the HEZ18, 7 days from the HEZ10, 11 days from the HEZ6, 22 days from the HEZ7, 48 days from the HEZ4 and 58 days from the HEZ2. This is because withdrawal of the southwest monsoon is followed by onset of the northeast monsoon over these HEZs. The contribution of rainfall due to WSs to the respective annual total varies from 60 to 79% in different HEZs except over the extreme north where it is only ~47%.

The HEZ2 experiences three WSs before onset of the monsoon and three WSs after the withdrawal; the HEZ4 one WS before and two WSs after; the HEZ1, the HEZ6 and the HEZ7 one WS before and one WS after; the HEZ15 one WS before and no WS after; and over the HEZ18 and the extreme north (HEZ19) two WSs before and no WS after. Over the remaining areas (HEZs 3, 5, 8-14, 16 and 17) the first WS occurs with the onset of the summer monsoon and the last WS ends with the withdrawal.

The effect of the La Niña against the El Niño on the wet spells parameters over the HEZs is, start of the first wet spell 8 days earlier, end of the last wet spell 5 days later, one wet spell more, total duration of the wet spells 11 days longer and total rainfall 158.0mm higher.

CONCLUSIONS

- The AISMCII provides considerable representation of the Asian monsoon circulation intensity and rainfall over India, but weak representation of the rainfall over other countries in the western Pacific region.
- During boreal summer, the general atmospheric circulation is weaker due to asymmetric tropospheric temperature rising trend over the two hemispheres – the southern hemisphere is rising at a faster rate (0.4°C to 2.0°C) than its northern counter part (-2.0°C to 0.4°C).
- The troposphere over the Tibet-Himalaya-China-Mongolia-Manchuria (THCMM) sector is anomalously cooler (-0.5°C to -2.0°C) during 1979-2009 compared to 1949-1978 and the upper tropospheric anticyclone weaker; consequently, the Asian-Indian monsoon circulation is weaker and rainfall over India lesser.
- However, the rain-producing convergences over western Indian subcontinent (WCIC, GKC and PAC) are stronger due to lower tropospheric warming and westward shift in 'heat low' over Middle East. The change in circulation is producing negative over the Indo-Gangetic plains and Bay of Bengal, consequently the convergences like the IGPC, the ECIC, the BBC and the ANC are weaker.
- This study corroborates the postulate of Sir Charles Normand that the monsoon is an active feature of the world weather (Normand, 1953). The effect of the troposphere temperature over the THCMM on the monsoon circulation percolates downstream as:

  i. *cooler northern upper troposphere* – weaker THIKHIHILs anticyclone, outflows from the anticyclone, subsidence over the deep highs and easterlies over equatorial central Pacific, and warmer SST over the Niño3, the Niño4 and the Niño3.4 regions (El Niño); and ii. *warmer northern upper troposphere* – stronger THIKHIHILs anticyclone, outflows from the anticyclone, subsidence over the deep highs and easterlies over equatorial central Pacific, and cooler SST over the Niño regions (La Niña).

- Climatic conditions (hydrological wet season, onset and withdrawal of monsoon and wet spells) across the major river basins/hydroecozones of the country are considerably adversely affected during El Niño years compared to La Niña years.

ACKNOWLEDGEMENTS

The authors are extremely grateful to Prof. B.N.Goswami, Director, Indian Institute of Tropical Meteorology, Pune for necessary facilities to pursue this study.

REFERENCES

Bjerknes, J. (1969) Atmospheric teleconnections from the equatorial Pacific. Monthly Weather Review, 97(3), 163-172.

Goswami, B. N., Krishnamurthy, V. and Annamalai, H. (1999) A broad scale circulation index for the interannual variability of the Indian summer monsoon. Quarterly Journal of Royal Meteorological Society, 125, 611-633.

IMD, (1943): Climatological Atlas for Airmen. India Meteorological Department. 100 plates.

Lighthill, M.J. (1969) Dynamic response of the Indian Ocean to the onset of the southwest monsoon. Phil. Trans. Roy. Soc., 265(A), 45-93.

Meehl, G.A. (1994) Coupled land-ocean-atmosphere and South Asian monsoon variability. Science, 266, 263-267.

NATMO (1986) Physiographic regions of India. National Atlas and Thematic Mapping Organization (NATMO), Kolkata, India, Plate 41.

NATMO (1996) Drainage. Land Resources Atlas, National Atlas and Thematic Mapping Organization (NATMO), Kolkata, India, Plate 3.

Normand, C. (1953) Monsoon seasonal forecasting. Quarterly Journal of Royal Meteorological Society, 79(342), 463-473.

Ranade, A., Singh, N., Singh, H.N. and Sontakke, N.A. (2008) On variability of hydrological wet season, seasonal rainfall and rainwater potential of the rivers basins of India (1813-2006). Journal of Hydrological Research and Development, 23, 79-108.

Singh, N., and Ranade, A. (2010a) The wet and dry spells across India during 1951-2007. Journal of Hydrometeorology (AMS), 11, 26-45.

Singh, N., and Ranade, A. (2010b) Determination of Onset and Withdrawal Dates of Summer Monsoon across India using NCEP/NCAR Re-analysis. Contribution from IITM Research Report No. RR-124, Indian Institute of Tropical Meteorology, Pune, 78 pp.

Singh, N., Ranade, A. and Singh, H.N. (2010a) Global temperature and Indian Monsoon. Geography and You, May-June 2010, 41-45.

Singh, N., Ranade, A. and Singh, H.N. (2010b) Evolution, climate Change and oriental monsoon. Geography and You, Nov-Dec 2010, 30-35.

Sontakke, N.A., Singh, N. and Singh, H.N. (2008a) Instrumental period rainfall series of the Indian region (1813-2005): revised reconstruction, update and analysis. The Holocene, 17, 1055-1066.

Sontakke, N.A., Singh, Nityanand and H.N. Singh (2008b) Chief features of Physiographic rainfall variations across India during instrumental period (1813-2006). Contribution from IITM Research Report No. RR-121, Indian Institute of Tropical Meteorology, Pune, 128 p.

Tomita, T. and Yasunari, T. (1996) Role of the northeast winter monsoon on the biennial oscillation of the ENSO/monsoon System. Journal of Meteorological Society of Japan, 74(4), 399-413.

Trenberth, K.E. (1976) Spatial and temporal variations of the Southern Oscillation. Quarterly Journal of Royal Meteorological Society, 102, 639-653.

Walker, G.T. (1924) Correlation in seasonal variations of weather, IX. A further study of world weather. Memoirs of Indian Meteorological Department, v. 24(9), 75-332.

Wang, B., Wu, R. and Lau, K.-M. (2001) Interannual variability of Asian summer monsoon: Contrast between the Indian and western North Pacific-East Asian monsoons. J. Climate, 14, 4073-4090.

Webster, P.J. and Yang, S. (1992) Monsoon and ENSO: selectively interactive systems. Quarterly Journal of Royal Meteorological Society, 118, 877-926.

Wyrtki, K. (1982) The Southern Oscillation, ocean-atmosphere interactions and El Niño. Mar. Tech. Soc. J., 16, 3-10.

Wyrtki, K. (1985) Water displacements in the Pacific and the genesis of El Niño cycles. Journal of Geophysical Research, 90(C4), 7129-7132.

List of Abbreviations

AISMCII	Asian-Indian Summer Monsoon Circulation Intensity Index
ANC	Andaman and Nicobar (Islands) Convergence
BBC	Bay of Bengal Convergence
CC	Correlation Coefficient
CASC	Central Arabian Sea Convergence
EAC	East Asian Convergence
ECIC	East Coast of India Convergence
EIC	East Indonesia Convergence
ENSO	El Niño-Southern Oscillation
GACII	General Atmospheric Circulation Intensity Index
GKC	Gujarat-Kutch Convergence
HEZ	HydroEcoZone
HWS	Hydrological Wet Season
ICPC	Indo-China Peninsula Convergence
IGPC	Indo-Gangetic Plains Convergence
IGPs	Indo-Gangetic Plains
IMD	India Meteorological Department
ITCZ	Intertropical Convergence Zone
MHoTT	Monsoon Hot Tropospheric Tower
NCEP-NCAR	National Center for Environmental Prediction-National Center for Atmospheric Research
NEIMC	Northeast India- Myanmar Convergence
NEWM	Northeast Winter Monsoon
PAC	Pakistan-Afghanistan Convergence
SAC	Saudi Arabia Convergence

SCS	South China Sea
SLC	Sri Lankan Convergence
SLP	Sea Level Pressure
SST	Sea Surface Temperature
THCMM	Tibet-Himalaya-China-Mongolia-Manchuria
THIKHIHILs	Tibet-Himalaya-Karakoram-Hindukush Highlands
WCDS	West Coast Drainage System
WNPC	Western North Pacific Convergence
WCIC	West Coast of India Convergence
WIC	West Indonesia Convergence
YRC	Yangtze River Convergence