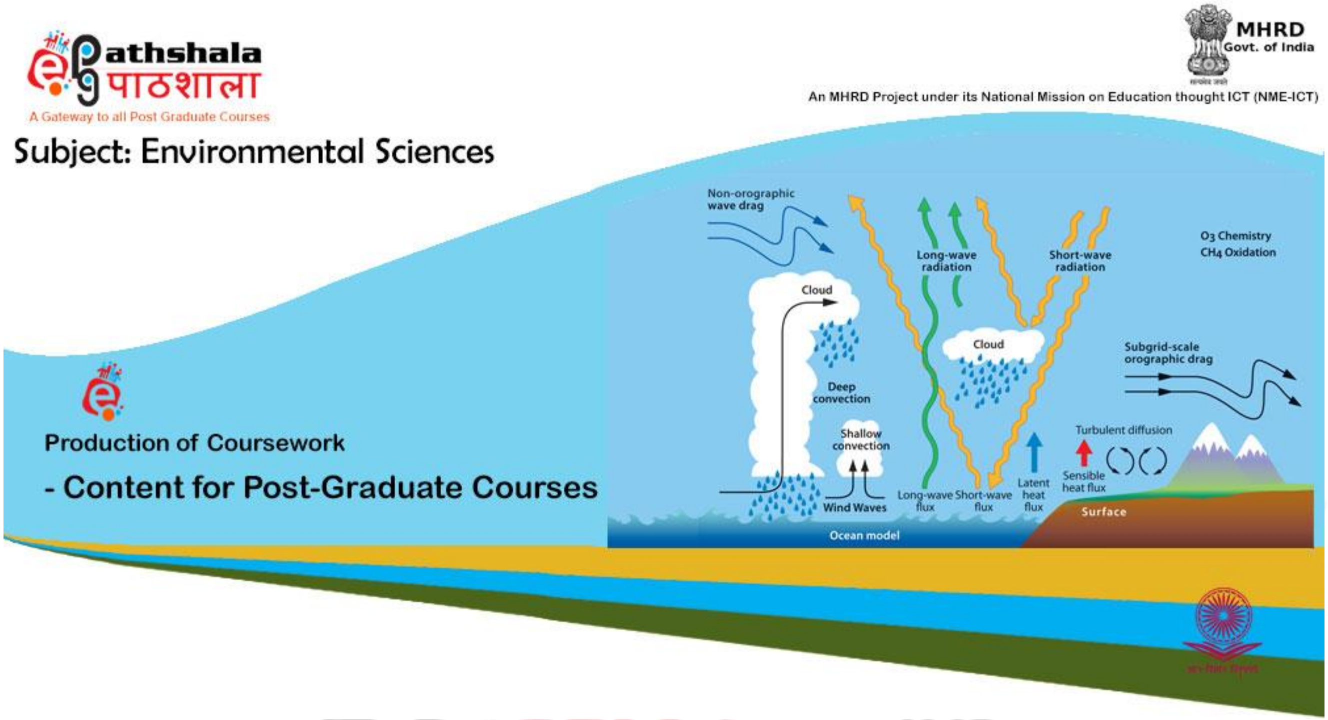

Paper No: 8 Atmospheric Processes

Module: 22 Coupled Ocean-Atmosphere System, El-Nino and Southern Oscillation (ENSO)

e-Pathshala पाठशाला
A Gateway to all Post Graduate Courses
MHRD Govt. of India

Development Team

Principal Investigator & Co- Principal Investigator	Prof. R.K. Kohli Prof. V.K. Garg &Prof. Ashok Dhawan Central University of Punjab, Bathinda
Paper Coordinator	Dr. Sunayan Saha Scientist, ICAR-National Institute of Abiotic Stress Management, Baramati, Pune
Content Writer	Dr. Lalu Das Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal
Content Reviewer	Dr. Anupam Hazra Indian Institute of Tropical Meteorology, Pune
Anchor Institute	Central University of Punjab

Description of Module	
Subject Name	**Environmental Sciences**
Paper Name	Atmospheric Processes
Module Name/Title	Coupled Ocean-Atmosphere System, El-Nino Southern Oscillation (ENSO)
Module Id	EVS/AP-VIII/22
Pre-requisites	
Objectives	• What is a coupled Ocean-Atmosphere system? • What is the mechanism of development of El Niño and La Niña? • How to monitor ENSO events? • What are the effects of El Niño and La Niña on Indian monsoon?
Keywords	El Nino, La lina, Coupled ocean-atmosphere system, ENSO, Nino 3.4 index, ISMR

Module: 22 Coupled Ocean-Atmosphere System, El-Nino Southern Oscillation (ENSO)

TABLE OF CONTENTS

1. Learning outcomes
2. Introduction
3. Coupled ocean-atmospheric system
4. El Niño and La Niña
5. Monitoring of ENSO events
6. Effects of El Niño and La Niña on Indian monsoon
7. Summary

1. *Learning outcomes*

At the end of the module you will able to answer the following questions:

- What is a coupled Ocean-Atmosphere system?
- What is the mechanism of development of El Niño and La Niña?
- How to monitor ENSO events?
- What are the effects of El Niño and La Niña on Indian monsoon?

2. *Introduction*

The notion that drought in India, Indonesia or the Philippines could be caused by the same condition that produce torrential rains in the United States, Peru and Chili might appear to the casual observer to defy logic but in fact, that is exactly what can happen during the extraordinary change of events known as El Niño. In the recent years, El Niño events have become the focus of intense scrutiny and discussion not only among scientists but within the ranks of the media and the general public as well, however, the conditions that give rise to these events have been well observed before a century.

El Niño and La Niña are the large-scale coupled ocean-atmospheric phenomenon linked to a periodic warming and cooling in sea surface temperature (SST) across the central and east-central equatorial pacific. The genesis behind their formation is complicated as they involve unstable air-sea interaction and planetary scale oceanic waves. Solar activity also plays a role for the development of these processes. They are important because of their global impact and mysterious history. Global impact in the sense they cause drought, flood, increased precipitation, hurricanes, mild winter, brush fire around different corners of the globe. They have a direct impact on the global food market as well global economy. The history behind El Niño and La Niña are mysterious. For example, during the late nineteenth century there were very strong El Niño events (1876-78, 1896-97 and 1899-1902) followed by famines that lead to the death of 30-60 million people all over the world. This was the time when there was a growth of colonialism and entry of capitalism in India, China, Brazil, Ethiopia, Korea, Vietnam, Philippines and New Caledonia.

The Indian monsoon rainfall is highly linked with the global meteorological situations which are technically called Southern Oscillation. The ENSO (El Niño Southern Oscillation) is known to have a pronounced effect on the strength of summer monsoon over India with the monsoon being weak (causing droughts in India) during the El Niño years. La Niña years had particularly good Monsoon strength over India. El Nina and La Niña can be predicted by the use of numerical models. Various ocean and atmospheric variable can be recorded by modern techniques like buoys and satellites. El-Nino and La-Nino episodes have very strong influence on Indian economy as it is fairly associated with drought or flood condition leading to damage to Indian agriculture.

3. Coupled ocean-atmosphere system

Ocean-atmosphere coupling (OAC) is one of the most important topics of climate dynamics essential for understanding climatic phenomena such as El Niño-Southern Oscillation (ENSO) and decadal to multi-decadal climate variability. Understanding the concept of OAC is crucial for predicting changes in global temperature patterns and properties of different modes of climate variability with global warming. The oceans and the atmosphere are the two large reservoirs of water in the earth's hydrologic cycle. The two systems are complexly linked to one another and are responsible for earth's weather and climate. Oceans help to regulate temperature in the lower part of the atmosphere while the atmosphere is in large part responsible for the circulation of ocean water through waves and currents. The theory behind OAC is straightforward: a large-scale anomaly of sea surface temperature (SST) induces diabatic heating or cooling of the atmosphere, which changes atmospheric circulation and hence the wind stress and heat fluxes at the ocean surface. As a result, ocean thermal structure and circulation gets modified, giving rise to a series of positive feedbacks that strengthen the initial SST anomaly. Ocean and atmospheric circulations are interdependent on each other, and the SST serves as a link combining the two elements (Fedorov, 2008). The strength of OAC varies from region to region. In the tropics, the OAC is very strong because tropical wind stress is largely controlled by SSTs whereas in mid-latitudes, atmospheric circulation depends on local SSTs to much weaker extent, which implies a weak dynamical OAC. El Niño is the warm phase of a natural oscillation driven by tropical OAC and perhaps the most striking example of active coupling. The explanation for El Niño and its cold counterpart La Niña, and for the mean zonal SST gradient along the equator (Dijkstra and Neelin, 1995), involves a circular argument: changes in sea surface temperature are both the cause and consequence of wind fluctuations. The details about the two phenomena are described in section 4.

Heat transfer by ocean currents is necessary to maintain ocean-atmosphere connection. The ocean and atmosphere work together in moving the heat and freshwater across latitudes to maintain a partially-stationary climate pattern. The thermohaline circulation fulfils this task for the ocean, by moving warm waters pole ward and colder water toward the equator. Heat exchange between ocean and atmosphere is a product of a number of processes such as (I) solar radiation heats the ocean, (II) net long wave back radiation cools the ocean, and (III) heat transfer by conduction and convection between the air and water generally cools the ocean as does evaporation of water from the ocean surface.

Any imbalance of the heat or freshwater budget due to sea-atmosphere fluxes is compensated by transfer of heat and freshwater by ocean currents. Generally heat transport across latitudes is from tropics to polar regions, but in the South Atlantic ocean the oceanic heat transport is directed towards the equator. This is due to the thermohaline circulation- as warm upper kilometer water is carried northward, across the equator, offsetting the southward flow of cooler north Atlantic deep water near 3000 m. Much of the heat lost to the atmosphere in the North Atlantic is derived from this cross equatorial heat transfer. The flux of freshwater in the north and South Atlantic is southward, as freshwater excess of the Arctic is brought in to offset the net evaporation and influx of salty water from the Indian Ocean.

4. El Niño and La Niña

For better understanding, the two terms are discussed in table 1.

Table 1: A brief definition of El Niño and La Niña

El Niño	La Niña
‘El Niño’ in Spanish refers to ‘the Christ Child’ as it appear in Christmas.	‘La Niña’ in Spanish refers to ‘the girl’.
It is the periodic warming in SST across the central and east-central equatorial Pacific.	It is the periodic cooling of SST across the central and east-central equatorial Pacific.
El Niño appears every 3 to 8 years interval and lasts about 9 months.	La Niña appears every 4-5 years and lasts for 1-2 years.

Mechanism and development:

Events that happen during an El Nina or La Niña year along with their mechanism and development vis-à-vis the condition prevailing during normal situation i.e. a year with no El Niño or La Niña events are discussed here.

Table 2: Ocean-atmospheric dynamics that prevails during a normal year, an El Niño year and a La Niña year

Parameters	**Normal Year**	**El Niño Year**	**La Niña Year**
Pressure	• Low pressure over western Pacific • High pressure over South America	• Higher pressure over western Pacific • Lower pressure over South America	• Lower than normal air pressure over the western Pacific • Higher than normal air pressure over South America
Flow of trade wind	Trade winds blow east to west as shown in Fig. 1	Trade winds weaken or blow west to east as shown in Fig. 1	Trade winds increase in strength and blow even stronger than normal from east to west
Position of thermocline	• Shallow thermocline along South America • Deeper thermocline near western Pacific (Fig. 2)	• Deep themocline along South America • Shallow thermocline along western Pacific (Fig. 2)	• Shallow thermocline along South America • More than normal deeper thermocline near western Pacific
Upwelling	Lots of upwelling, cold water at surface	Little upwelling, warmer water at surface	More than normal upwelling brings cold, nutrient-rich waters to the surface
Thermal status of	Warm ocean waters, clouds and moisture are	• Western Pacific Ocean: Colder	• Western Pacific Ocean: Warmer

Parameters	Normal Year	El Niño Year	La Niña Year
water	pushed away from North America	• Eastern Pacific near the coast of South America: Warmer • Warm surface water sloshes back along equatorial Pacific (Fig. 3)	• Eastern Pacific near the coast of South America: Colder • Warm ocean waters, clouds and moisture are pushed away from North America (Fig. 3).

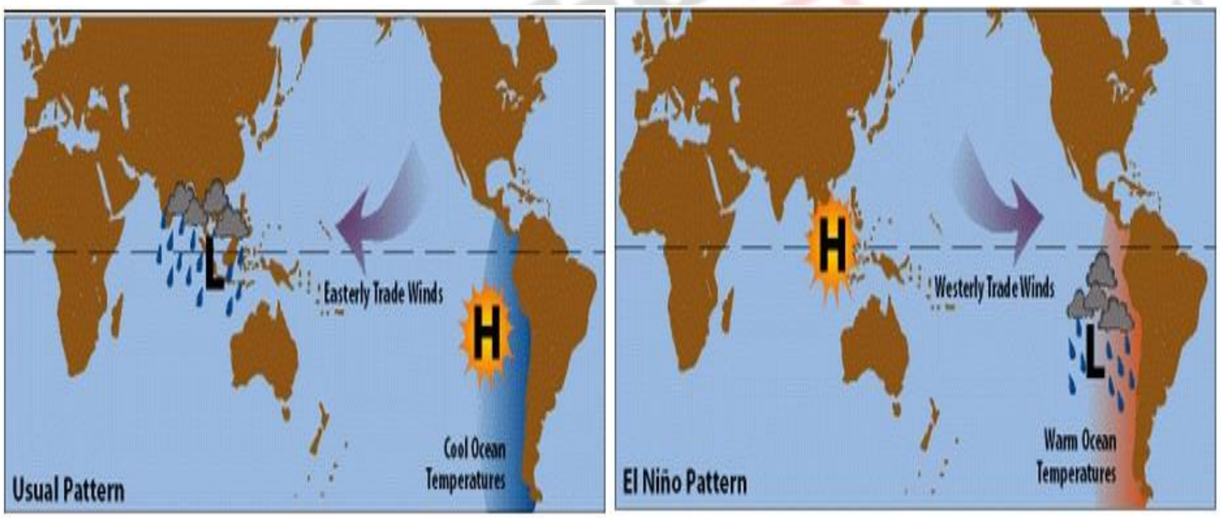

Figure 1: Figure showing the pressure and direction of flow of trade winds during a normal year (left) and during an El Niño year (right). In the figure H stands for High pressure, and L stands for low pressure (Source: http://www.chm.bris.ac.uk/webprojects2002/yung/mechanisms.htm)

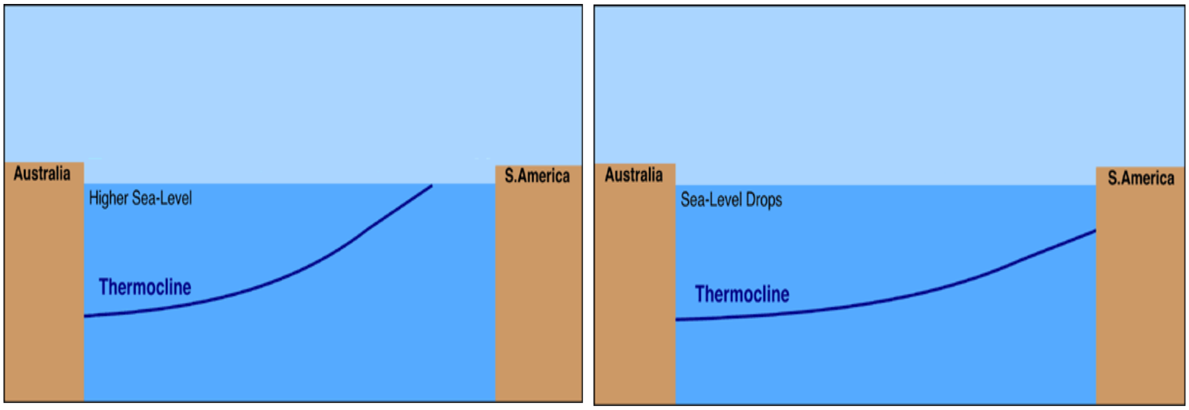

Figure 2: Figure showing the level of thermocline during a normal year (left) and during an El Niño year (right) (Source: http://www.physicalgeography.net/fundamentals/7z.html)

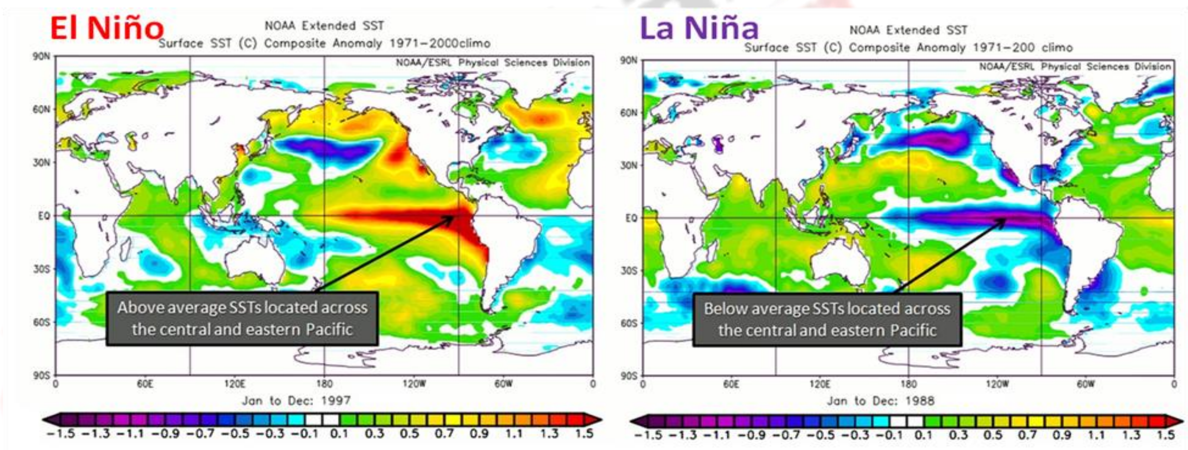

Figure 3: Figure showing the SST during an El Niño year (left) and during a La Niña year (right) (Source: https://www.nc-climate.ncsu.edu/climate/patterns/ENSO.html)

In a normal year with no El Niño condition, Indonesia and the surrounding equatorial areas (western Pacific) have monsoon season during summer. Strong easterly trade winds blow warm surface water from eastern pacific towards western pacific (nearby Australia and Indonesia). This allows cold water to upwell around the eastern pacific (coast of South America), this is when the ocean begins interact with the atmosphere. Colder water results in noticeably high pressure and warmer water results in noticeably low pressure. It is the physical dynamics of the atmosphere that, if there is a warm pool of water and there is a low pressure along with ample of moist air, the prevailing air rises upward and results in formation of clouds and thunderstorm (adiabatic cooling). Much of the moist air mix with the upper-level jet stream flowing towards north America, cools and sinks (adiabatic heating) over the eastern pacific hence completing a cycle (Walker circulation). This process repeats itself again and again until there is an El Niño event (Fig. 4).

During an El Niño year which is also known as the 'warm phase of the ENSO', pressure changes and there is a weakening of the pressure belts. Pressure near the South America (or sometimes near the central equatorial pacific) coast becomes low and the pressure surrounding the Australia and Indonesia coast becomes high. The weaker easterly trade winds otherwise known as 'persistent westerly wind' blows from western pacific towards eastern pacific due to the pressure gradient. The region of rising air moves east with the warm pool, and so does the pumping of heat and moisture into the upper atmosphere, distorting the usual paths of the jet streams, which eventually causes convective rainfall over the central pacific and sometimes over the eastern pacific. Distortion in the usual flow of jet stream also causes the change in weather condition all over the globe. With the weakening of the trade winds, there is a less upwelling found along the South America coast and strong upwelling towards the Australian coast and hence, the thermocline deepens across the eastern pacific (See Fig. 4).

During a La Niña year which is also known as the 'cold phase of the ENSO', pressure again changes to the normal situation and there is much stronger easterly trade winds blows warm surface water from eastern pacific towards western pacific. This causes a strong upwelling across the eastern pacific and the thermocline becomes shallower. Cold water gets build up toward the eastern pacific allowing nutrient-rich water to the surface. During this time, the convection becomes strong over the far western pacific and the normal walker circulation gets enhanced. The dynamics of equatorial pacific atmosphere during a La Niña year is similar to the dynamics during a normal year, but they are stronger and more enhanced than the normal (Fig. 4).

Both El Niño and La Niña began as an atmospheric event which quickly transforms into an oceanic event as the water masses in the equatorial pacific redistribute themselves in response to changes in the wind. This redistribution of mass results in 'flows' which is what we call 'current' but, the redistribution of mass associated with water is also the redistribution of heat and as the heat is moved around this then feeds back into the atmosphere and over quite long distances.

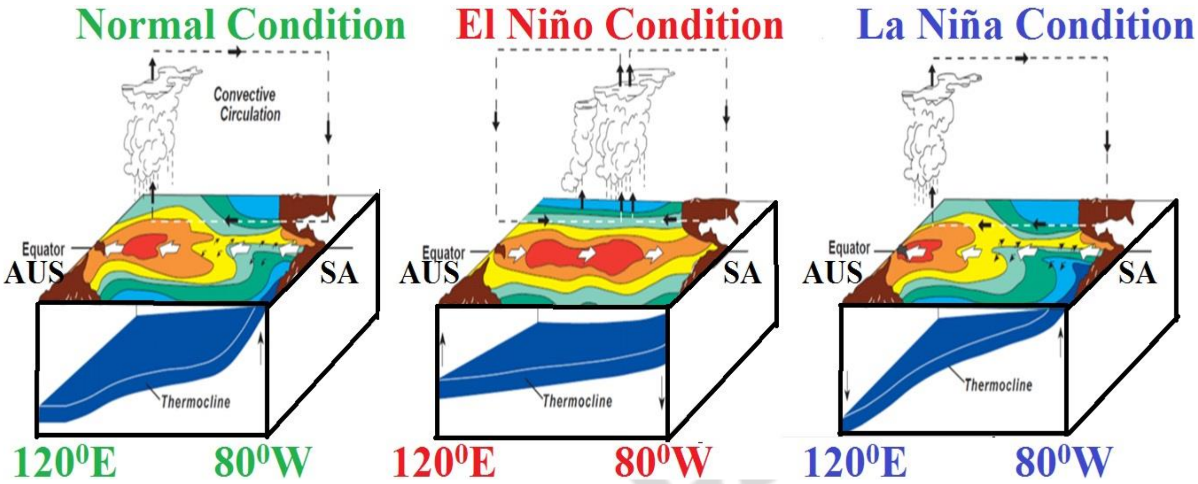

Figure 4: (Left) Neutral conditions showing easterly (east to west) trade winds over the tropical Pacific Ocean which leads to cold water along the equator and warm water in the western tropical Pacific. Convective rainfall is concentrated in the western Pacific. (Center) El Niño conditions showing weakening of the trade winds over the tropical Pacific Ocean that causes relatively warm water to propagate towards the east and convective rainfall shifting to central Pacific. (Right) La Niña conditions showing strengthening of the trade winds over the tropical Pacific Ocean that causes more warm water to build up in the western Pacific and convective rainfall shifting further west than during neutral conditions (Source: http://www.pmel.noaa.gov/tao/proj_over/diagrams/)

5. Monitoring of ENSO events

Monitoring of ENSO conditions primarily focuses on wind and sea surface temperature (SST) anomalies in 4 geographic regions of the equatorial Pacific. The regions are named as Nino1+2, Nino3, Nino4 and Nino3.4 (comprising portions of Niño regions 3 and 4). A brief description about the individual region is given in Fig. 5.

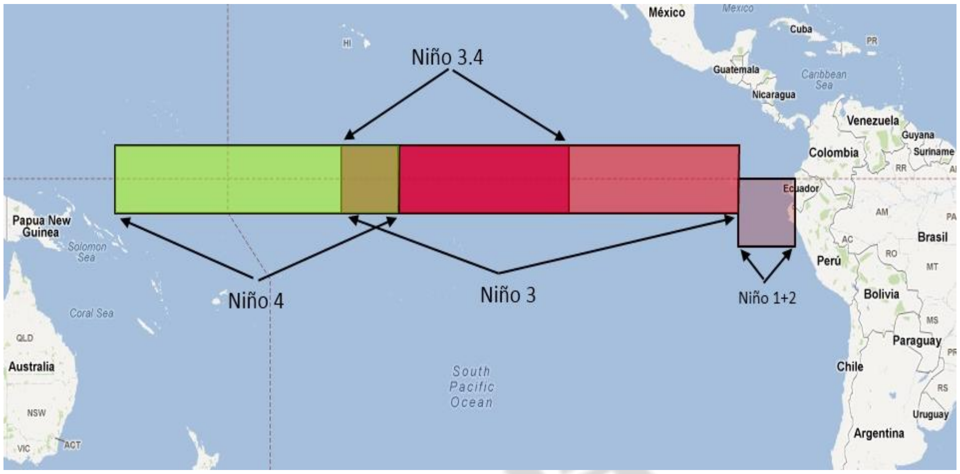

Figure 5: Different Nino Index region for monitoring of ENSO events

(Source: https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php)

- *Nino1+2 (0-10S, 80-90W) region*: This region typically warms first when an El Niño event develops. It is the region of coastal upwelling off the coasts of Peru and Ecuador. This region includes the Galapagos Islands
- *Nino3 (5S-5N; 150W-90W) region*: This region shows largest variability in sea-surface temperature on El Niño time scales. This region encompasses the central equatorial Pacific, where the El Niño and La Niña signals are strong.
- *Nino3.4 (5S-5N; 170W-120W) region*: This region is closer (than NINO3) to the region where changes in local sea-surface temperature are important for shifting rainfall and is typically located in the far western Pacific. This region has become one of the most frequently used areas for monitoring ENSO.
- *Nino4 (5S-5N: 160E-150W) region*: This region includes part of the "warm pool" of the western equatorial Pacific. In this region changes of SST lead to 27.5^{0}C which is an important threshold in producing rainfall

6. *Effects of El Niño and La Niña on Indian monsoon*

Sir G. Walker reported (Walker 1928) that quantity of rainfall in the Indian subcontinent was often negligible in the years of high pressure at Darwin (and low pressure at Tahiti). Conversely, low pressure at Darwin bode well for the precipitation quantity in India. Thus he established the relationship of Southern Oscillation with quantities of Monsoon rains in India. The ENSO is known to have a pronounced effect on the strength of SW Monsoon over India with the Monsoon being weak (causing droughts in India) during the El Niño years. La Niña years had particularly good Monsoon strength over India.

Kumar et al (2006) reported, years with moderate to extreme cold states (Niño3 index < -1) have had abundant monsoon rains in India without exception. On the other hand, years of moderate to extreme warm states (Niño3 Index > -1) have not been reliably dry. The six leading droughts since 1871 have occurred along with a standardized Niño3 index > +1 as shown in figure 6, but the presence of El Niño has not guaranteed drought in India. There is no simple association that describes the relation between the Indian monsoon and Niño3 SSTs when moderate to strong El Niño conditions exist.

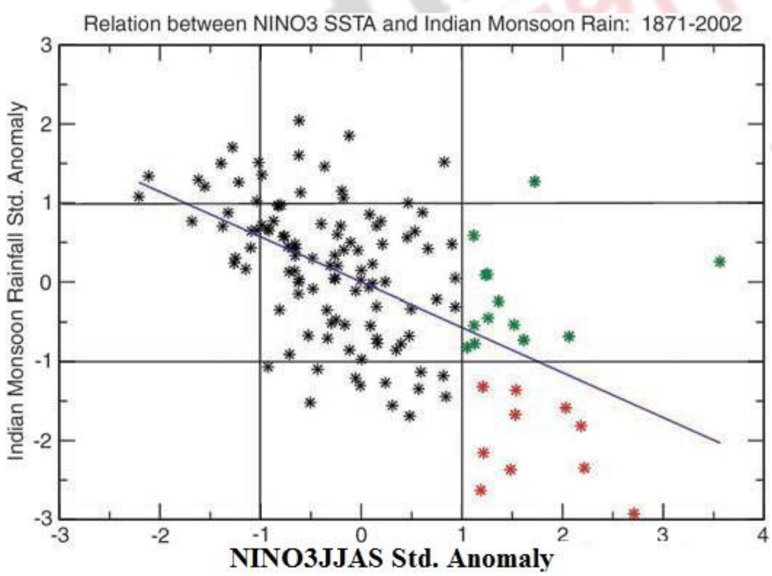

Figure 6: Plot of standardized, all-India summer monsoon rainfall and summer Niño3 anomaly index. Severe drought and drought free years during El Niño events (standardized Niño3 anomalies >1) are shown in red and green, respectively (Krishna Kumar et al., 2006)

The All-India area-weighted mean summer monsoon rainfall (AISMR), based on a homogeneous rainfall data set of 306 rain gauges in India, developed by the Indian Institute of Tropical Meteorology, is widely considered as a reliable index of summer monsoon activity over the Indian region. Long time series of this index since 1871 have revealed several interesting aspects of the interannual and decadal-scale variations in the monsoon as well as its regional and global teleconnections.

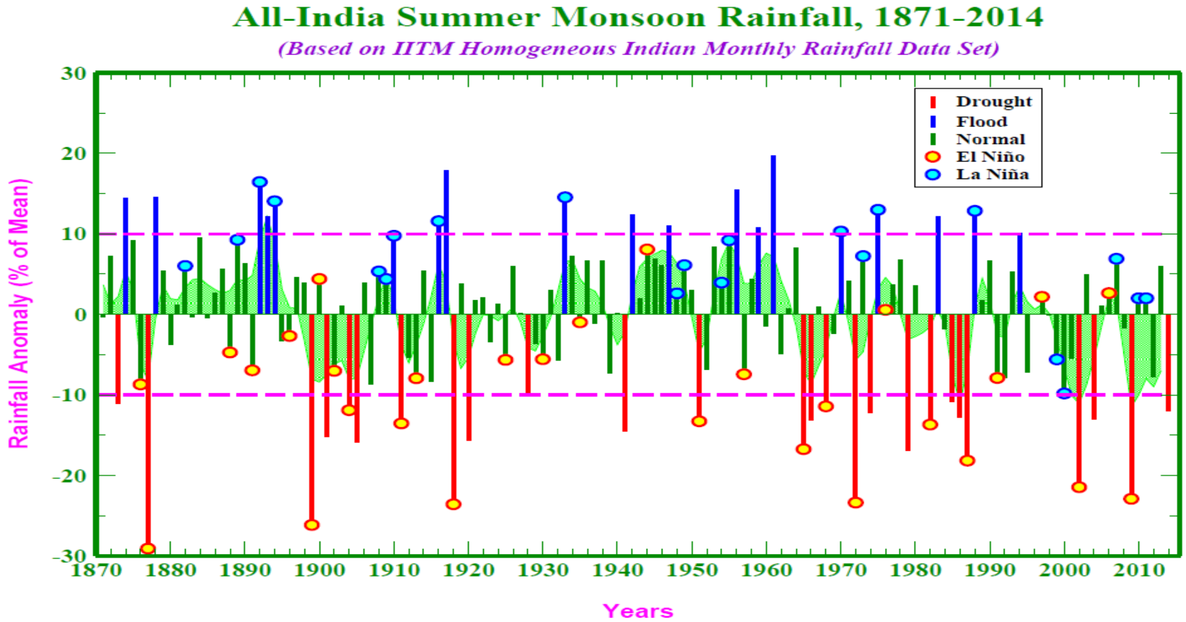

Figure 7: All-India area-weighted mean summer monsoon rainfall, based on a homogeneous rainfall data set of 306 rain gauges, developed by the IITM, Pune

(Source: http://www.tropmet.res.in/~kolli/MOL/Monsoon/Historical/aismr1871-2014.pdf)

It is interesting to note that there have been alternating periods extending to 3-4 decades with less and more frequent weak monsoons over India. For example, the 44-year period 1921-64 witnessed just three drought years as shown in Fig. 7; during such epochs, the monsoon was found to be less correlated with the ENSO. During the other periods like that of 1965-87 which had as many as 10 drought years out of 23, the monsoon was found to be strongly linked to the ENSO (Parthasarathy et al., 1991)**.**The years of flood and drought are given below for the reference of readers.

Flood years: During the period 1871-2014, there were 19 major flood years, defined as years with AISMR in excess of one standard deviation above the mean (i.e., anomaly exceeding +10%; blue bars above) the flood years are 1874, 1878, 1892, 1893, 1894, 1910, 1916, 1917, 1933, 1942, 1947, 1956, 1959, 1961, 1970, 1975, 1983, 1988, 1994. (See fig. 7)

Exceptional flood years: Usually La Niña years in India caused more than normal summer monsoon rainfall but there are years like 1999, 2000 when the amount of rainfall was scanty (or less than the normal rainfall) (See fig. 7)

Drought years: During the period 1871-2014, there were 25 major drought years, defined as years with AISMR less than one standard deviation below the mean (i.e., anomaly below -10%; red bars above) the drought years are 1873, 1877, 1899, 1901, 1904, 1905, 1911, 1918, 1920, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987, 2002, 2004, 2009, 2014 (See fig. 7).

Exceptional drought years: Usually El Nino years in India caused less than normal summer monsoon rainfall (or drought like condition) but there are years like 1900, 1944, 1976, 1997, 2006 when the amount of rainfall was abundant (or more than the normal rainfall) (See Fig. 7).

Table 3: El Niño /La Niño association with all-India summer monsoon rainfall anomalies during 1880-2008

Parameters	**Indian Summer Monsoon Rainfall, 1880-2008**					
	Deficit < - 1.0	**Below Normal - 0.5 to 0.5**	**Near Normal -0.5 to 0.5**	**Above Normal 0.5 to 1.0**	**Excess > 1.0**	**Total**
El Niño	7	5	5	0	1(1944)	18
Normal	14	13	39	14	6	86
La Niña	0	0	7	7	10	24
Total	**21**	**18**	**51**	**21**	**17**	**128**

7. *Summary*

- The coupling between ocean and atmosphere is straight forward: A large-scale anomaly of SST induces diabatic heating/cooling of the atmosphere, which modifies atmospheric circulation as well as the wind stress and heat fluxes at the ocean surface. As a result, ocean thermal structure and circulation gets modified, giving rise to a series of positive feedbacks that strengthen the initial SST anomaly.

- El Niño and La Niña both develop due to large-scale interaction of ocean and atmosphere. SST and Sea surface pressure are the main drivers of these processes. Both of them have significant impact on a global scale due to teleconnection. The impacts of El Nino and La Nina are more devastating than fortunate.
- El Niño episode is characterised by deficient/less than normal rainfall in Indian subcontinent while La Niña episode is characterised by more than normal rainfall in the Indian subcontinent. There is no simple association describes the relation between the Indian monsoon and Niño3 SSTs when moderate to strong El Niño conditions exist.

A Gateway to All Post Graduate Courses