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Relationships Between the Indian Monsoon,
El Niño, and La Niña

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RELATIONSHIPS BETWEEN THE INDIAN MONSOON, EL NIÑO, AND LA NIÑA

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This research examines the relationships between the Indian Monsoon system and three phenomena that occur across the equatorial Pacific Ocean: El Niño, La Niña, and the Southern Oscillation. The Indian Monsoon can be divided into a winter and summer component. These two components may affect oceanic and atmospheric conditions across the Pacific Ocean. In contrast, the oceanic and atmospheric state of the Pacific Ocean may affect the dynamics of the two components of the Indian Monsoon. Dr. Peter Webster of the University of Colorado at Boulder has shown that the Indian Monsoon system tends to be stronger during years associated with La Niña conditions and the system tends to be weaker during years associated with El Niño conditions. To show that there are relationships between the two components of the Indian Monsoon, El Niño, and La Niña, this research will examine oceanic and atmospheric mechanisms across the equatorial Pacific Ocean, illustrations, and graphs to determine why there is variability in the monsoon system.

Settlements across the world have long depended on the weather for agricultural success and economic prosperity, in particular, Southeast Asia and India. Over the past few hundred years, explorers and scientists have become very interested in the secrets of the atmosphere. Early traders in southern Asia had knowledge of annual wind currents and they were able to adapt their trading practices to them. Once the secrets of the wind were released to other mariners and trading societies, well known trade routes quickly arose that coincided with the wind. After an Arab pilot showed the ancient Portuguese mariner, Vasco de Gama, the secret of navigation between East Africa and India, routes that followed the monsoon winds became the basis of lucrative European trade and cultural link between eastern and western civilizations (6 Webster et al). Now that many years have passed since the dawn of this diversifying cultural link, the development of sophisticated technology has made it possible for scientists to determine the mechanisms behind these wind currents. Recorded data of land and ocean temperature profiles, sea level pressure, atmospheric pressure at different heights of the atmosphere, rainfall amounts, crop yields, and the ability to view satellite images and radar have given scientists the power to better predict the strength and persistence of the monsoon system. The purpose of this research is to identify the mechanisms that are responsible for the development of the Indian Monsoon and determine how these mechanisms coincide with other oceanic and atmospheric phenomenon that may be responsible for the variability of the monsoon system.

On a large scale, the Indian Monsoon system develops due to the astrophysical behavior of the Earth. During perihelion, the Earth's axis is tilted in such a way that the northern hemisphere receives less direct radiation from the sun. The result is winter in the northern hemisphere and the corresponding winter component of the monsoon. The large continental area of Asia is allowed to cool considerably forming a dense, descending air mass over land. The constant cool, dense air mass descending over the continent allows for a higher atmospheric pressure to develop. In contrast, the Indian and Pacific Oceans are in a state where the water is still relatively warm due to the heating of the previous summer. These oceans cool more slowly than the continent because water can retain heat longer. The persistent warm, less dense air mass ascending over the ocean allows for a lower atmospheric pressure to develop. A pressure gradient forms due to high pressure that has developed over the continent and low pressure that has developed over the ocean. As these two pressures become more extreme the pressure gradient increases. Atmospheric motion takes place because the work done by the pressure gradient force converts the potential energy into kinetic energy (17 Webster et al). The result is that air begins to flow in a direction of high pressure to low pressure, and consequently, from the land to the ocean. Figure 1 illustrates the wind flow from high pressure towards low pressure. Since there is little moisture available over land, dry winds blow off of the continent and over the ocean. There are several other factors that lead to the dynamics of the pressure gradient field but they will not be discussed here.

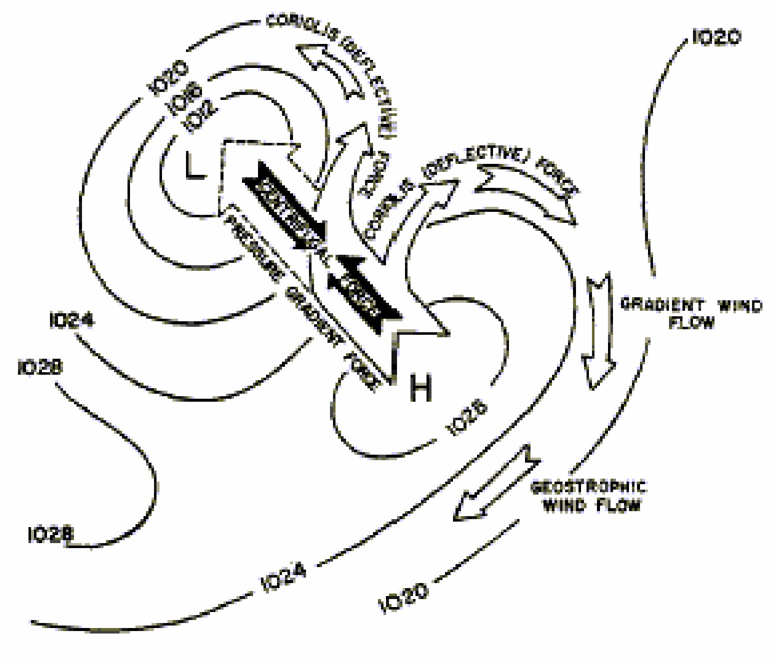

Fig. 1. Pressure Gradient Force resulting from the development of high and low pressure over the surface of the Earth. The solid lines represent areas of equal barometric pressure. (Courtesy of Integrated Publishing)

During aphelion, the Earth's axis is tilted in such a way that the northern hemisphere receives more direct radiation from the sun. This results in summer in the northern hemisphere and the corresponding summer component of the monsoon. The large continental area of Asia is allowed to warm considerably forming an ascending, less dense air mass over land. The warm, less dense air mass ascending over the continent allows for a lower atmospheric pressure to develop. In contrast, the Indian and Pacific Oceans are in a state where the water is now relatively cool compared to the land, due to the cooling of the previous winter. The specific heat, defined as the amount of heat required to raise a given mass of a substance one degree Celsius, of water is twice that of dry soil (12 Webster et al). Thus, the heating over Southeast Asia and India creates a land temperature higher than the ocean temperature. The relatively cool, dense air mass over the ocean allows for a higher atmospheric pressure to develop. A pressure gradient forms due to low pressure that has developed over the land and high pressure that has developed over the ocean. As in the winter scenario, these two pressures become more extreme and the pressure gradient increases. The pressure gradient force again causes atmospheric motion to take place. See also Figure 1. The abundant moisture available over the ocean causes moist winds to blow over the continent. This signals the beginning of the rainy season over Southeast Asia and India.

Even though these mechanisms of the monsoon system are consistent, the monsoon is not like an on/off switch, there is variability that occurs in the system. The main forces that drive the variability of the monsoon system are El Niño, La Niña, and the Southern Oscillation. El Niño and the Southern Oscillation are often grouped together and referred to as El Niño/ Southern Oscillation, or ENSO. The strength of the Indian Monsoon depends on the strength of these atmospheric phenomena. Likewise, the strength of these phenomena depends on the strength of the Indian Monsoon. Every few years, an El Niño event produces a warming of the sea surface temperatures (SSTs) in the central and eastern Pacific, accompanied by diminished easterly trade winds and an eastward shift in tropical convection. A La Niña event, which sometimes follows a warm event, produces an anomalous westward shift in warm SSTs and convection, as well as enhanced easterly trades (2670 Torrence and Webster). The Indian Monsoon is affected greatly by the differences that are introduced by El Niño and La Niña. The position of the warm SSTs and resulting convection over the Pacific Ocean is very important when considering the strength of the monsoon. When an El Niño event is occurring the Indian Monsoon tends to be much weaker than normal. The result of the weak monsoon is drought conditions across much of Southeast Asia and India and fires in Australia. In South America disastrous floods may occur resulting in depression of their economy. When a La Niña event is occurring the Indian Monsoon tends to be much stronger than normal, characterized by flooding rains over Southeast Asia , India, and Australia. South America and Mexico may experience drought conditions along with fires. It can also be seen that a strong monsoon tends to inhibit warm events and favor cold events (2670 Torrence and Webster). It is very difficult to predict a strong or weak monsoon because of the dependence of ENSO on the monsoon and the monsoon on ENSO.

The Southern Oscillation component of ENSO is measured by the Southern Oscillation Index (SOI), usually defined as the anomalous sea level pressure (SLP) in the eastern Pacific at Tahiti (17.6°S, 149.6°W) minus SLP in the western Pacific at Darwin, Australia (12.4°S, 130.9°E) (2680 Webster and Torrence). The Southern Oscillation is the oscillation of SLP that occurs across this region. When the waters off the west coast of South America are abnormally warm, the SLP in the eastern Pacific drops. The reduction of the SLP results in a weakening of the trade winds (Hodell and Thomas). The warming of the water and the weakening of the trade winds are innate relationships but it is not known which one occurs first. It is possible that the relationship may be due to a building frictional force of the trade winds as they try to blow west up the pressure gradient. The weakening trade winds prevent water from being transported westward across the equator along the North Equatorial Currents (NEC) and the South Equatorial Currents (SEC). There is also a current known as the Pacific North Equatorial Countercurrent (NECC) that occurs in between the NEC and the SEC. The NECC is a major surface current in the tropical ocean, transporting more than 20 Sv of water eastward out of the warm pool region (Yu and Kessler). It may be that the reduction of westward flowing water due to weakening trade winds decreases boundary friction along the NECC resulting in more eastward warm water propagation. The warm pool of the western Pacific will then contribute to the increase of abnormally warm water over the eastern Pacific. The warm water that is moving into the eastern Pacific Ocean reduces the amount of cold water upwelling in that region. The result is a low SLP in the eastern Pacific and a negative SOI. The corresponding relationship is a weak monsoon year with deficient rainfall. Figure 2 illustrates this relationship. When the SST of the eastern Pacific is above normal, the SOI is low, and the rainfall in India is below normal.

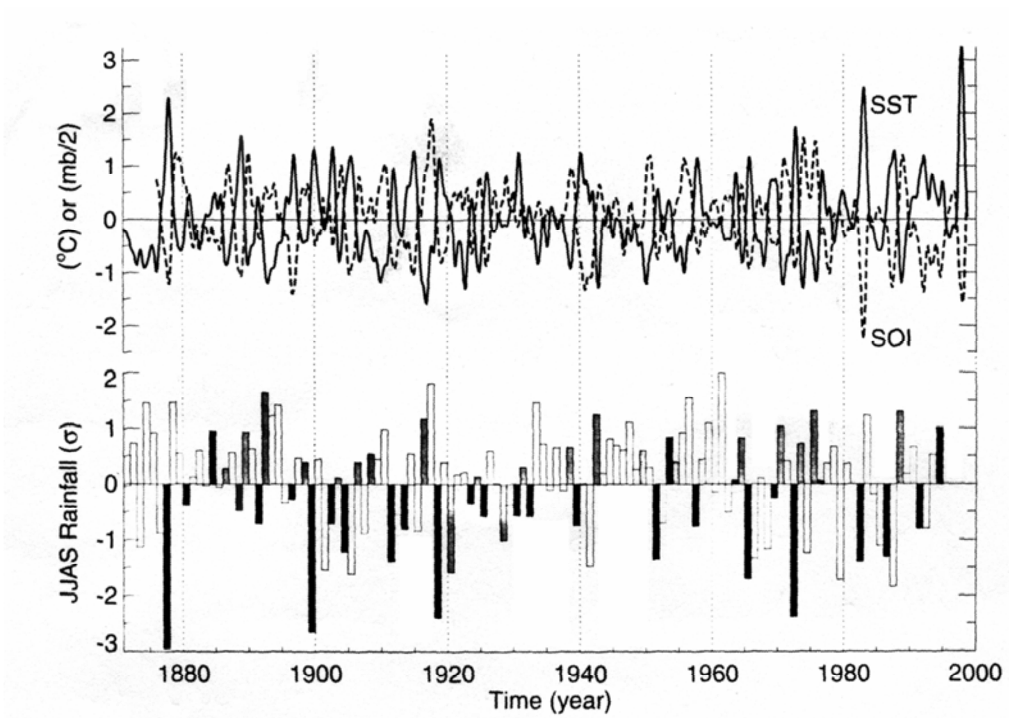

Fig. 2. The solid line represents the SST of the eastern Pacific. The dashed line represents the SOI. The light bars indicate rainfall amounts for June, July, August, and September for India during El Niño. The dark bars indicate rainfall amounts for the same period during La Niña. (Courtesy of Torrence and Webster, 1999: *Journal of Climate*, **12**, 2682)

It is now important to consider the effects the ocean has on the atmosphere to determine any other relationships that may exist between the Indian Monsoon and the equatorial Pacific Ocean. When the water in the eastern Pacific is warmer there is more evaporation and convective cloud motions. The large scale rising air motions that occur over the eastern Pacific reach the top of the troposphere and flatten out. These upper level air currents then travel in an eastward and westward direction. The upper level air currents that flow eastward descend east of South America. It is possible that this may decrease the frequency of hurricane formation over the Atlantic Ocean. The upper level wind currents that are traveling westward eventually descend over the western Pacific. While these winds are traveling westward they come in contact with the Walker

Circulation. It is well known that substantial difference of the sea surface temperature between the western and the eastern part of the Pacific Ocean causes the longitudinal-orientated mean circulation called the Walker Circulation (Yano and Clayton). In most cases the water in the western Pacific is warmer than the water in the eastern Pacific, except during El Niño conditions. When the westward traveling wind currents come in contact with the Walker Circulation they cause it to break down. The normal convection that occurs over the western Pacific is either displaced in a direction towards the large scale El Niño convection or becomes weak and almost disappears. Figure 3 illustrates the displacement of the Walker Circulation during an El Niño. The displacement of the

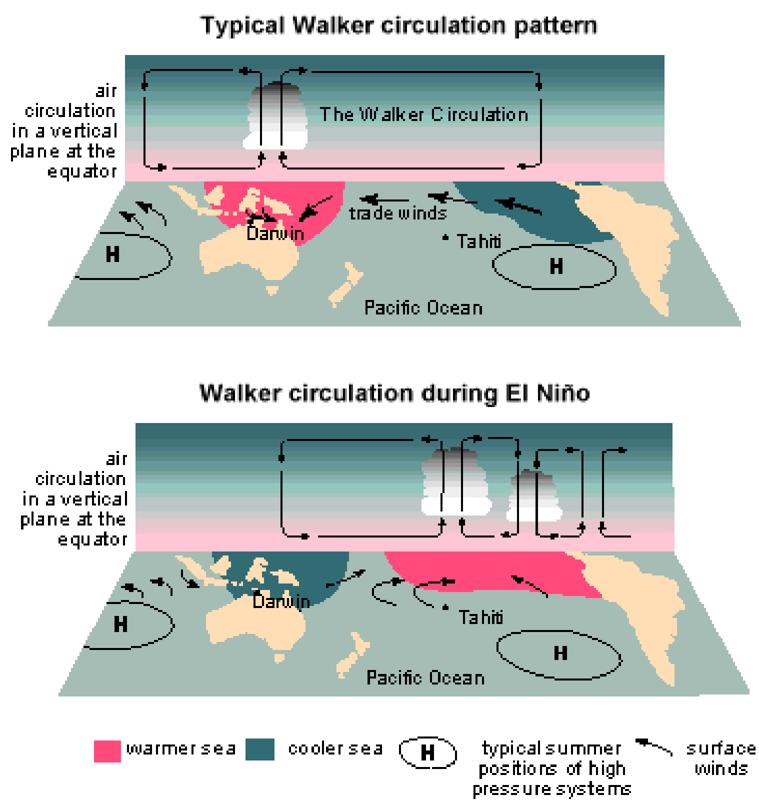

Fig. 3. The Walker Circulation is displaced to the east during periods of El Niño. Rising air motions in the western Pacific are replaced by descending air motions due to El Niño. (Courtesy of the Bureau of Meteorology)

Walker Circulation magnifies the weak monsoon due to the large scale descending air motions over the western Pacific and Southeast Asia region.

Now that the Walker Circulation has been displaced or even somewhat vanished the area of convection that would normally occur across this area is absent. When the winter monsoon is developing it is possible that a stronger high pressure results because the air is already descending over the region. The large-scale strong high pressure that forms will cause winds to blow away from land in a more dramatic manner and the forcing from the winter monsoon increases. The strong pressure gradient force may allow for winds over southern Asia to blow farther away and interact more heavily with the Pacific Ocean. The water that is forced across the Pacific Ocean by strong westerly winds will eventually build up along the coast of South America. The sea level will slowly rise in the eastern Pacific until it becomes higher than the sea level in the western Pacific. Warm water that is present in the eastern Pacific will be forced down the gradient towards the west. The trade winds in this area are increased so water may be transported more rapidly along the NEC and the SEC. The increase of the NEC and SEC surrounding the NECC may increase boundary friction along the NECC and decrease the transport of warm pool water to the east. In addition, the increased flow of water to the west results in upwelling of cold water along the coast of South America. Cold water takes over this region therefore evaporation and convection in the eastern Pacific is reduced. The Walker Circulation may resume its typical role as seen in Figure 3. This type of atmospheric circulation is more associated with non-El Niño conditions and La Niña. The persistence of El Niño may allow for the Walker Circulation to drift east until the winter monsoon can build up enough force to push ocean water to the east and cause the SOI to become positive. As seen in Figure 2, when SST in the eastern Pacific is below normal, the SOI is positive, and rainfall in India is above normal.

All of these ideas are not concrete due to the chaotic manner of the atmosphere but they do strongly suggest there are relationships that exist. Dr. Peter Webster says either the monsoon system is part of an evolving and systematic series of feedbacks and processes, or it is a part of a complex hierarchy of circulations and processes where relationships between them periodically wax and wane. It would seem that the emerging view is one where the monsoon is seen as a coupled-ocean-atmosphere system, where the monsoon interacts with ENSO and eventually ENSO feeds back on the monsoon. One mechanism stated by Webster that could affect the seasonal monsoon circulations and rainfall is that boundary anomalies, such as produced by ENSO, produce a temporally persistent and spatially large-scale descent over the monsoon region reducing rainfall either by reducing the intensity and life cycle of the monsoon disturbances or by producing a displacement of the mean rainfall patterns (14,504 Webster et al). The hypothesis that is suggested in regards to the Walker Circulation is simply a circulation pattern that could cause variability in the monsoon due to ENSO. In general, when there is a warm episode in the Pacific Ocean there will be a weak monsoon and when there is a cold episode in the Pacific Ocean, there will be a strong monsoon. A study that was performed by Webster et al showed that there was a 0.61 correlation of all Indian rice production to El Niño and La Niña. The study showed that some periods of production deficit are associated with El Niño years in the Pacific Ocean while some abundant years are associated with La Niña, or "cold" events in the Pacific (14,452 Webster et al). A correlation equal to 1.00 would yield a perfect relationship. So it is obvious that the relationship is not perfect but the correlation is relatively high for global weather phenomena.

In conclusion, there are several factors that lead to the variability of the Indian Monsoon. Ultimately, El Niño, La Niña, and the Southern Oscillation are the main contributors to this variability. The strength of the Indian Monsoon can affect the strength and duration of El Niño and La Niña, and vice versa. Even though the relationships between these atmospheric phenomena are not perfect, continuing professional studies make it possible for atmospheric scientists to better predict the onset times and duration of these events. The ultimate goal to understanding the relationships between the Indian Monsoon, El Niño, and La Niña is to forewarn communities that live in these areas when the monsoon will come and for how long it will last. This is important because it gives farmers the knowledge about what kinds of crops to be planted and when to plant them. This will indeed have impacts on the economics of Southeast Asia, India, and the whole world.

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