Monsoons Elsewhere in the World

R. R. Kelkar[1]

1. Introduction

The phenomenon which is commonly known as the monsoon can be looked upon, from the meteorological standpoint, as the response of the state of the atmosphere to the annual migration of the sun relative to the earth, between the Tropic of Cancer in the northern hemispheric summer and the Tropic of Capricorn in the southern hemispheric summer. The monsoon is actually an extremely complex and intricate combination of physical processes that operate not only in the atmosphere, but involve land and ocean as well. Monsoons should therefore be found over the entire tropical belt of the earth and possibly even extend into the sub-tropics. That we do not find monsoons everywhere in this region, is more because of a restrictive definition of the monsoon than otherwise.

The first scientific explanation of the monsoon was postulated by Sir Edmund Halley, a British mathematician and astronomer in whose honour a comet has been named. Drawing from the experiences of various mariners and navigators who were well-acquainted with conditions in the tropics, Halley made an extensive analysis of the global patterns of trade winds that blew over the Atlantic, Pacific and Indian oceans and the seasonal change of wind direction associated with the monsoons. In 1686, he presented to the Royal Society in London his own hypothesis (Halley 1686) that the monsoon was caused by the differential heating between the Asian landmass and the Indian Ocean. In other words, the monsoon has the character of a giant land-sea breeze that reverses its direction twice during a year. In April, when the sun starts heating the land, the southwest monsoon begins and blows until October; then the land cools and the northeast monsoon blows in the winter until April.

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[1] The author was Director General of Meteorology, India Meteorological Department from 1998 to 2003 and ISRO Space Chair Professor, University of Pune from 2004 to 2008.

The beauty of Halley's empirical proposition lies in its simplicity. That is why it has survived for more than three centuries and is still talked about. It is difficult to discard it altogether and it is even more difficult to offer an equally elegant alternative. In fact, land temperatures over the Eurasian continent and sea surface temperatures over the Indian Ocean are the two factors that have continued to dominate all efforts to understand and predict the monsoon, but of course in an increasingly complex manner. However, Halley's definition of the monsoon is based only upon the reversal of wind and it does not involve rainfall (Figure 1). From the practical point of view, rainfall is a very important byproduct of the wind reversal process, perhaps more important than this process itself. In this respect it would be unfair to blame Halley as in his times, a global observation system hardly existed. It is only now that we know that rainfall over the entire tropical belt and the adjoining subtropics shows an annual oscillation (Figures 2 and 3).

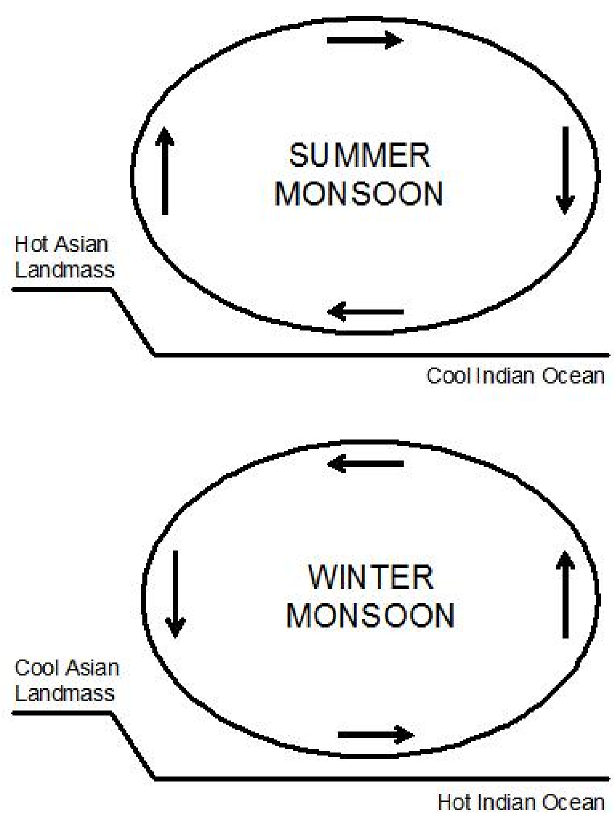


Figure 1. A conceptualisation of Halley's hypothesis that the Indian monsoon is a giant land-sea breeze between the Asian landmass and the Indian Ocean (from Kelkar 2008)

The oceans had been a generally data-sparse region for long, but particularly so in the case of rainfall. It was only after the launch of geostationary meteorological satellites like INSAT, that it became possible to indirectly estimate the large scale precipitation over the oceans (Arkin, Rao and Kelkar 1989) and the real breakthrough came with the Tropical Rainfall Measurement Mission (TRMM) satellite that carried an onboard precipitation radar. Under the Global Precipitation Climatology Project (GPCP), rain gauge measurements and satellite-based rainfall retrievals have been skillfully blended and extensive rainfall data sets and statistics have been compiled. With the help of the GPCP global analyses it is now possible to quantify the seasonal alternation of the precipitation patterns in the monsoon domains of the world, something that Halley could only have conceptually visualized in 1686, in the absence of any data to support his argument. The GPCP maps which are based upon data from 1979 onwards, clearly depict how in January (Figure 2), the Indian subcontinent is almost devoid of any significant precipitation, the rainbelt associated with the ITCZ having shifted to the south of the equator over the Indian Ocean. In July (Figure 3), on the other hand, some of the rainiest areas of the world are over the Bay of Bengal, northeast India, and the west coast of India in association with the southwest monsoon.

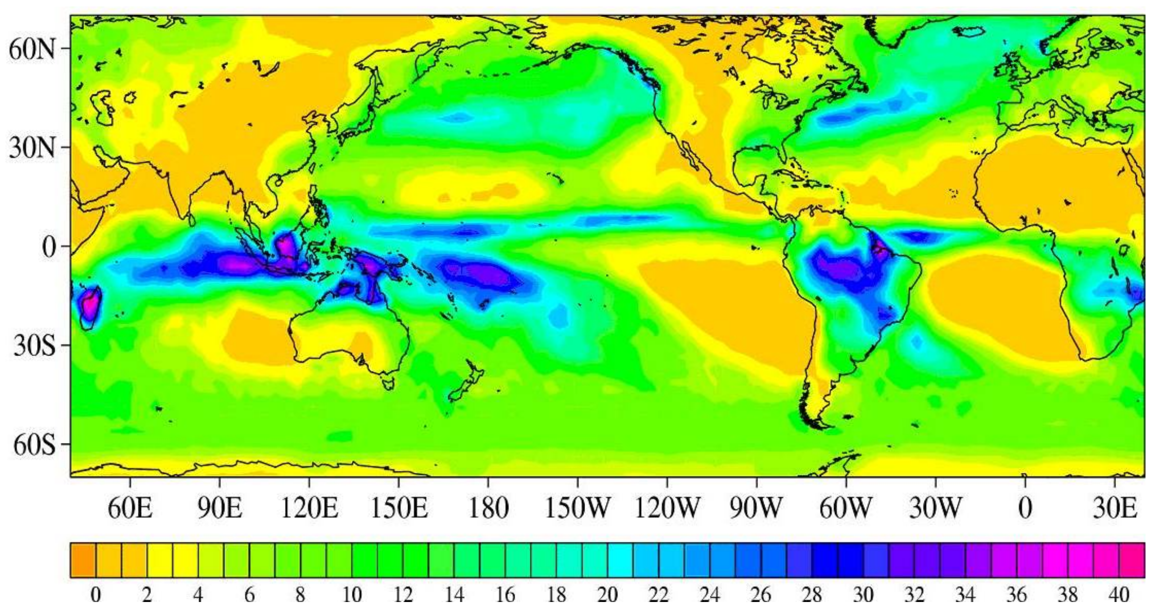


Figure 2. Average January precipitation in cm (from Global Precipitation Climatology Project GPCP 2008)

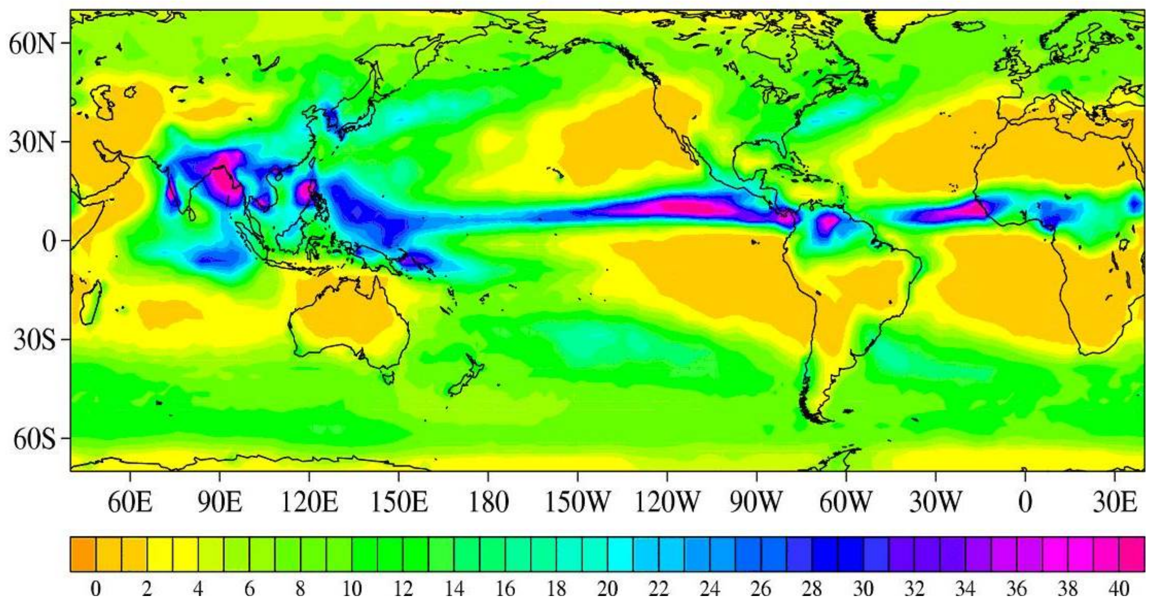


Figure 3. Average July precipitation in cm (from Global Precipitation Climatology Project GPCP 2008)

2. Delineation of Monsoon Regions

Although by the twentieth century it was known that monsoons prevailed in many parts of the world, it was Ramage (1971) who made the first attempt to delineate the monsoon regions on the basis of objectively prescribed criteria. He stipulated that for any given geographical region to qualify being called a monsoon region, the wind patterns over it in January and July must be distinctly different and should satisfy certain basic considerations. Ramage's criteria were that the prevailing winds in these two months should blow in a preferred direction at least 40% of the time, they should have a minimum strength of 3 m/sec and there should be a change of at least 120º in the prevailing wind direction between the two months. On this basis, he delineated the monsoon region as the geographical area bounded by the latitudes 35º N and 25º S, and the longitudes 30º W and 170º E (Figure 4). Although Ramage's criteria were objective, they were still arbitrary to a certain extent, and they restricted the monsoons to south and southeast Asia, northern Australia and tropical Africa. These came to be regarded as the traditional or classical monsoon domains.

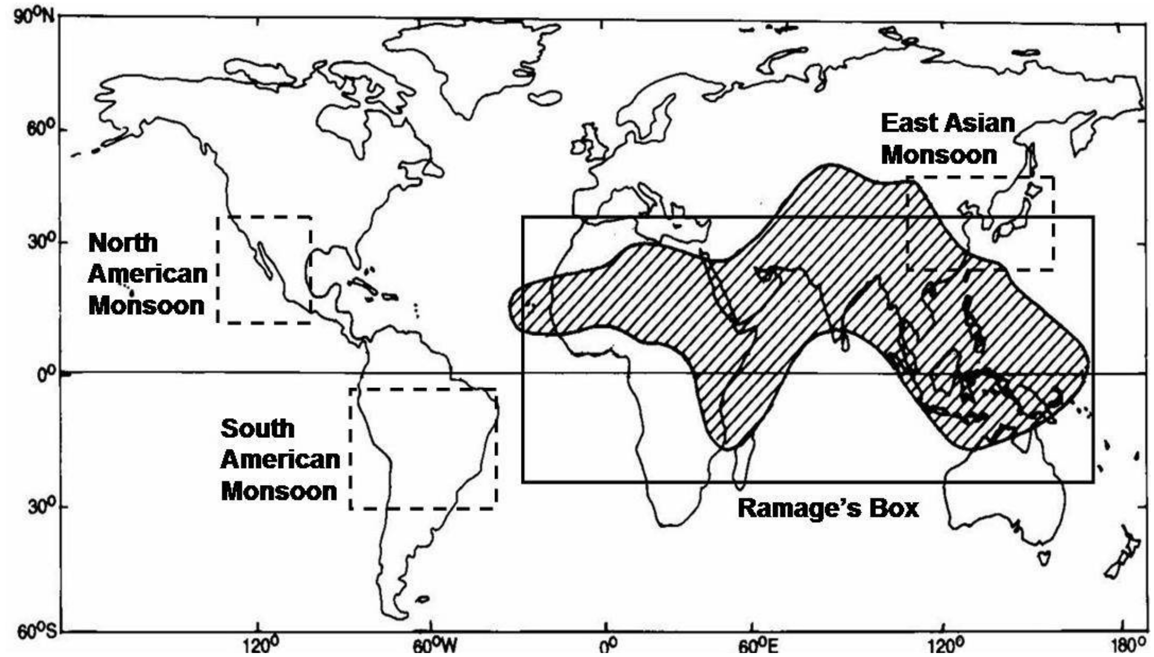


Figure 4. Classical African, Asian and Australian monsoons (hatched area), Ramage's delineation, and the new monsoon zones shown by dashed lines (from Kelkar 2008)

3. Monsoons and the ITCZ

Perhaps the most inclusive definition of the monsoon was that given by Asnani (1993) in which the role of the Inter-Tropical Convergence Zone (ITCZ) was brought into consideration. The ITCZ that circles the globe (Figure 5) is a region of lower tropospheric wind discontinuity with horizontal velocity convergence and net upward motion. While the ITCZ band has a large latitudinal width, the band as a whole exhibits a north-south movement in association with the march of the sun, and the belt of heavy tropical rainfall also shifts along with it. The seasonal wind reversals and changes in precipitation patterns are not just confined to the traditional monsoon domains, but they also occur elsewhere in the ITCZ region.

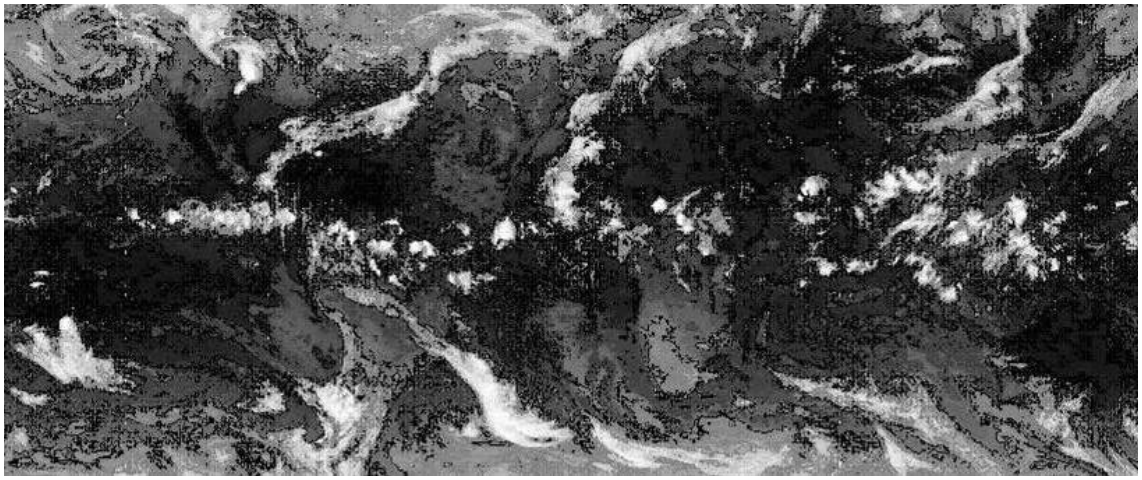


Figure 5. A typical montage of satellite images showing the ITCZ as a band of cloud clusters encircling the globe (from Kelkar 2008)

An important feature of the ITCZ is the large regional variations in its seasonal alignment (Figure 6). Over the eastern Pacific and Atlantic oceans, it remains to the north of the equator throughout the year. In other regions, it moves from the north of the equator in northern summer to the south of the equator in southern summer. Over land the ITCZ is located over the warmest regions, while over the sea it is located over the highest sea surface temperature (SST) regions. From west Africa to southeast Asia, there is a discontinuity between the westerlies in the near-equatorial region and the easterly trade winds on either side of the ITCZ. The westerlies are largely the southeast trade winds which have changed direction after crossing the equator. Over the Atlantic and Pacific oceans, the discontinuity is between the northeast and southeast trades of the two hemispheres.

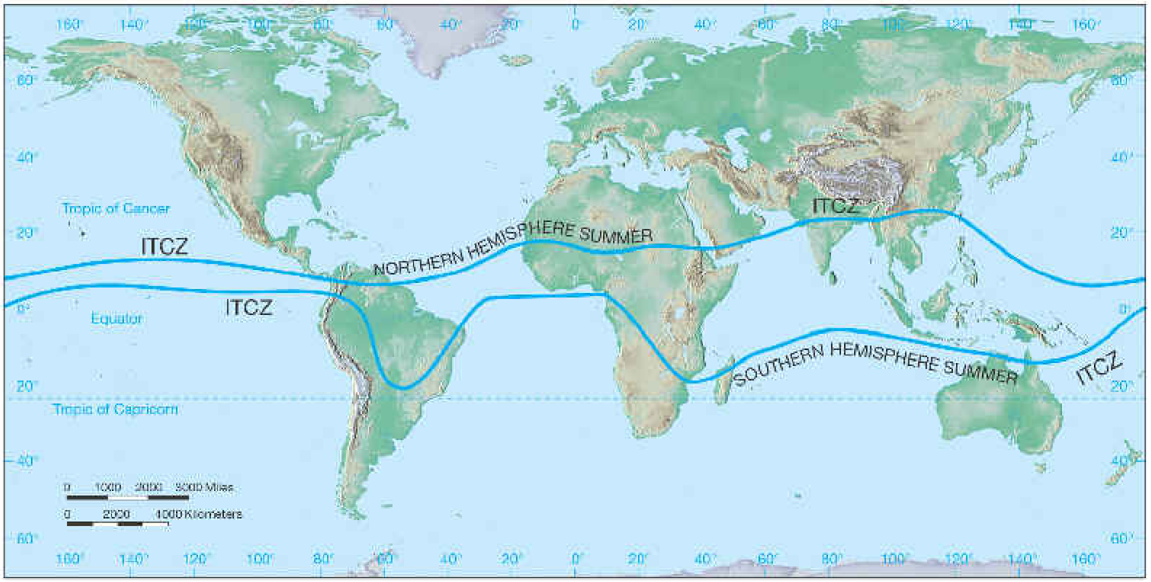


Figure 6. The alignment of the ITCZ in January and July

Asnani's definition of the monsoon was simple: 'the monsoon is where the ITCZ is', but it paved the way for what could be called the globalization of the monsoon. Going by this inclusive definition, the monsoons could now be said to prevail over the entire area covering the global tropics and adjoining subtropics (Asnani 2005a, 2005b). Therefore, our contemporary view of the monsoons is not just in terms of the seasonal reversal of winds, which of course remains an important consideration, but more in terms of the amplitude of the seasonal change, which is larger over the monsoon regions than elsewhere in the tropics. The cause of the larger amplitude is that over the continental regions the land surface heating is determined by the net radiation, whereas the ocean heating is influenced additionally by the winds that drive the ocean circulation. In the non-monsoonal oceanic regions, the location of the maximum SST does not vary with the seasons (Gadgil 2007).

As far as the south Asian monsoon is concerned, the monsoon oscillation is stronger in the northern hemisphere than in the southern hemisphere, and it is stronger over south and southeast Asia than elsewhere in the northern hemisphere. This can be attributed to the Himalayan mountains and the elevated Tibetan plateau producing diabatic heating over a large area of the middle troposphere, the Indian Ocean to the south providing abundant moisture supply and the strong meridional gradients of temperature (Asnani 2005c).

Despite the fact that over large areas of the Pacific and Atlantic oceans the ITCZ does not oscillate between the southern and northern hemispheres, the monsoon is currently being viewed as a persistent global scale overturning of the atmosphere which occurs over the entire tropics and subtropics and has an annual cycle (Trenberth et al 2000). Embedded within this global monsoon circulation are the more significant and well-known regional monsoons of Asia, Australia and Africa. Against the concept of a global monsoon, Hadley's classical notion of a large scale thermally driven land-sea breeze appears to be greatly idealized and region-specific. In fact, over some of the newly identified monsoon regions such as north and south America and east Asia, the wind reversal factor is not significant.

4. Asian Monsoon

The Asian monsoon in its totality is by far the largest monsoon system of the world. Over land, the Asian monsoon region includes the Indian subcontinent and the Indo-China peninsula, and extends northeastwards across mainland China further into Korea and Japan. Over the ocean, it covers the South China Sea and the northwest Pacific Ocean. However, the Asian summer monsoon system could be said to consist of two large and distinct regional subsystems: the Indian southwest monsoon or the south Asian monsoon and the east Asian monsoon. These two subsystems are indeed interrelated, but they are also capable of operating independently of each other at times. The phenomenon of the Asian monsoon has been treated exhaustively by Asnani (2005d) and a concise description of the east Asian summer monsoon has been given by Kripalani et al (2007).

The east Asian summer monsoon is largely a subtropical phenomenon and its most significant is the quasi-stationary front that extends from south China to Japan. Different parts of this long-winding front bear different local identities: like Mei-yu in China, Chang-ma in Korea and Bai-u in Japan. The front can be traced along the northwestern periphery of the north Pacific subtropical high whose alignment and strength have a direct influence on the monsoon (Figure 7). When the high extends more to the west, the low level jet to its northwest gets strengthened, bringing more moisture into the Yangtze river basin and leading to increased monsoon precipitation. The west Pacific warm pool which is situated at the southern edge of the high also influences the east Asian monsoon.

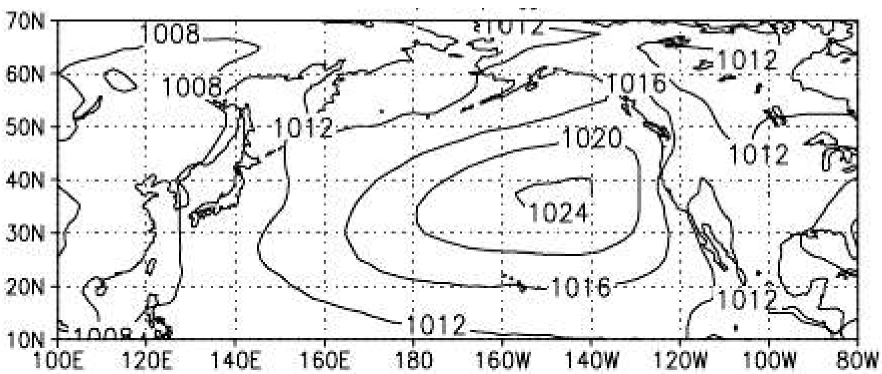


Figure 7. Average June-August sea level pressure in hPa over the east Asian monsoon region showing the north Pacific subtropical high (from Kripalani et al 2007)

The climatological mean date of onset of the monsoon over the South China Sea is around the middle of May. This results as a combination of the tropical deep convective rainfall over the equatorial region and the rainfall associated with the subtropical front over south China. After this onset has taken place, the monsoon rainbelt runs from the Arabian Sea across the Bay of Bengal, through the South China Sea, to the northwest Pacific Ocean. It is associated with the characteristic southwesterly winds that connect the south Asian and east Asian monsoons. The monsoon then advances to the north and northeast across the Yangtze river basin into south Japan by middle of June. It subsequently enters north China, Korea and north Japan. The advance of the east Asian monsoon does not proceed at a steady pace and it could be very rapid or extremely sluggish in phases. The southeastern plains of China receive a mean annual precipitation of over 150 cm. The northwestern regions are much drier, the Gobi desert getting only 25 cm of rain, and in some parts even less than 10 cm, annually. The average June-August precipitation pattern over the east Asian monsoon region is shown in Figure 8.

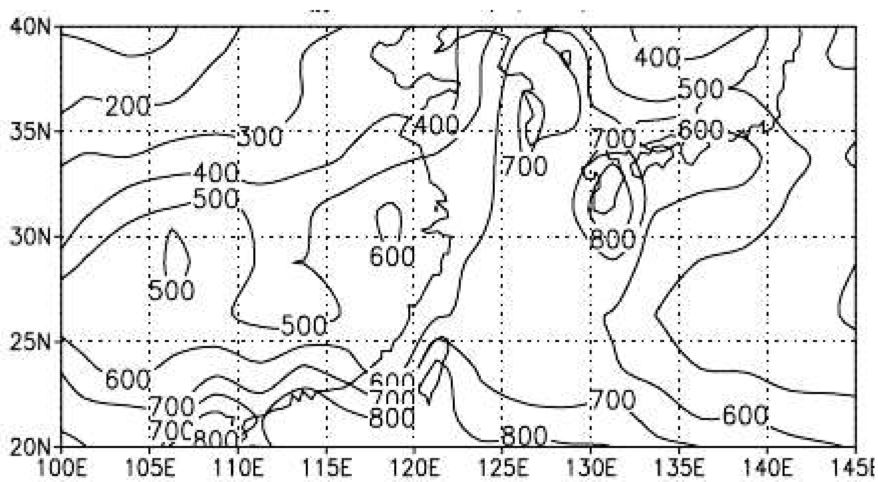


Figure 8. Average June-August precipitation in mm over the east Asian monsoon region (from Kripalani et al 2007)

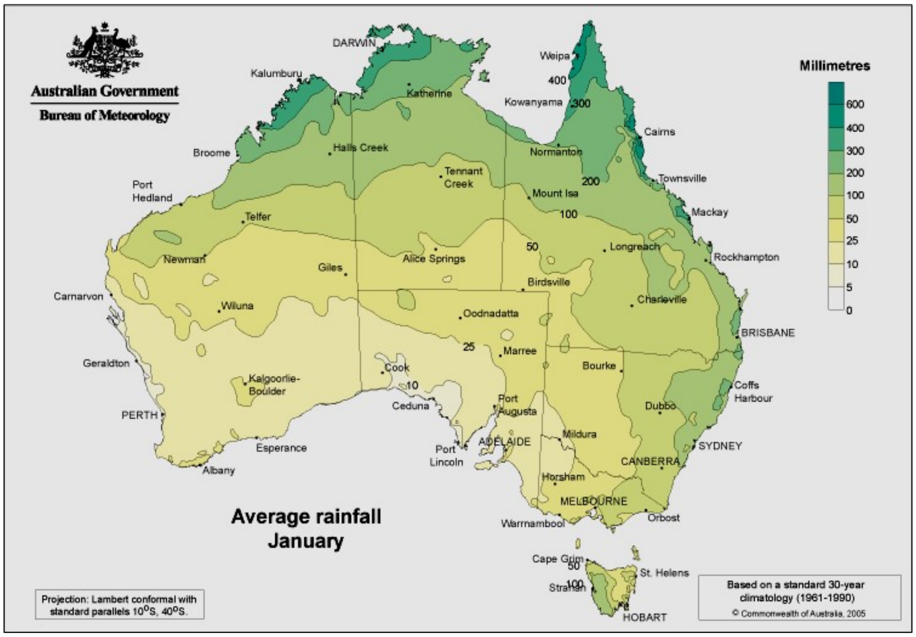
The Asian monsoon was the subject of intense investigation under the GEWEX Asian Monsoon Experiment (GAME) which was carried out under the overall umbrella of the Global Energy and Water Cycle Experiment (GEWEX) between 1996 and 2005. The objectives of GAME were: to understand the role of the Asian monsoon in the global energy and water cycle, to improve the simulation and seasonal prediction of the Asian monsoon, and to assess the impact of monsoon variability on the regional hydrological cycle. Japan, China and Korea were the main players in GAME. Special observation programmes were conducted over four selected regions: Siberian Taiga forests and Tundra area, the Tibetan plateau, the Huai-he river basin in China, and the Chao Phraya river basin in Thailand. The last phase of GAME was devoted to a detailed analysis of the observations and modelling studies.

GAME has been followed by another programme called Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI) whose objective is to develop a hydro-meteorological prediction system for the region. The planning for MAHASRI began in 2005 and it has the support of Japan, China, Thailand, Vietnam, Bangladesh and other countries. While MAHASRI is essentially a continuation of the hydrometeorological component of GAME, it has some wider objectives. An expansion of the target scientific field from air-land interactions in GAME to air-land-sea interactions is envisaged. The area is also to be expanded beyond the GAME area and the investigations are to cover the winter monsoon as well. MAHASRI is expected to establish a prototype system that would demonstrate the recording of hydrometeorological observations and data transmission in real time, which will help in flood management in Asian monsoon countries. It will also generate weekly to monthly scale dynamic probabilistic monsoon predictions for water resources and agricultural management in these countries. For this purpose, intensive observational programmes will be carried out for limited periods.

Another new international experiment called the Asian Monsoon Year (AMY) has been mooted recently and it has since been accorded a formal status by the international community with Japan and China playing a major role in its planning and execution. The AMY08 experiment of 2008-2009 is a crosscutting observation and modelling effort aimed at understanding the radiation-monsoon-water cycle interaction and the ocean-land-atmosphere interaction of the Asian monsoon system, and on improving monsoon prediction. The impact of elevated aerosols on the radiation-monsoon-water cycle interaction is one of the new areas of investigation under the AMY. A wide range of scientific questions are being addressed by AMY (AMY 2009).

5. Australian Monsoon

The monsoonal character of the climate over north Australia has been known since long. Almost 90% of its annual rainfall occurs during the southern hemispheric summer months from November to April. Figure 9 shows the contrasting rainfall patterns that prevail over Australia in January and April. There is a marked seasonal shift from a dry easterly lower tropospheric wind regime in winter to a moist westerly one in summer (Figure 10). The heated Australian mainland and the cooler waters of the Pacific Ocean to the north provide the thermal contrast required for the monsoon to develop. It has now become the practice to regard the north Australian monsoon as part of a larger phenomenon called the Australian-Indonesian monsoon, covering the area south of the equator to north Australia and between 100 and 170° E longitudes.



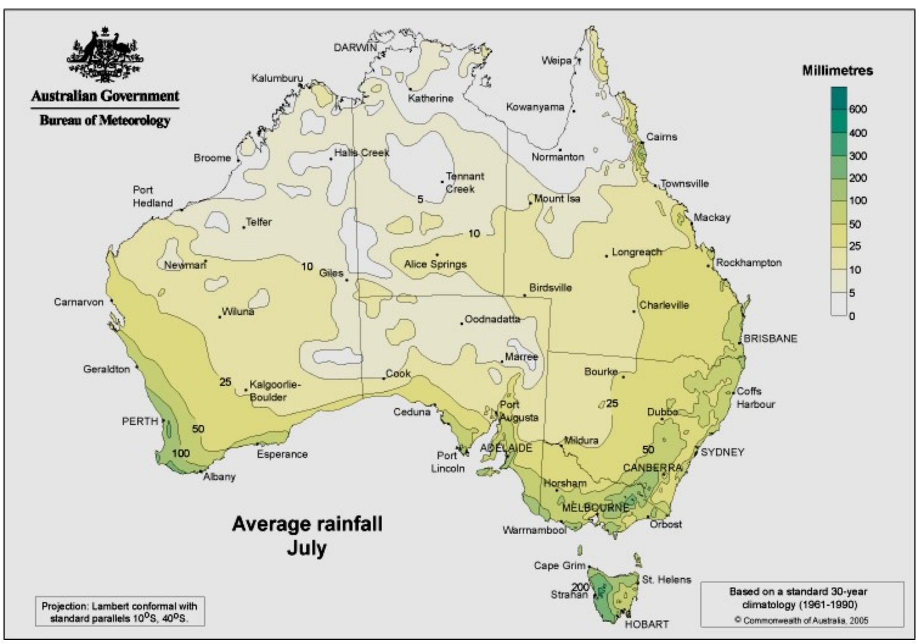


Figure 9. Average January and July rainfall in mm over Australia (from BOM 2009)

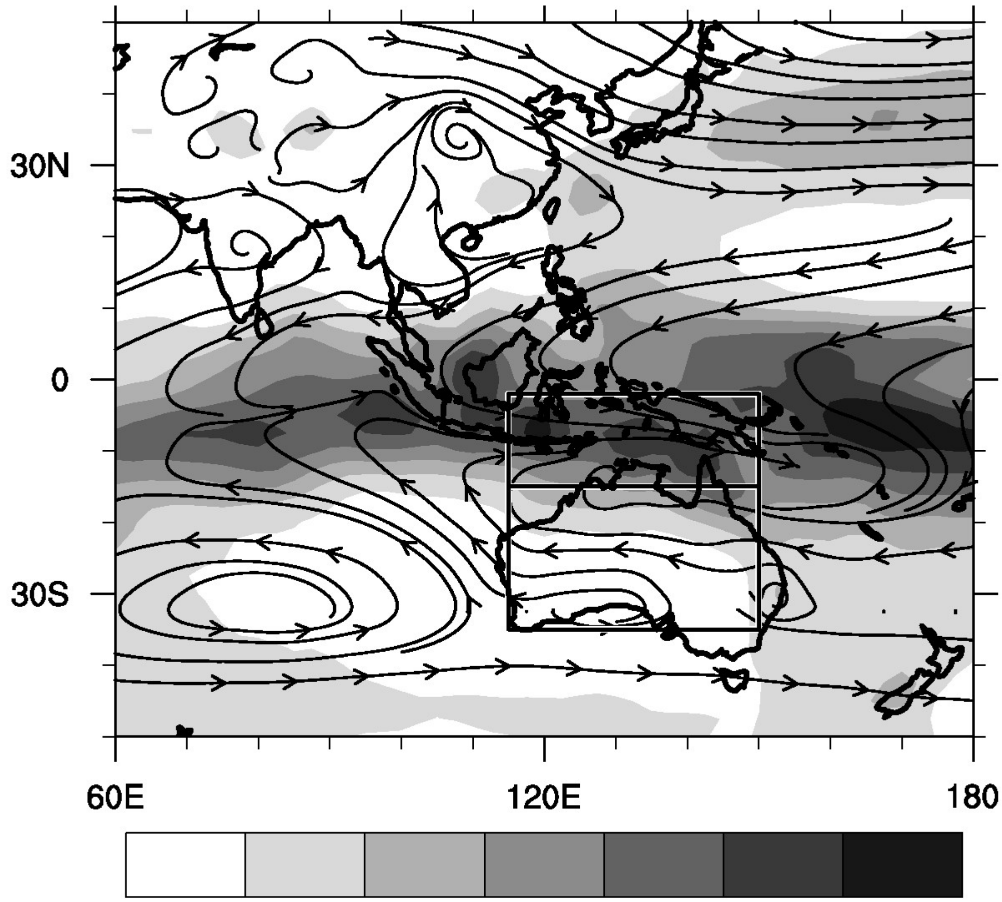


Figure 10. Average Dec-Feb 850 hPa streamline pattern and precipitation in mm/day ranging from white 0-2 to black 12-14 (from Hung et al 2004)

A heat low develops over northwest Australia and the ITCZ runs through it. The maximum monsoon rainfall occurs over the region of confluence of the ITCZ and the South Pacific Convergence Zone (SPCZ). The Australian monsoon is triggered by cold surges from the South China Sea and surges in the low level southerlies along the west Australian coast. The deep tropical convection over north Australia and Indonesia provides the upward branch of the Walker circulation over the Pacific Ocean which governs the southern oscillation.

The onset date over Darwin is around 25 December but it has a standard deviation of about a fortnight (Hendon et al 1990). The onset of the Australian monsoon has been investigated in depth by Hung et al (2004) who found that the land-sea thermal contrast and barotropic instability act as a seasonal preconditioning for the onset. The onset of the

Australian summer monsoon generally coincides with the arrival of the eastward-propagating MJO. When the MJO is weak or absent, the onset gets triggered by some other disturbance like the midlatitude trough.

There are many commonalities between the Indian southwest monsoon and the north Australian monsoon (Asnani 2005e). The north Australian monsoon has a well-marked onset and withdrawal. There are intraseasonal and interannual variations in the intensity of the Australian monsoon (Holland 1986). There is a monsoon trough, equatorward of which there are lower level westerlies and upper level easterlies, and monsoon depressions form over the adjoining oceans. Although the characteristics of the Australian monsoon quite resemble those of the Indian southwest monsoon, the absence of tall mountains like the Himalayas in Australia makes a lot of difference and the diabatic heat supply from the land to the atmosphere remains confined to the lower levels. The net result is that the Australian monsoon is not as intense as the Indian southwest monsoon. Many specific features of the Australian monsoon were investigated during the BMRC Australian Monsoon Experiment (AMEX) conducted during 1986-1988, details of which have been described by Holland et al (1986).

6. North American Monsoon

In both north and south America, there are regions which receive more than half of their annual rainfall during the summer months, with a relatively dry winter season, like in other summer monsoon regions of the world (Asnani 2005f and 2005g). They also exhibit many of the basic features that characterize other major global monsoon regimes, such as the land-sea temperature contrast, a thermally direct circulation with a continental rising branch and an oceanic sinking branch, land-atmosphere interactions, intense low level inflow of moisture into the continent, and associated seasonal changes in regional precipitation.

In the monsoon regions identified by Ramage (1971), north and south America had not found a place. In fact, until the late 1970s, the very existence of monsoons over north and south America had been doubted. However, the Southwest Arizona Monsoon Project (SWAMP) which was implemented in 1990-1993, the ongoing North American Monsoon Experiment (NAME) and its 2004 field campaign, and the Monsoon Experiment South America (MESA) have all resulted in a significant improvement in the scientific understanding of the north and south American monsoon systems. It has by now been widely accepted that the monsoon does indeed prevail over parts of north and south America and it is characterized by large-scale seasonal changes in the wind and rainfall patterns.

The north American monsoon is also known as the southwest U. S. monsoon, Mexican monsoon or Arizona monsoon, or just as the summer thunderstorm season. This is because the core of the north American monsoon is actually situated over northwestern Mexico, but it influences much larger areas of the southwestern U. S. (Adams et al 1997, Douglas et al 1993).

The moisture supply that sustains the north American monsoon originates from two main sources. Middle and upper level moisture comes from the Gulf of Mexico, usually when it has warm SSTs. Lower level moisture comes from the Gulf of California, particularly when it is warm and SSTs off the Baja coast are relatively cooler, setting up a thermal gradient. Another phenomenon that comes into play is the gulf surge, which occurs when the low level jet brings moisture directly into Arizona from the Gulf of California.

The wet season begins in the middle of June and continues up to the end of September (Figure 11). Over Tucson, Arizona, the total June-September rainfall is 15 cm on the average, with the months of July and August each receiving about 5 cm. However, the total monsoon rainfall can vary widely from year to year. For Tucson, the driest monsoon year was 1924 when the rainfall was less than 25% of the normal, and the wettest monsoon was in 1964 when it was 230% of the normal (NOAA/NWS 2009).

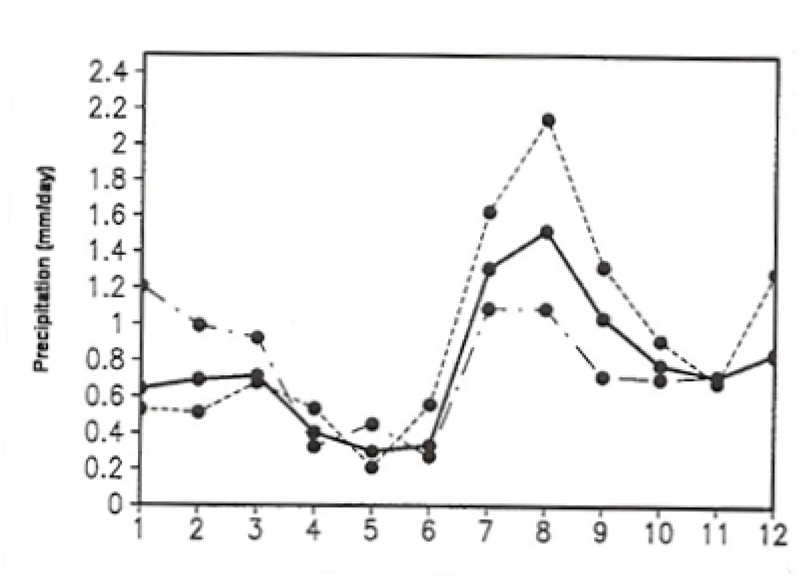


Figure 11. Monthly average precipitation in mm/day over Arizona and New Mexico, dash-dot line representing dry monsoons, dashed line wet monsoons and the solid line a composite of all monsoons (from Higgins et al 1999)

The north American monsoon circulation pattern begins to evolve around late May or early June over southwest Mexico. By mid-June or later the monsoon comes to northwest Mexico, and by early July to the southwestern U. S. Large scale synoptic conditions over north America can help or block the moisture advection from the Gulf of Mexico into the southwestern U. S. In June, the 850 hPa monsoon ridge is situated over Mexico (Figure 12) and it actually prevents middle and upper tropospheric moisture from moving north into Arizona. However, by July, this ridge shifts northwards into the southern Plains and southern Rockies (Figure 13) facilitating middle and upper level moisture incursion from the Gulf and low level moisture surges from Mexico into Arizona.

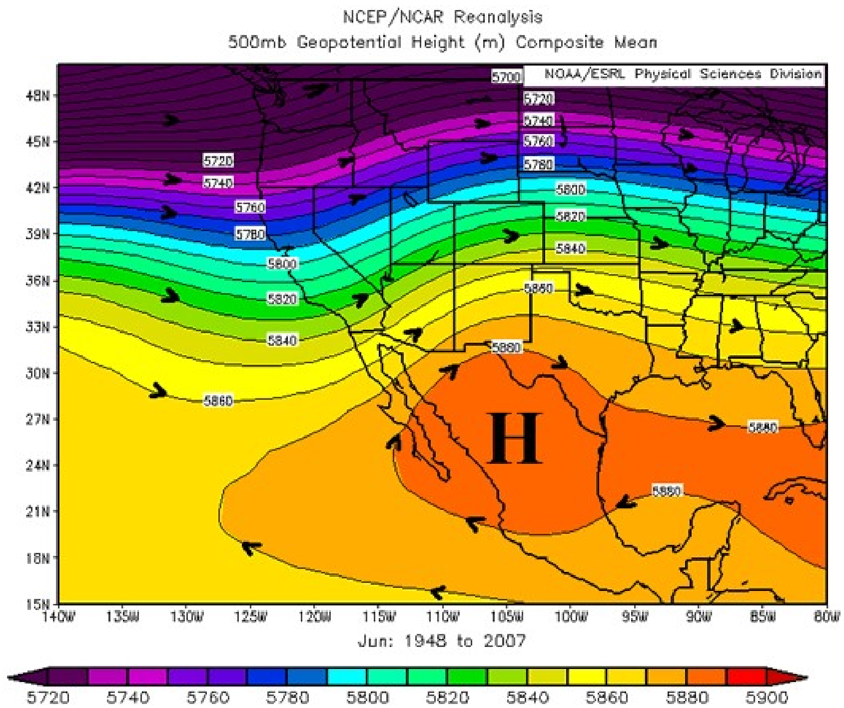


Figure 12. Average June 500 hPa geopotential height in m showing the ridge over northwest Mexico which blocks the moisture in the Gulf of Mexico from entering southwest U. S. (from NOAA/NWS 2009)

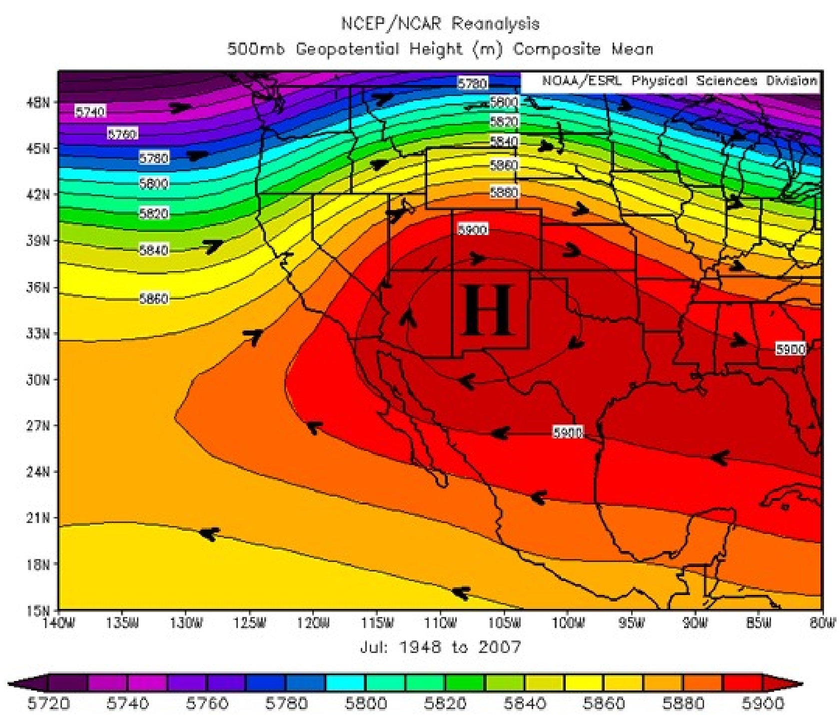


Figure 13. Average July 500 hPa geopotential height in m showing strong ridge located over the Great Plains which allows moisture flow from the Gulf of Mexico into southwest U. S. (from NOAA/NWS 2009)

As the low level moisture flow is not always very strong or continuous, it is the higher level moisture influx, which is influenced by the location and strength of the monsoon ridge, that largely modulates the monsoon rainfall. This is one of the causes of the high variability of the rainfall on different temporal and spatial scales.

July and August are the months of peak monsoon activity, barring occasional breaks. There are frequent moisture incursions from the Gulf of California, commonly called Gulf surges in this period. The actual mechanism of the Gulf surges is quite complex and has been the subject of continuing research (Zehnder 2004). However, the surges are known to be produced because of an increased thermal gradient and pressure imbalance between the two ends of the Gulf and evaporation over the warm Gulf waters. By the end of August, the monsoon ridge begins to weaken and return southeastwards. The retreat is completed by the end of September, by which time the jet stream strengthens and moves deeper into the U. S.

Under the North American Monsoon Experiment (NAME), an international team of scientists from the United States, Mexico and Central America carried out a major field campaign during the summer of 2004. The aim was to develop an improved understanding of the north American monsoon system that would lead to an improvement in the precipitation forecasts. This field campaign provided an unprecedented observing network for studying the structure and evolution of the north American monsoon. Higgins et al (2007) have given an overview of the results and addressed the motivating science issues as well as some unresolved questions. Johnson et al (2007) have studied the multi-scale characteristics of the flow from the large scale to the mesoscale using atmospheric sounding data from the enhanced observing network. Becker et al (2008) have examined the structure of the diurnal cycle of precipitation associated with the north American monsoon using a diverse set of observations, analyses and forecasts from the NAME field campaign of 2004.

7. South American Monsoon

Just as in the case of the north American monsoon, the existence of a monsoon over south America had not been accepted for a long time. Easterly winds prevail over eastern South America throughout the year and the seasonal reversal of surface winds is not immediately apparent. However, Zhou et al (1998) showed that when the annual mean is removed from summer and winter composites of surface winds, the characteristic reversal in anomalous low-level circulation does show up. Further supporting evidence has become available more recently, as a result of coordinated research and observational efforts, like the South American Low Level Jet Experiment (SALLJEX) organised in 2002-2003.

Most of the south American landmass lies within the tropics. However, surface conditions vary between the Amazonian rain forest and the dry Altiplano plateau. Moisture supply from the Pacific Ocean is blocked by the Andes mountain range, but it is brought in by the easterly winds from the Atlantic Ocean and by midlatitude systems. It is now known that the south American monsoon regime does show a distinct life cycle from onset to decay, the onset usually being characterized by a sharp change from hot, dry conditions to cool, wet ones. The south American monsoon makes its onset in the middle of August over the equatorial Amazon. From there it spreads rapidly both eastward and southeastward across the Amazon basin and covers Brazil typically within just four to six weeks (Figure 14). November-February are the months of heaviest monsoon precipitation. Thereafter convection weakens and gradually retreats towards the equator, bringing the rainy season to an end in March.

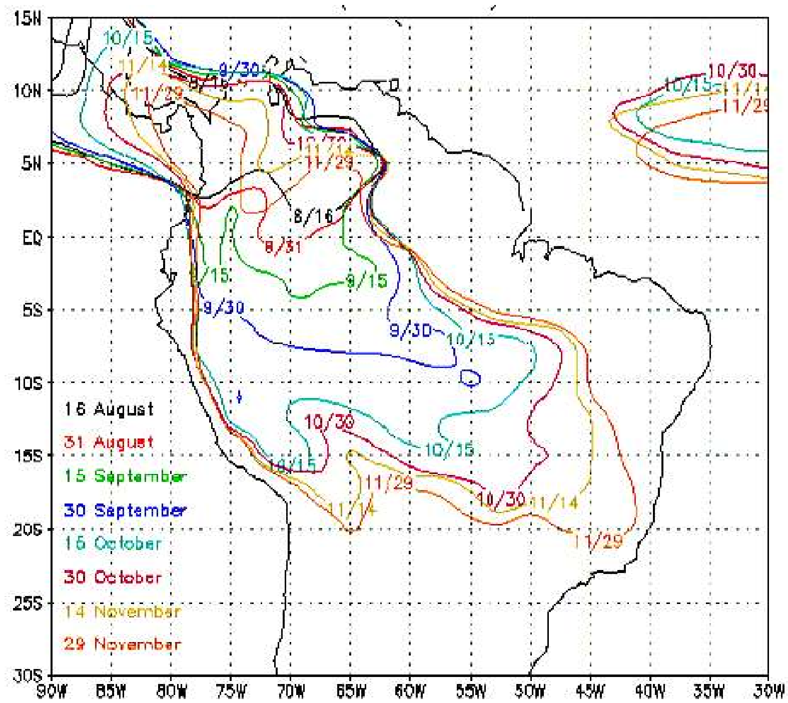


Figure 14. Average dates of onset of the south American monsoon (from VAMOS 2009)

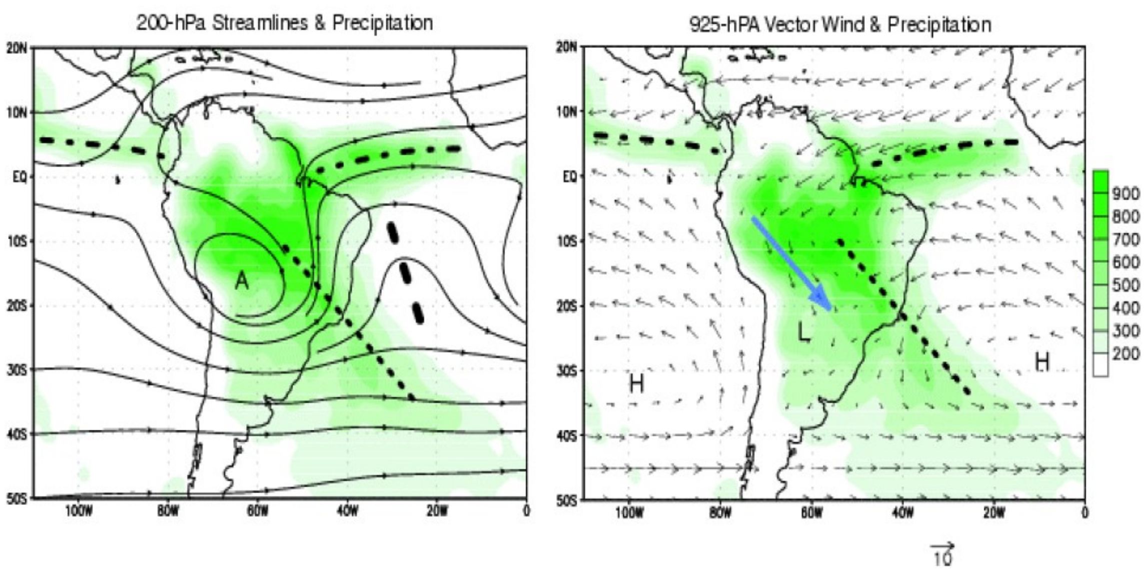


Figure 15. Average Dec-Feb 200 hPa streamline pattern showing the Bolivian high (A), and 850 hPa wind pattern showing the subtropical surface highs (H), the Chaco low (L), the low level jet (thick vector), SACZ (dotted line), ITCZ (dash-dot line), the Nordeste trough (heavy dashed line), and precipitation amounts in mm as shaded green areas (from Nogués-Paegle et al 2002)

Over south America, the upper levels of the atmosphere are characterized by a high pressure area centered near 15° S, 65° W over the Altiplano, known as the Bolivian high, and a low pressure area located over northeast Brazil, called the Nordeste trough. These features are observed throughout the year but they are most pronounced during summer and at the 200 hPa level. At lower levels, there is an easterly flow from the Atlantic Ocean which is deflected southward by the Andes mountains. During the period of peak monsoon activity, a band of deep convection known as the South Atlantic Convergence Zone (SACZ) is seen to extend from central to southeast Brazil on towards the Atlantic Ocean. SACZ is the Atlantic counterpart of the South Pacific Convergence Zone (SPCZ) which is important to the Australian monsoon. A schematic representation of these synoptic features is given in Figure 15 with the precipitation pattern superimposed. The thick arrow in Figure 15 represents one of the strongest low level jets in the atmosphere, called the South American LLJ or SALLJ. It plays an important role in the transport of moisture from the Amazon to the La Plata basins and has a strong influence on the precipitation.

The south American monsoon exhibits variability on the intraseasonal scale, primarily in association with the movement of the SACZ, the location and strength of the SALLJ and the migratory mid-latitude systems. The interannual and longer term variability is attributable to oscillations like the MJO, NAO and ENSO.

Currently a major experiment called the Variability of the American Monsoon System (VAMOS) is in progress under the umbrella of the Climate Variability (CLIVAR) programme which in turn is a component of the World Climate Research Programme (WCRP). VAMOS is a concerted attempt towards achieving a better understanding of the north and south American monsoon systems in their totality (Higgins et al 2003, Nogues-Paegle et al 2002, VAMOS 2009). VAMOS has launched two complementary international programmes called the North American Monsoon Experiment (NAME) and Monsoon Experiment South America (MESA). The common objectives of NAME and MESA are to understand the key components of the two American monsoon systems, their variability and their role in the global water cycle, to build observational data sets and to improve the simulation and monthly to seasonal scale prediction of the monsoons. It also has sub-experiments and field campaigns such as the South American Low Level Jet Experiment (SALLJEX) designed to study specific phenomena like the low level jet (Vera 2006).

The results of NAME and MESA have already started providing new insights into various aspects of the American monsoon systems such as moisture transport processes, structure and variability of the South American low level jet, and the diurnal cycle of precipitation in the core monsoon regions. They are also helpful in model development and hydrological applications. As research on the American monsoon systems proceeds further, a unified view of the climatic processes modulating continental warm season precipitation is expected to emerge (Vera et al 2006).

8. African Monsoon

An exhaustive description of the monsoon systems that prevail over different parts of Africa has been given by Asnani (2005g). The region of central Africa between 15º N and 15º S receives the highest rainfall over the continent while Sahara in the north and Kalahari and Nahib in the south are desert areas. The coastal strip of north Africa receives its rainfall in association with extratropical westerly waves and low pressure systems which move across the Mediterranean Sea in winter. Over west Africa, the ITCZ has a north-south oscillation, but it remains north of the equator throughout the year (Figure 6). However, the air on both sides of the ITCZ being dry, there is no rain in the vicinity of the ITCZ. In northern hemispheric summer, the ITCZ reaches its most northerly location giving rains over Sahel and areas to its south up to the Gulf of Guinea. When the ITCZ moves southwards, Kenya and Uganda receive what are called 'short rains' in the months of October to December and as it goes northwards once again, they get 'long rains' from March to June. Tanzania gets its rains between November and March. The onset and withdrawal of the summer monsoon do not have a clear association with the migration of the ITCZ because of the influence of major orographic features like Lake Victoria and the Great Rift Valley and local topography.

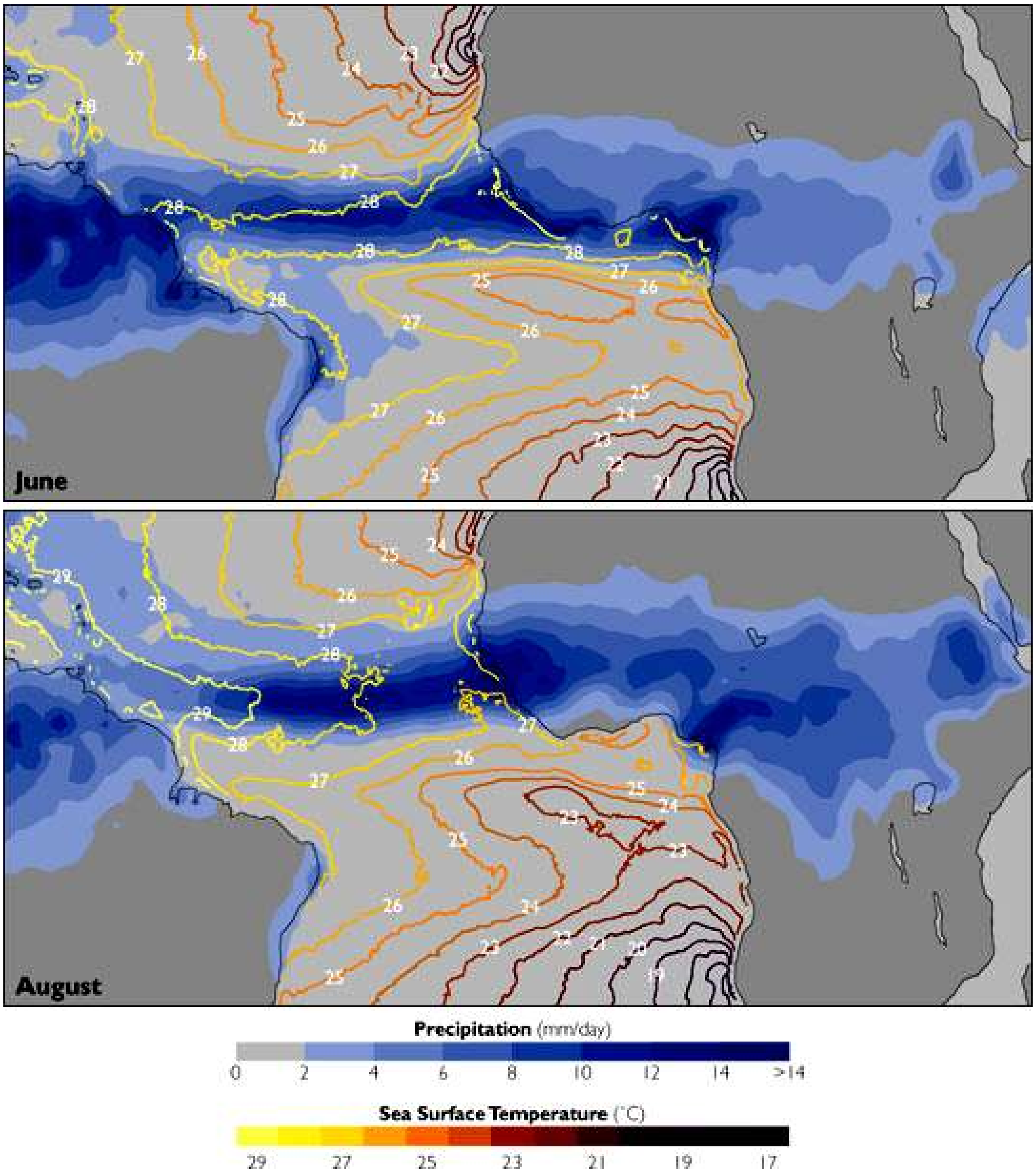


Figure 16. Average June and August precipitation in mm/day and SST in °C over the west African monsoon region (from NASA 2009)

In a recent investigation based on TRMM precipitation data (Gu et al 2004), the African monsoon season has been found to consist of two distinct sub-seasons (Figure 16). The first is in late spring and early summer, when the West African Coast near the Gulf of

Guinea, at 5° N latitude gets the heaviest rainfall, under the influence of strong sea surface temperature gradients off the coast. The second is in late summer when the heavy rainfall region shifts to 10° N in association with atmospheric easterly waves. Rainfall in the two periods is anti-correlated.

Sanjeeva Rao and Sikka (2007) have discussed the commonalities and differences, as well as possible interactions between the African and Indian monsoon systems. Both monsoons develop in close proximity and have similar large scale atmospheric features, but the Indian monsoon is much stronger than the African monsoon and extends further north in the peak phase in July. The Indian monsoon is dominated by a 30-50 day oscillation and there is a possibility of its being modulated by an eastward propagating Madden-Julian Oscillation (MJO), when travelling over the near-equatorial African region. This interaction can be detected through eastward moving low outgoing longwave radiation (OLR) pulses and corresponding fluctuations in the 250 hPa velocity potential. A comparison of the occurrence of drought over India and the Sahelian and sub-Sahelian regions of Africa has shown that although the drought years may not exactly match, there is a signal of a common multi-decadal mode in the monsoon variability over the two regions.

An international project known as the African Monsoon Multidisciplinary Analysis (AMMA) is currently under implementation. This major initiative is aimed at improving the knowledge and understanding of the west African monsoon and its variability on time scales ranging from daily to interannual. Among the monsoons of the world, the west African monsoon is marked by an extremely high interannual and decadal-scale variability (Le Barbe et al 1992). This region which had wet conditions during 1950-70, suffered from a dramatic change to drought conditions thereafter, resulting in devastating environmental and socio-economic impacts on food and water security.

The present observational and monitoring system over the west African region is inadequate for the purposes of numerical prediction and also for studying the diurnal, seasonal and annual cycles of monsoon rainfall. From a wider perspective, the latent heat release through deep convection in the ITCZ over Africa is a significant heat source that affects the global circulation, including Atlantic Ocean hurricanes, many of which have their origins in west African systems (Landsea et al 1992). AMMA aims at investigating the west African monsoon in a holistic manner, including the role played by the Saharan region which is the world's largest source of atmospheric dust and aerosols. One of the objectives of AMMA is to study the phenomenon of the west African monsoon from the global and regional scales down to the mesoscale and submesoscale and how the scale interaction results in the observed features of the monsoon and its variability. The AMMA project is motivated by an interest in fundamental scientific issues and also by the need for an improved prediction of the west African monsoon. Since 2006, over 400 scientists from more than 25 countries, representing more than 140 institutions have been involved in AMMA. The latest information on this project can be obtained from the AMMA web site on the internet (AMMA 2009).

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