National Weather Service

Monsoon Inter-annual Variability

Monsoon variability from one summer to the next is substantial, and exceeds the normal monsoon seasonal precipitation at most locations. For example, the normal monsoon precipitation at Tucson, AZ is 6.06 inches. The driest monsoon season measured 1.59 inches, and the wettest measured 13.84 inches. Therefore a variation between seasons of 12.25 inches exists, which is over twice the normal monsoon precipitation at Tucson. Understanding the causes for this huge variation is the first step in developing an ability to forecast an upcoming monsoon season.

Research within the past decade or so has investigated the possible causes behind North American Monsoon variability. Specific factors examined include:

1. Sea surface temperature anomalies,
2. Large-scale circulation patterns,
3. Land surface conditions,
4. Tropical convergence zones,
5. Moisture transport mechanisms.

All of these research factors uncovered important details affecting the monsoon in the Southwest, but none of them provided a perfectly clear picture of all conditions affecting its variability. These factors are related to each other and are not independent. For example, sea surface temperatures affect all the other factors to some extent. In additional to inter-annual monsoon variability, multi-decadal variability has been observed. In other words, data from 1963 through 1996 may show results in one aspect, while larger data sets from 1900 through 1963 uncover results not seen in the later time periods.

The role of sea surface temperature anomalies

From a climatic perspective, an important factor to examine in any precipitation regime is the surrounding sea surface temperatures (SSTs). Atmosphere-ocean coupling is a strong driver in many seasonal patterns observed around the globe. The El Nino/Southern Oscillation is perhaps the most well known. Sea surface temperature anomalies (SSTAs) are the primary data set used in these studies. SSTAs can be statistically correlated to many observed conditions such as precipitation, maximum temperature or snow cover, and SSTs vary slowly when compared to changing weather patterns. Monsoon variability research shows that Pacific SSTs are an important factor in determining summertime drought or rainy conditions in both the Southwest and the Great Plains. Additionally these Pacific SSTs help modulate the previous winter season precipitation amounts. These analyses show winters preceding early-onset monsoons are characterized by cold SSTA in the mid-latitudes of the North Pacific and warm SSTA in the subtropics of the North Pacific; the opposite is true for late onset monsoons. The

SSTA analysis shown in **Figure 1** depicts a typical early onset monsoon pattern. Blue colors represent colder than normal temperatures; yellows and reds represent warmer than normal. The actual temperature scale in degrees Celsius is given at the bottom.

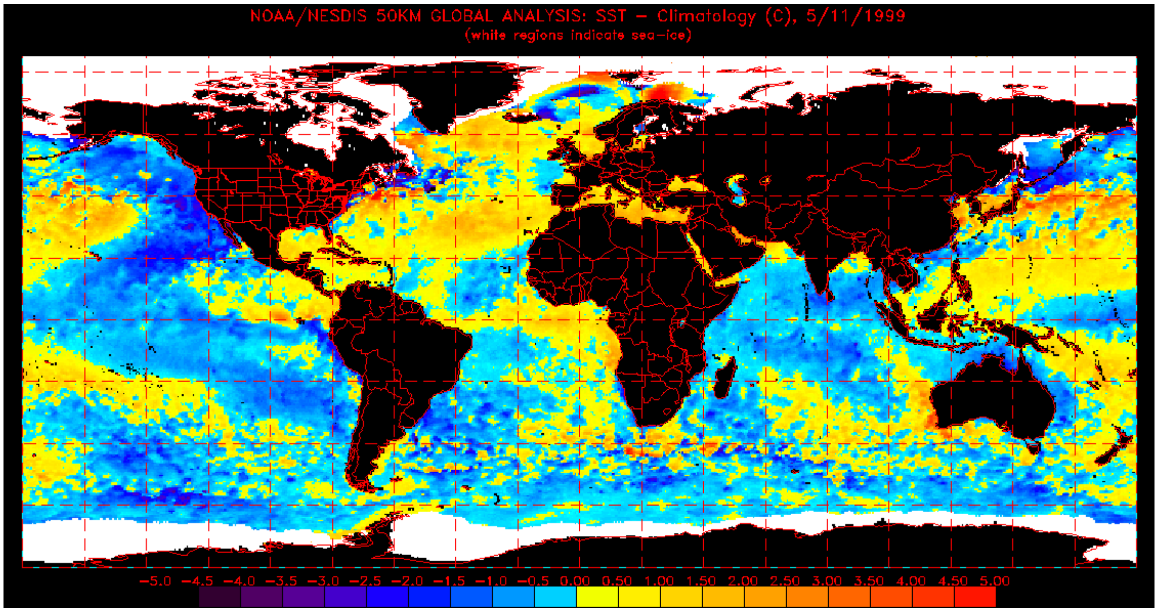

Figure 1 - Sea surface temperature anomalies with cooler than normal temperatures (blue) off the western U.S. Cooler water in this location is typical of an early onset monsoon pattern.

A significant correlation exists in the observed data such that wet winters are generally followed by dry monsoons, and dry winters are generally followed by wet monsoons. Dry and wet conditions are classified as the bottom or top 25% of the years examined. Therefore the Southwest summer rainfall is modulated by the Pacific SSTs. Unfortunately SSTs are not the only factor involved, since 16 consecutive wet (dry) winters and wet (dry) monsoons have been observed in the past 100 years. Likewise near normal winter or monsoon precipitation, the middle 50% or half of the years examined were unrelated to each other.

The role of the large scale circulation

The North American monsoon is closely linked to the large scale (continental) weather patterns over the United States. The monsoon onset is connected with a shift in the Bermuda high toward the west, which in turn provides light easterly flow at mid and upper levels into Mexico and the Southwest. The exact location of the summertime ridge over the United States is a big factor in monsoon variability from one year to the next. Additionally the location of this ridge is affected by SSTs in the months of May of June. These two figures illustrate an idealized relationship between the ridge location and the character of monsoon observed over the Southwest July and August.

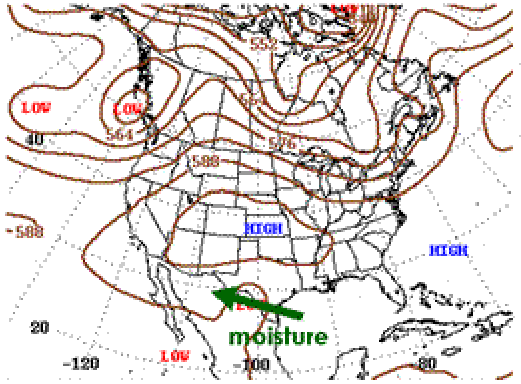

Figure 2 – Strong upper level ridge located in the Great Plains is positioned for carrying moisture from the Gulf of Mexico into the Southwest.

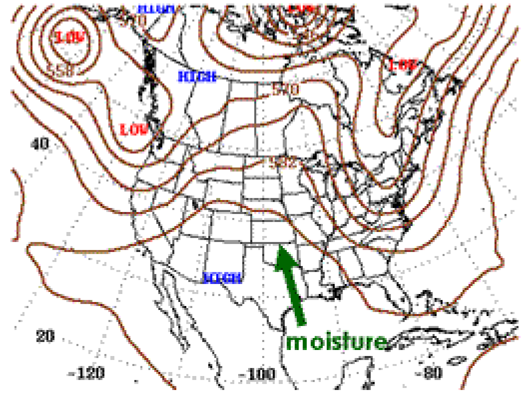

Figure 3 – Upper level ridge centered in northwest Mexico blocks the moisture in the Gulf of Mexico from entering the Southwest.

Two idealized configurations of the ridge exist. The first configuration **(Figure 2)** has a strong ridge located in the Great Plains. Upper level easterlies carry moisture and disturbances from the Gulf of Mexico south of the ridge. In this configuration the monsoon arrives early in the Southwest and is wet. The second configuration **(Figure 3)** centers the ridge in northwest Mexico because a trough occurs in the western U.S. This situation directs moisture into the Great Plains. The Southwest is dry and monsoon onset is late.

Another important concept in examining the large scale circulation is the thermal contrasts between the land and sea. This thermal contrast is what establishes a large scale thermally direct circulation of hot, rising air over the continent and cooler, sinking air over the ocean. The monsoon thermally driven circulation is physically similar to a sea breeze observed near an ocean or lake, except on a much larger scale.

The North Pacific sea surface temperature patterns affect these large scale circulations by influencing the summer precipitation in the Great Plains. Warmer water in the eastern North Pacific favors a ridge in that area with a trough over the West. Conversely cold water in the eastern North Pacific supports a strong ridge in the Great Plains. Many studies have found a strong relationship between the Southwest and the Great Plains. During the summertime, when the Great Plains is persistently wet, the Southwest will tend to be dry. If the Great Plains is experiencing a summer drought, the Southwest will tend to be wet. This reversal of phase observation is directly related to the large scale circulations present, and is a factor in monsoon variability from one year to the next.

The role of land surface conditions

A significant correlation exists in the observed data such that wet winters in the Southwest are generally followed by dry monsoons, and dry winters are generally followed by wet monsoons. One of the possible physical explanations for this observation is found in examining the spring snow pack in the southern Rocky

Mountains. A heavy snow pack in southern Utah and Colorado may delay the development of the summer ridge over the U.S. because more solar energy goes toward melting snow instead of heating the atmosphere necessary to build the monsoon ridge. A statistical analysis of this feedback indicates it influences western New Mexico the most and to a lesser extent Arizona and the Plains. The scatter plot in Figure 8c depicts this relationship well.

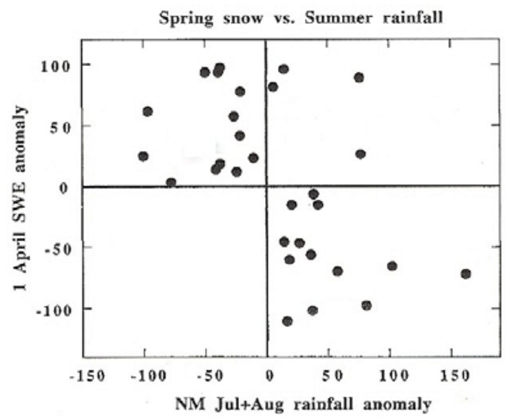

Figure 4 – Snow water equivalent (SWE) on April 1 plotted with the amount of New Mexico rainfall observed that year in July and August (Gutzler, 2000).

Figure 4 illustrates the relationship between spring snowfall and summer rainfall in New Mexico. Solid dots above the horizontal center line occur when the water equivalent of the spring snow pack is above normal. Below the center line indicates less than normal snow pack. The vertical center line differentiates above (right of line) or below (left of line) normal monsoon rainfall. As you can see, most of the solid dots occur in the upper left quadrant (above normal snow, below normal rainfall) and lower right quadrant (below normal snow, above normal rainfall). These data are from a 30 year period 1961 to 1990.

The evolution of the monsoon as it develops over North America is characterized by the rains starting in southwest Mexico in May and moving northward into the U.S. by July. As the rains move northward, a rapid green up in vegetation is observed and is associated with this increase in precipitation. The abundant vegetation then improves the ability for moisture to remain in the lower levels of the atmosphere, due to transpiration by plants, and assists the moisture moving northward. Drier lower levels in the atmosphere can impede moisture movement, since much of the rainfall evaporates before it reaches the ground. Hence the lower levels never reach saturation. These monsoon moisture conditions remain until a large-scale circulation pattern change occurs and dries out the atmosphere. The effect of vegetation on atmospheric moisture is most important during the latter part of the monsoon in August and September.

Given this evolution of the monsoon, a question arises: does an early start in Mexico imply an early start in the Southwest? This question is important because an early start to the monsoon in the Southwest invariably leads to a wet monsoon.

Therefore, if we know what is happening in Mexico we may be able to anticipate what happens in Arizona and New Mexico A late start often has a "sputtering" monsoon with below normal precipitation. **Figure 5** depicts how the start date affects the amount of precipitation received and was created using data from 1963 to 1988.

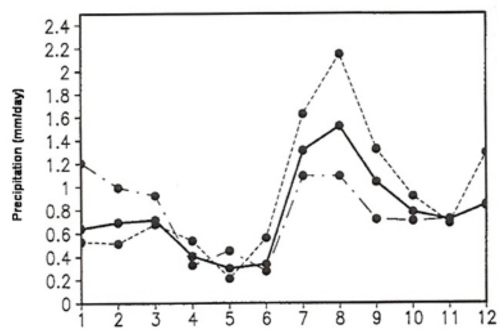

Figure 5 – Precipitation amounts received in Arizona and New Mexico throughout a year. Dash-dot line represents dry monsoons; dashed line wet monsoons and the solid line is a composite of all monsoons (Higgins, 1999).

In **Figure 5** the dashed line represents wet monsoons, the dash-dot line represents dry monsoons and the solid line is a composite of all monsoons. Additionally Figure 5 illustrates the relationship between a dry winter/wet monsoon and wet winter/dry monsoon.

Coming back to the question about how an onset date in Mexico relates to Arizona and New Mexico; the answer is no relationship exists between the southwest Mexico onset date and seasonal rainfall anomalies. Thus an early monsoon start in Mexico is not related to the monsoon precipitation characteristics elsewhere.

The role of the inter-tropical convergence zone

The inter-tropical convergence zone (ITCZ) is an area of convection located between 5^o and 10^oN as shown in Figure 6. On a satellite picture, the ITCZ appears as an area of thunderstorms north of the equator. The activity in this zone off the coast of Mexico during the spring directly impacts the type of monsoon observed. For example, a wet monsoon in the Southwest is associated with suppressed precipitation in the eastern Pacific ITCZ and enhanced precipitation north and south of this zone. Likewise an active ITCZ area during the spring preceding monsoon onset is indicative of a dry monsoon.

The shifts in the ITCZ can be affected by sea surface temperatures. Warmer temperatures favor a stronger and more southward displaced ITCZ off the Mexican coast. Cooler temperatures tend to weaken the convergence zone and displace it further north. Thus cooler sea surface temperatures can both increase the land-sea temperature gradient and inhibit the ITCZ; warmer SSTs have the opposite effect.

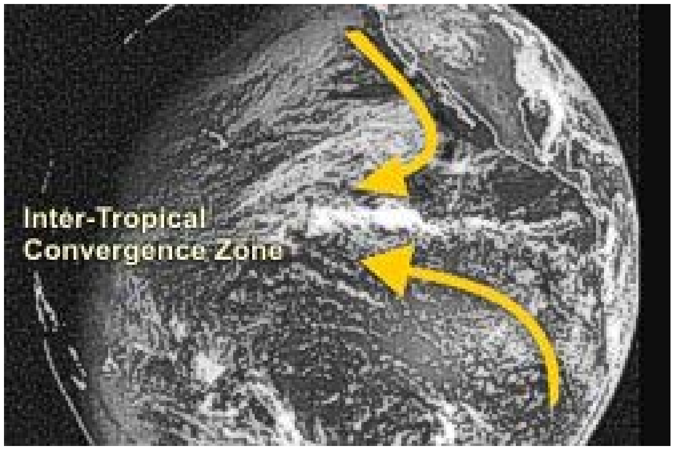

Figure 2 - Visible satellite picture illustrating an inter-tropical convergence zone.

The physical reason behind the ITCZ/monsoon interaction is not entirely clear. A tropical convergence zone is maintained by lower level westerly winds from the equator colliding with lower level easterly winds from the northern latitudes. The stronger the intensity of these winds, the stronger the storms in this convergence zone. When ITCZ activity off the southern coast of Mexico is weak, a plausible explanation related to the monsoon is that the land-sea interactions associated with the monsoon can more easily develop. Moisture and abundant rainfall then enters southern Mexico under these conditions. A strong ITCZ inhibits this critical circulation pattern from developing over Mexico.

The role of moisture transport

Moisture entering the Southwest during the North American Monsoon generally comes from two locations, the Gulf or Mexico or the Gulf of California. Analysis data shows mid and upper level moisture primarily originates from the Gulf of Mexico, while lower level moisture advection originates from the Gulf of California. Of course, once thunderstorms start in Arizona or New Mexico, all levels of the atmosphere become moist. However the variability of where this moisture originates in the first place helps explain the variability from one monsoon to the next.

Local sea surface temperatures (SSTs) are an important aspect of this moisture transport. Research has shown that roughly 80% of the rainfall in Arizona and New Mexico occurs after SSTs in the northern Gulf of California exceed 28.5^{o}C. Likewise positive correlations with SST anomalies over the Gulf of Mexico have been found too. Hence the warm water in these areas increases the availability of moisture to be transported elsewhere.

One common method for transporting moisture from one place to another is by increasing the low level winds. Regions of lower level wind speed maximum are referred to as lower level jets. Two lower level jets exist affecting the Southwest; one in the Gulf of California and another over the Great Plains. A lower level jet coming up the Gulf of California directly transports moisture into Arizona and is called a gulf surge. One factor affecting the variability of moisture transport in the Gulf of California is the SSTs along the California and northern Baja coasts. An increased thermal gradient in this region promotes the formation of lower level jet episodes as shown in Figure 7.

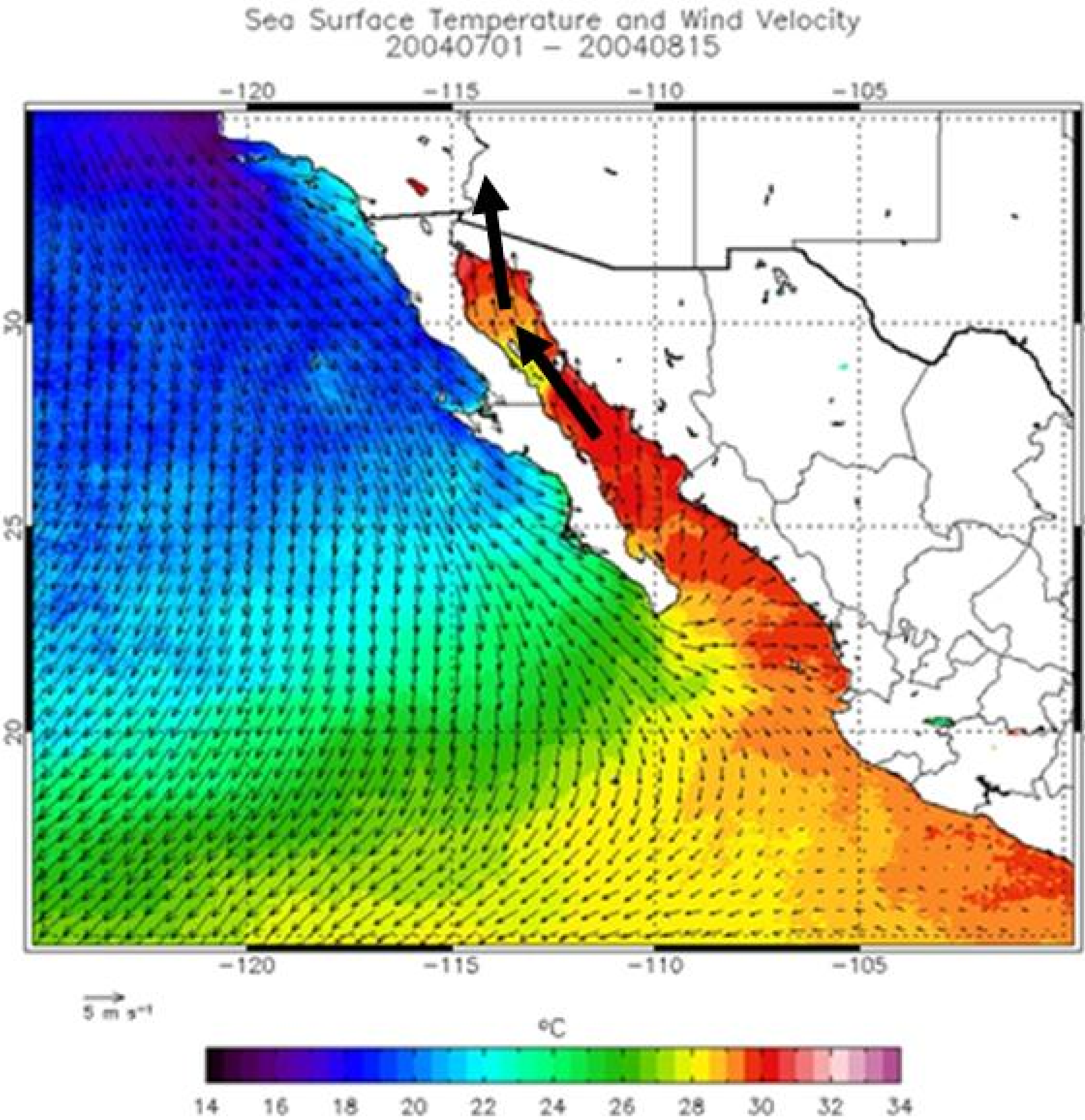

Figure 7: Cooler sea surface temperatures off the Baja coast is a favorable condition for moisture transport from the Gulf of California into Arizona and California.

The lower level jet in the Great Plains primarily determines the type of summer precipitation over Texas, Oklahoma and Kansas. The eastern portion of New Mexico may directly experience affects from the Great Plains lower level jet moisture, but most of the Southwest does not. The importance of this jet is that it weakens when the large-scale circulation pattern reduces precipitation in the Plains. Instead of moving north, this moisture gets shunted into Mexico and eventually into the Southwest as the source of mid and upper level moisture.

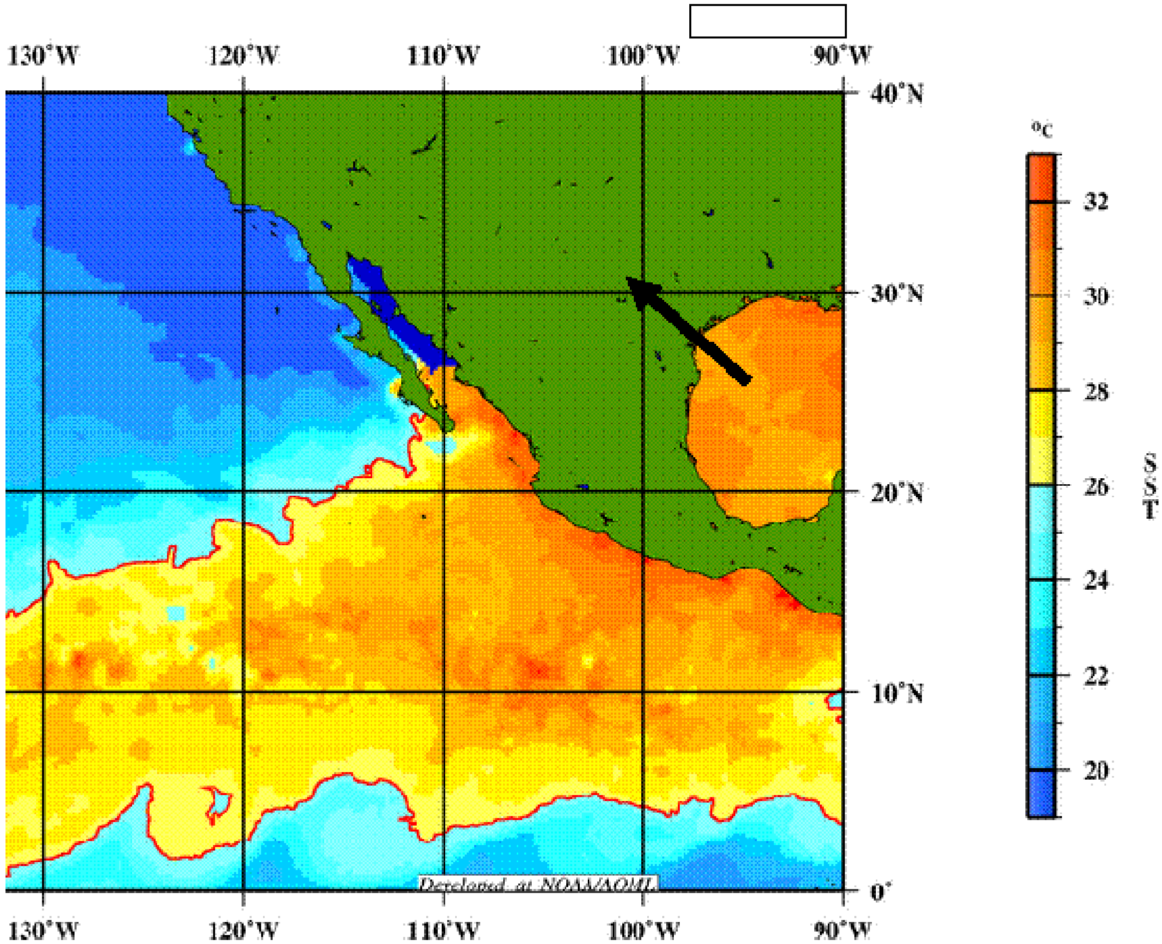

Figure 8: Warm sea surface temperatures in the Gulf of Mexico which can promote mid and upper level moisture transport into the Southwest.

Climate Change and the Monsoon

A question of concern is how the North American Monsoon will be altered in the future as a result of climate change. Global warming projections are given by numerical computer models, such as those documented by the Intergovernmental Panel on Climate Change. Unfortunately the IPCC models poorly represent the North American Monsoon in the Southwest. Hence this question does not have an accurate answer at this time.

Summary

Many factors influence the variability from one monsoon season to the next. All of these factors are inter-related to each other, and likewise none of them totally account for monsoon variability. The scientific understanding of this variability has increased substantially over the past 15 years and remains an active research area.

Further Reading and References:

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