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1. Atmospheric Water

1a. *Atmospheric Circulation*

The three main drivers of wind are

- Pressure Gradient Force: This force goes from higher to lower pressures and is directed at right angles from the isobars.
- Coriolis Force: Describes an apparent force that is due to the rotation of the earth. Coriolis force causes the wind to deflect to the right of its intended path in the Northern Hemisphere and to the left of its intended path in the Southern Hemisphere. It is zero at the equator, and maximum at the poles. Coriolis increases with the objects speed. Changes only the direction of the motion, not the speed.
- Friction (close to the surface)

The idealized model of atmospheric circulation is a system of three cells in the latitude bands 0°-30° (Hadley Cell), 30°-60° (Ferrel Cell) and 60°-90° (Polar Cell). in each hemisphere and the jet streams. The three cells have the task of energy redistribution. This three-cell circulation pattern arises because of the unequal latitudinal distribution of radiation and the rotation of the Earth.

- Hadley cell - huge thunderstorms develop as the air rises and condenses. Latent heat released during storms continues to drive the Hadley cell. The zone of low pressure is formed at the equator called the inter-tropical convergence zone. High pressures at about 30° called the subtropical highs. This is why the major deserts of the world are at that latitude. As the air rises in the equator it diverges and moves toward the subtropics Coriolis deflects the winds to the right in the NH and to the left in the SH. Providing westerly winds aloft. As the surface air returns to the equator in the NH it will flow NE to SW and SE to NW in the Southern Hemisphere. These are called the trade winds that converge in the inter tropical convergence zone (ITCZ).
- Ferrel cell - is a thermally indirect cell because it is driven by the motions of the cells on either side. At upper levels the model predicts easterly motion while at the surface there is a strong belt of surface midlatitude westerlies. However in reality we observe upper level westerlies in midlatitudes so this

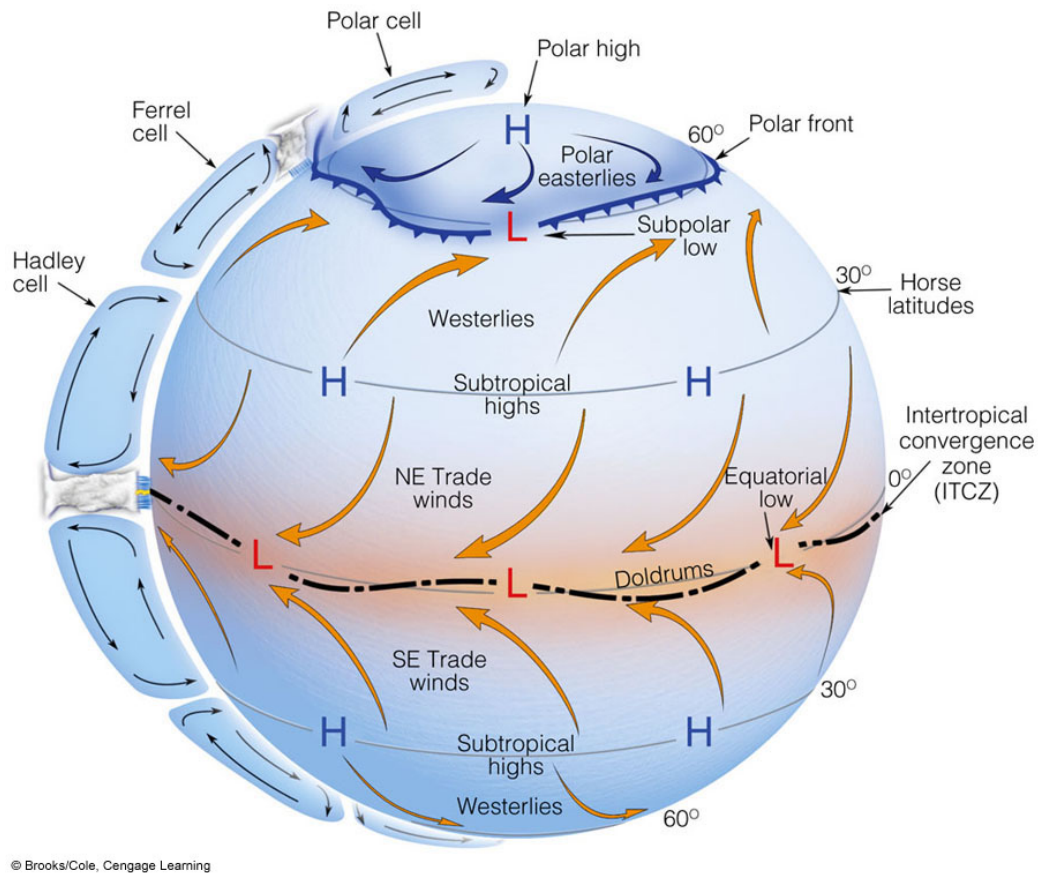


Figure 1: Idealized wind and surface-pressure distribution over a uniformly water-covered rotating earth. From Ahrens

model breaks down. The reason is that at upper levels there is high pressure in the equator (due to higher temperature) and lower pressure at the poles. For this reason there is a pressure gradient from equator to pole and the actual wind is deflected due to Coriolis so this causes predominant westerlies at upper levels that are stronger in the winter. For this reason the weather systems migrate from west to east.

- Polar Cell - Similar to the Hadley in that at about 60° there is rising motion and movement towards the pole at upper levels with westerly motion. There is a subpolar low where storms and clouds develop. The air sinks at the poles producing the polar high and at the surface there is deflection to cause polar easterlies as the air moves from poles to the subpolar low. A polar front separates cold air coming from the poles from milder air coming from midlatitudes, and the peaks of precipitation in the mid-latitudes are primarily produced by extra-tropical cyclones that develop along this front.

While this idealized model is fairly good, it breaks down due to surface conditions (land vs. ocean). In reality the world is not covered by belts of high and low pressure but by a number of semi-permanent cells. These cells undergo seasonal variations in position and intensity.

- Winter NH we have the Bermuda High, Pacific High characterized by easterlies to the south and westerlies to the north. The SH has better defined high pressure systems. The Siberian high and Canadian high are due to cold temperatures in the winter.
- Winter NH the Icelandic low and Aleutian low are where we would expect the polar front. Continuous belt of low pressure that encircles the globe in the SH.
- In the summer NH now have low pressures over land. Subpolar lows practically disappear.
- ITCZ pressure systems and wind belts shift north in July and south in January.

These circulation patterns play a dominant role in determining the temporal and spatial distribution of rainfall over the continents. For example, during winter, air from the Pacific enters the west coast of the US invigorating rainfall over the region. During the summer the Pacific High moves north and tends to keep summer weather along the west coast of NA dry.

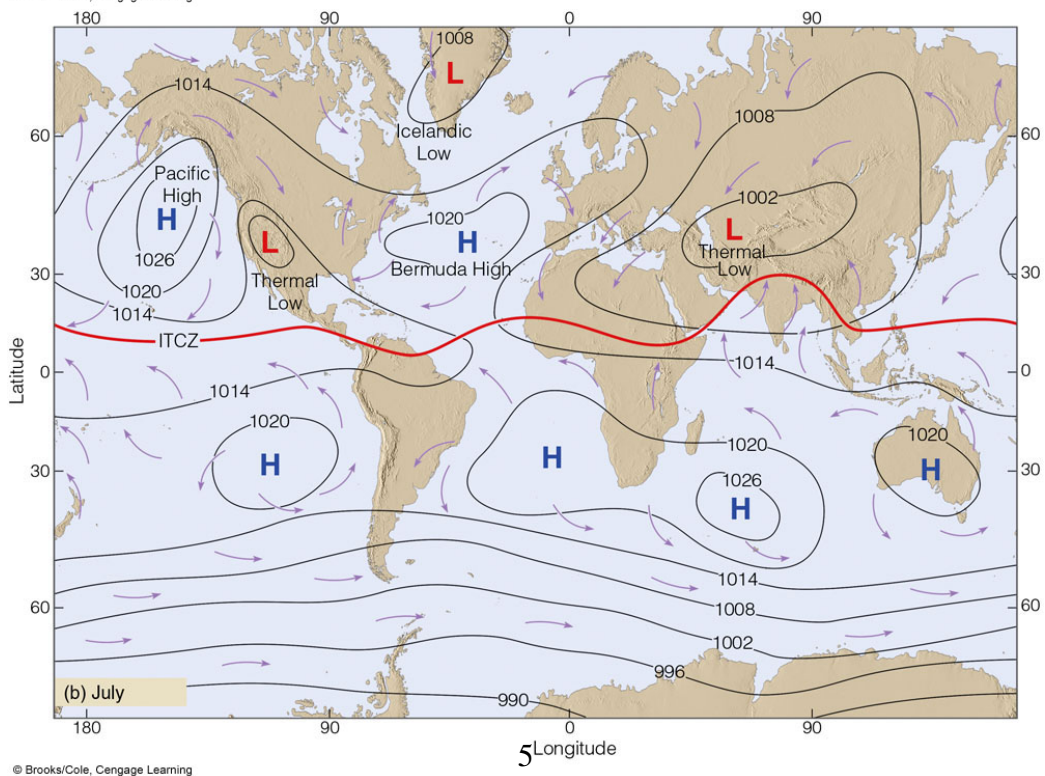
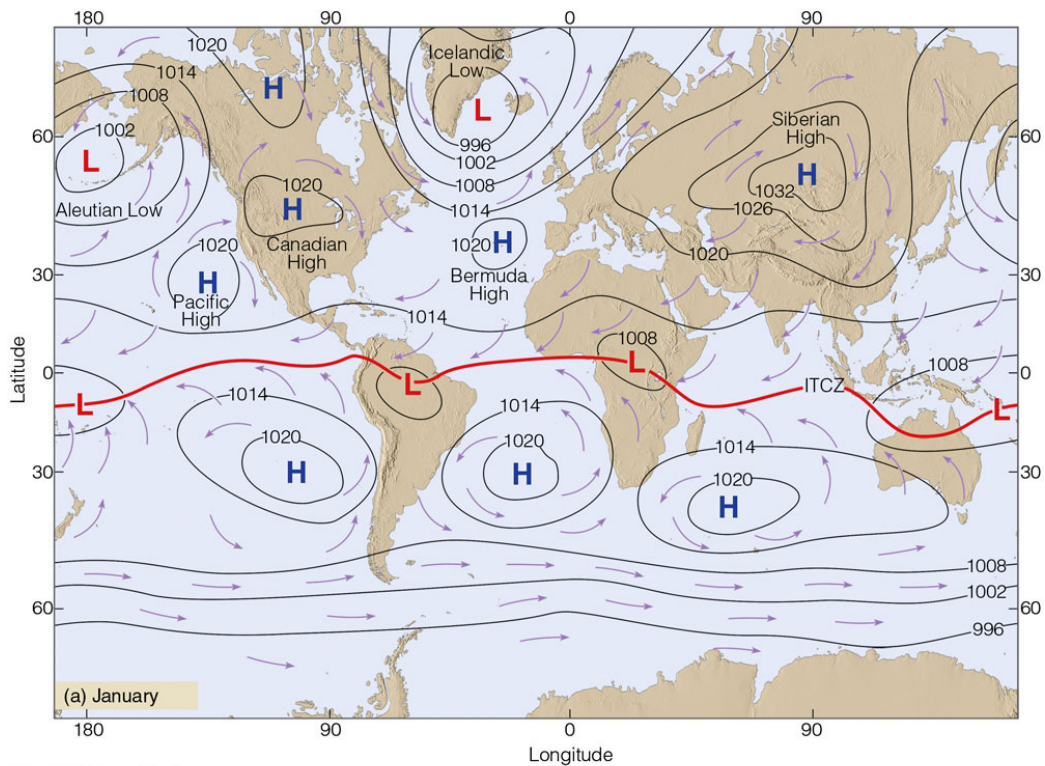


Figure 2: Average sea-level pressure distribution and surface wind flow patterns for January (a) and July (b). From Ahrens

1b. The Jet Streams

Jet streams are swiftly flowing air currents, thousands of km long and a few hundred km wide, and only a few km thick. There are two jet streams in the NH, one at about 30°, the **subtropical jet** and one at about 60° the **polar jet**. Both occur in the tropopause. They occur at the boundaries between areas of temperature change.

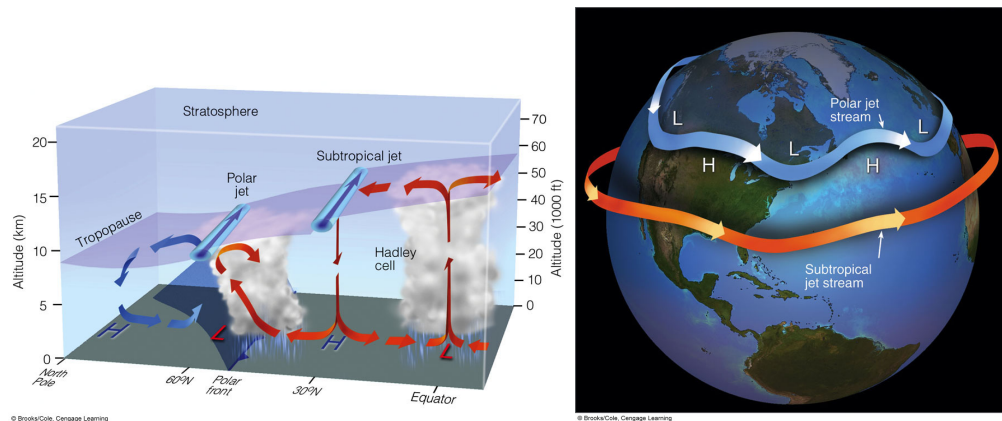


Figure 3: Jet stream is a swiftly flowing current of air that moves in a wavy pattern. In reality they are discontinuous. From Ahrens

2. El Nino, La Nina and the Walker Circulation

2a. The Walker Circulation

Similar to the Hadley cell that transports air from the equator to the subtropical latitudes (meridional circulation), there are zonal mean circulations (east-west oriented). One of these, the Walker circulation, plays a primary role in determining where rainfall will fall near equatorial regions and throughout the globe. Under normal conditions, the easterly trade winds move warm surface waters westward, causing higher temperatures in the western Pacific. The air overlying this warm water is in turn heated and rises to high levels of the atmosphere, diverges outwards, east and west, and finally sinks over the eastern Pacific.

Rising air is associated with a region of low pressure, towering cumulonimbus clouds, and rain. High pressure and dry conditions accompany the sinking air. There is also upwelling of cold nutrient-rich water off the coast of Peru. This is very important for fishing in this region.

2b. *El Nino*

Develops when the easterly trade winds weaken or even reverse and flow eastward. The warm water normally found in the western Pacific moves eastward and the waters in the eastern Pacific warm a couple of degrees centigrade. The upward branch of the Walker circulation shifts eastward to the central or eastern Pacific and the sinking branch shifts to Indonesia. El Nino occurs every 4-7 years around Christmas (this is why it is called el Nino).

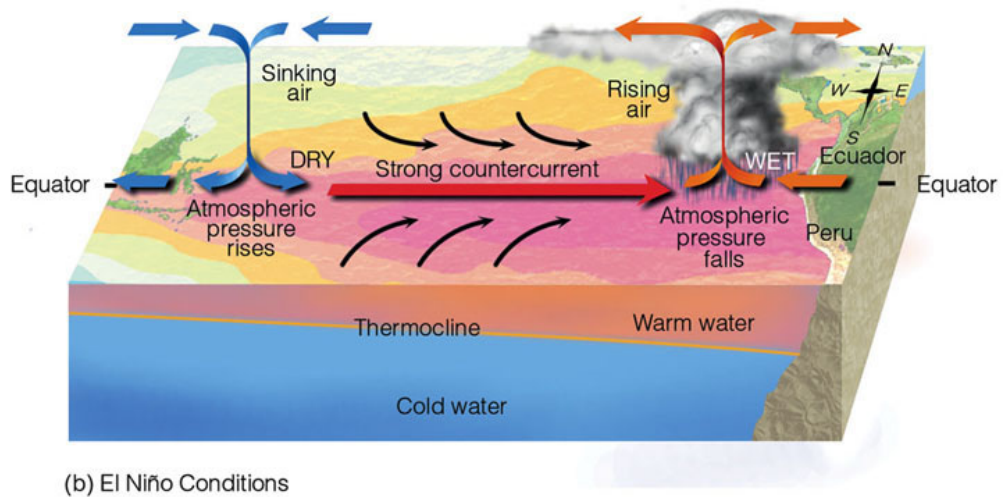
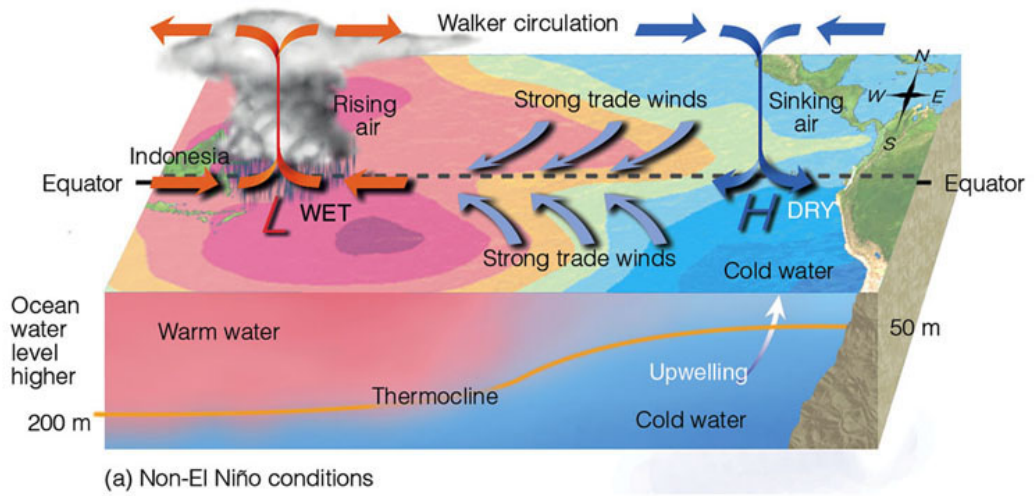
The seesaw pattern of reversing surface air pressure at opposite ends of the Pacific Ocean is called the Southern Oscillation and we call the whole phenomenon ENSO (El Nino Southern Oscillation). ENSO affects temperature and precipitation patterns throughout the world.

Even though it happens in the Pacific, it shifts the jet stream to the south (warm phase) north (cool phase). The most important teleconnections are:

- Drought in Australia and northern South America
- Heavy rainfall in Ecuador and Peru
- Wet and cool winters in the Southwestern US and in Florida
- Warm and dry winters in Northwestern US

3. Monsoons

A monsoon wind system changes direction with seasons, blowing from one direction in the summer and the opposite direction in the winter. In the winter, the land is cold and the air moves from land to sea. There is a clockwise circulation and the wind flows toward the southeast fair weather. In the summer, the land is warmer than the ocean. A low over land creates a counter-clockwise circulation.



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Figure 4: Diagram for Non-el Nino and El Nino conditions. From Ahrens

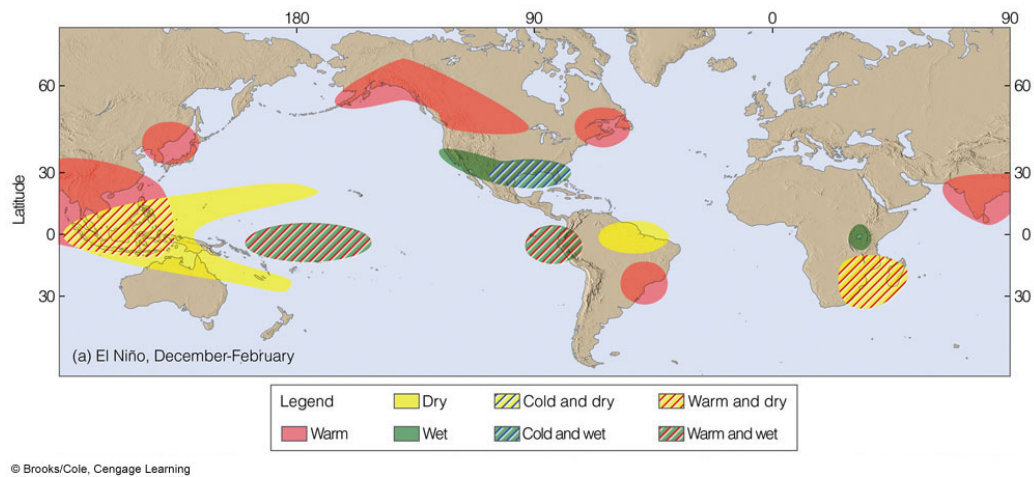


Figure 5: Regions of climate abnormalities associated with ENSO during Dec-Feb. From Ahrens based on CPC

Lifting is also provided by mountains. Winds coming from the ocean are full of moisture. The summer monsoon of southeastern Asia lasts from June- September and brings most of the rainfall in the season.

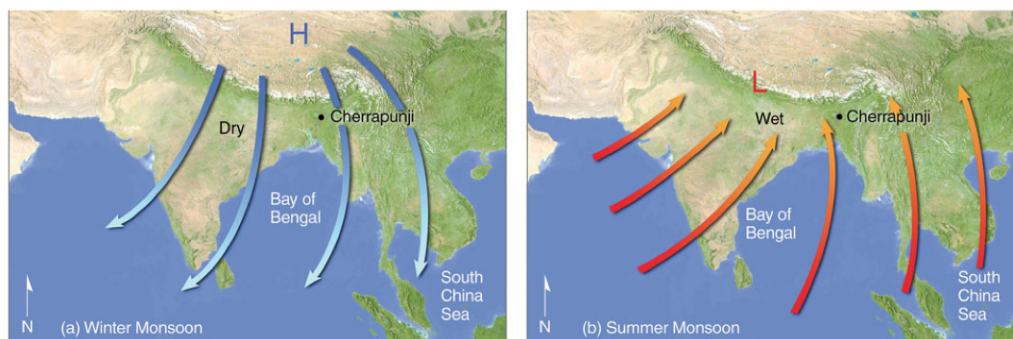


Figure 6: Monsoonal circulation. From Ahrens based on CPC

Why is the strongest monsoon in India? To the north of India is the Himalaya Mountains and the Plateau of Tibet, with an average elevation of over 15,000 ft. and a horizontal extent of more than 1000 miles. Contrast between the elevated

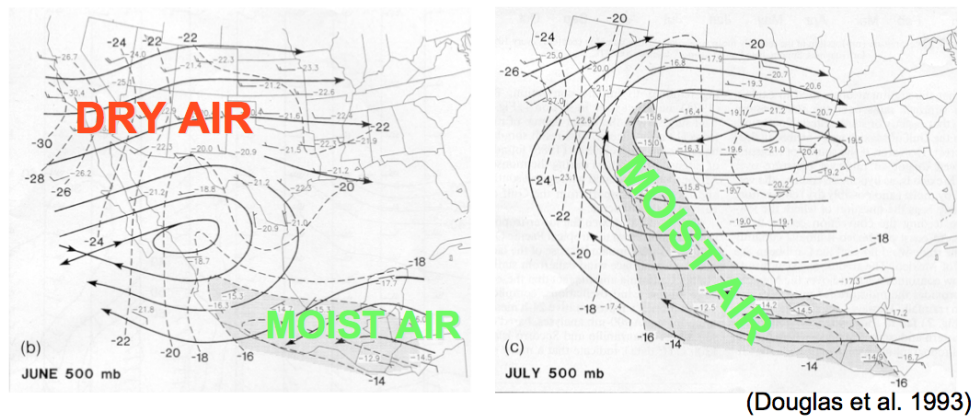
plateau and the surrounding bodies of water south of India sets up a giant thermally direct circulation. Some regions of India receive A LOT of rainfall. Cherapunji receives 1080cm a year !!!!! (we receive 30cm). India, with a population of over 900 million, depends heavily on Monsoon rains for agriculture, drinking water. But, monsoons are unreliable in intensity and duration...the research community is intensely working on improved monsoon predictability. Other regions in the world also experience monsoons...Australia, Africa, South America and the Southwestern US and Northern Mexico. These monsoons are much smaller than the Asian monsoons.

Why a North American Monsoon? Similar to Asia, North America has a giant elevated plateau in the western U.S. and Mexico. However, in our case, the Mexican plateau is only about 4000-7000 ft. in elevation, depending on where you are. Though it is not as high as Tibet, it IS high enough that there is a regular seasonal reversal of circulation.

4. Climate Change and the Hydrologic Cycle- South-western US

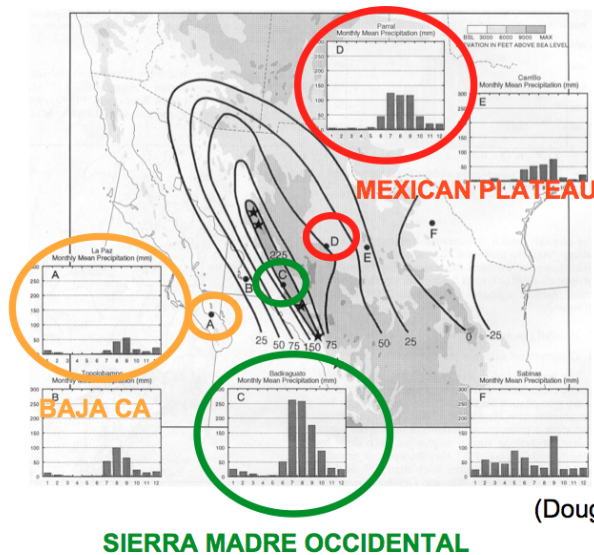
- Tropospheric water vapour is increasing (Figure TS.8). Surface specific humidity has generally increased since 1976 in close association with higher temperatures over both land and ocean.
- Long-term trends in precipitation amounts from 1900 to 2005 have been observed in many large regions (Figure TS.9). Significantly increased precipitation has been observed in the eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia.
- Substantial increases in heavy precipitation events have been observed. It is likely that there have been increases in the number of heavy precipitation events (e.g., above the 95th percentile) in many land regions since about 1950, even in those regions where there has been a reduction in total precipitation amount. Increases have also been reported for rarer precipitation events (1 in 50 year return period), but only a few regions have sufficient data to assess such trends reliably

Evolution of Monsoon Ridge and Upper-Level Moisture



Shaded areas indicate region of relatively high mixing ratio (i.e. atmospheric moisture content)

Monthly rainfall in western Mexico



The core of the North American monsoon is in Mexico, not Arizona

It accounts for about 60-70% of the rainfall there, so it is a pretty big deal for the country and its population, as a relatively large percentage of the population depends on subsistence agriculture.

(Douglas et al. 1993)

Figure 7: North American Monsoon. Courtesy of Christopher Castro

- More intense and longer droughts have been observed over wider areas, particularly in the tropics and subtropics since the 1970s. While there are many different measures of drought, many studies use precipitation changes together with temperature.⁶ Increased drying due to higher temperatures and decreased land precipitation have contributed to these changes.
- The current severe, multi-year drought in the western U.S. is the most extreme in 500 years, and has drastically reduced available water resources for people and wildlife (Cook et al. 2004, Glick 2006).
- The timing of snowmelt runoff has shifted to earlier in the snowmelt season for 84 rivers in the western U.S. This shift has not been gradual, but appears to have occurred as a step change (significant difference in value) during the mid-1980s, related to a regional increase in spring-summer temperatures (McCabe and Clark 2005).
- Daily observations from automated snow- pack telemetry (SNOTEL) stations from within the drainage basin of the Great Salt Lake over the period from 1982 to 2007 show a shift toward an earlier date of peak snow water equivalent (SWE) by around fifteen days and reductions in the amounts of peak SWE and April 1 SWE (Bedford 2008).
- April 1 snow pack has on average decreased at most monitoring sites in the Great Basin since about 1950. Snowpack decline in the dry interior U.S. (including the Great Basin) has been among the largest observed, with the exception of central and southern Nevada (Baldwin et al. 2003).
- The onset of snow runoff in the Great Basin is currently 1015 days earlier than 50 years ago, with significant impacts on the downstream utilization of this water (Ryan et al. 2008).
- Water supply in the Colorado River basin is unsustainable under current environmental and management conditions due to a combination of currently scheduled depletions (loss of water from consumptive use), water losses due to evaporation/infiltration, and reductions in runoff due to climate change (Barnett and Pierce 2008).
- Approximately 85% of the water used by humans in the Great Basin and Rocky Mountain region flows from spring melt

- of mountain snowpacks. Warmer winter-time temperatures and earlier melt dates will deplete this virtual reservoir, leaving much less available water for natural systems and human uses. Water resources in the region are totally allocated, with 80% of available water used for agriculture. Regional human populations and water needs are expected to double in the next 40 years, taxing resources even further (Wagner 2003, Service 2004).
- The majority of the observed low-frequency changes in the hydrological cycle (river flow, temperature, and snow pack) over the western U.S. from 1950 to 1999 are due to human-caused climate changes from greenhouse gases and aerosols (Barnett et al. 2008).
- There is broad consensus among climate models that the arid regions of the southwestern U.S. will become drier in the 21st century, and that a transition to a more arid climate is already underway. This forecast reverses earlier projections that the southwest might receive more rainfall as the climate warms (Lenart et al. 2007, Backlund et al. 2008).