3. The general circulation of the atmosphere and ocean

The *general circulation* is the ever-changing pattern of winds and currents. It is responsible for transporting heat meridionally from the tropics to the poles, and upward from the surface into the troposphere. Large-scale features that help determine regional climate include oceanic currents and *gyres*, atmospheric storm tracks, and seasonal mean low and high pressure centers. We will explore fundamental global modes of interannual variability, including the *El Nino Southern Oscillation (ENSO)*, the *North Atlantic Oscillation (NAO)* or *Northern Annular Mode (NAM)*, and the stratospheric *Quasibiennial Oscillation (QBO)*. Any global trend must be interpreted in the context of this natural variability. Perturbations to the earth system such as volcanic eruptions often manifest themselves in these natural modes of variation. Observed geographical patterns of temperature trends in the Arctic and Antarctic, the "global warming fingerprint", bear a strong resemblance to the structure of annular modes.

3.1. The general circulation as a response to differential heating

Q: What happens to the sunlight that reaches the earth?

The globally-averaged energy balance for space, the atmosphere, and the earth's surface is shown in Fig. 3.1. From the principle of conservation of energy, we know that Energy In = Energy Out (eqn. 2.5) for each part of the system. The energy transfer processes are partitioned into solar radiation, infrared radiation, and air motions.

Consider the fate of 100 units of incoming solar energy: 30 are reflected back to space by the earth system, 20 are absorbed by the atmosphere, and 50 are absorbed at the earth's surface. Absorption of sunlight and re-emission at earth temperatures converts energy from visible to infrared wavelengths. The earth emits 90 units of infrared upward at 288 K, while the atmosphere emits 70 units upward and 70 units downward at 255 K (140 units total).

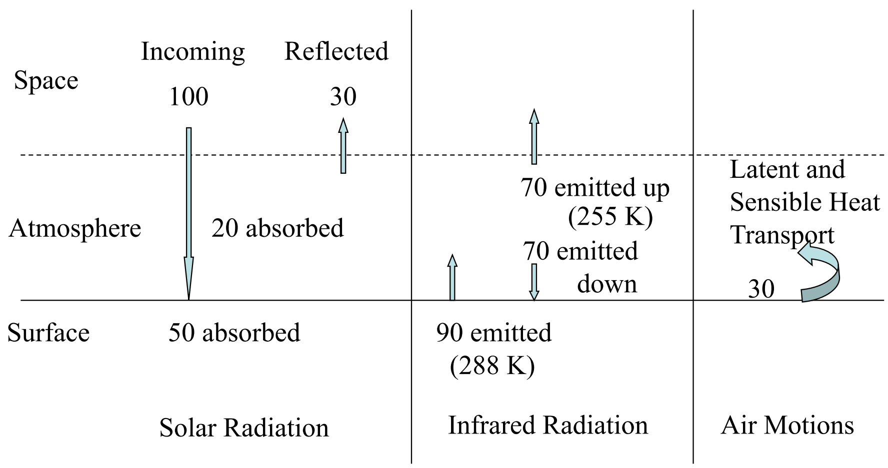


Figure 3.1. Schematic diagram of globally-averaged vertical energy transfer processes among space, the atmosphere, and the surface, distinguishing energy transfer by solar radiation (left), infrared radiation (middle), and atmospheric motions (right).

Q: Does radiative transfer account for all of the energy budget?

For the energy balance between the planet and space, yes. Of the 100 units of solar radiation that reach the earth, 30 units are reflected and 70 are emitted to space in the infrared by the atmosphere, verifying the fundamental radiative balance assumed in calculating T_{re} from (eqn. 2.7).

The radiative energy budgets for the surface and the atmosphere are not balanced. The surface receives 50 units of sunlight and 70 units of infrared from the atmosphere, while emitting 90 units of infrared, for a gain of 30 units, net radiative heating. The atmosphere receives 20 units of sunlight and 90 units of infrared from the surface, while emitting 140 units of infrared, for a loss of 30 units, net radiative cooling. This implies that 30 units must be transferred from the surface to the atmosphere by conduction and complex motions, as shown at the right in Fig. 3.1.

This radiative imbalance, which heats the surface and cools the atmosphere, causes warm, moist air near the surface to rise, and cool, dry air aloft to sink, effectively transporting heat upward. The resulting motions, including thermals, thunderstorms, tropical cyclones, and midlatitude cyclones, may be regarded as the response of the general circulation to this radiative imbalance.

Q: What is "latent heat"?

The atmosphere is heated from below like a pot of boiling water. Of the 50 units of solar energy that reaches the surface, about 30 go into simply evaporating water from the ocean and wet land surfaces. So about 30% of the solar energy reaching earth goes into evaporating water! Water is surprisingly stubborn to heat up. It takes 2.5 million J of energy to evaporate 1 kg of water, hence the latent heat of vaporization is 2.5×10^6 J/kg.

A profound amount of energy goes into enabling water molecules to leap from the liquid phase into the high speed gaseous phase. As the temperature of water increases it becomes easier and easier for water to evaporate. The amount of water vapor that air can hold increases exponentially with increasing water temperature.

Since it takes energy to vaporize water at constant temperature, the energy goes into the phase change. From the point of view of temperature, this form of energy is hidden. We call this form of energy storage for water vapor "*latent heat*". Winds moving moist and dry air around are transporting latent heat. We can sense warm and cold air with our skin, so that type of energy is called sensible heat. The atmosphere transports warm and cold air (sensible heat transport), and moist and dry air (latent heat transport). The energy associated with water vapor is latent until it condenses due to cooling processes. The phase change retards the cooling process during the formation of rain and snow, since energy must be removed to cause vapor to condense onto a rain drop or freeze onto an ice crystal. Latent heat is the fuel which drives the interesting storms that affect our lives. Rain or snow and latent heat release can occur quite far from where the water evaporated. Atmospheric transport of water is an important part of the energy flow in the climate system.

Q: Why are the poles cold?

Differential heating between the equator and poles is the fundamental cause of large-scale atmospheric and oceanic motions. But why are the poles colder than the equator? It may be tempting to conclude that it is because at noon the equator is 6367 km closer to the sun than the poles. But this is minuscule compared to the average distance of 150,000,000 km to the sun. The answer lies in the spherical shape of the earth. The sun's rays spread out across the surface near the poles, so that a square meter of surface receives much less radiation than in the tropics.

Q: What causes the general circulation?

Since the poles are colder than the tropics, the Stephan-Boltzmann law implies that less radiation is emitted to space. Yet on an annual average there are large imbalances between Energy In and Energy Out for radiative processes alone. Figure 3.2 shows that much more solar radiation is absorbed in the tropics than is emitted to space in the infrared. At high latitudes, the amount of infrared emitted to space far exceeds the solar radiation absorbed. If radiative processes were the only ones operating, after a while the poles would get much colder and the tropics much warmer, until emission and absorption were equal. In this thought problem, the equator to pole annual mean difference would be ~ 100 K. The observed difference is only ~ 35 K, about 1/3 as big as it would be without meridional (north-south) heat transport. Atmospheric and oceanic heat transport arises in response to differential radiative heating, and acts to reduce temperature differences caused by differences in radiative heating.

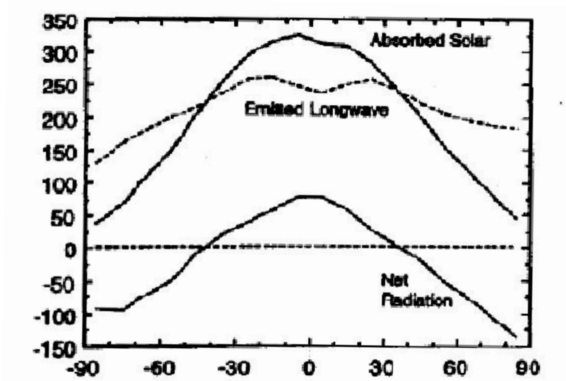


Figure 3.2. Latitudinal profile of annually and zonally averaged solar heating (solid) and infrared cooling (dashed) in W m^2. The difference between absorbed solar and emitted infrared radiation, the net radiation into the earth system, is shown in the bottom curve [Peixoto and Oort 1984].

3.2. Atmospheric and oceanic heat transport

Differential radiative heating leads to density differences, rising and sinking motions, hence the winds and currents which accomplish the net heat transport across ~ 37° latitude. These motions tend to occur in organized, large-scale patterns influenced by the distribution of continents. Figure 3.3 shows the atmospheric and oceanic heat transport contributions to the total required heat transport. About 1/3 of the heat transport occurs in the ocean, with warm currents going poleward on the west edges of the ocean basins, and cold currents going equatorward on the east edges of the oceans. There are equal contributions of latent and sensible heat transport in the atmosphere, with warm moist tropical air moving poleward, being replaced by cold dry polar air moving equatorward. To see film loops of this phenomenon, visit www.aos.wisc.edu/weather/forecastmaps and click on the Global Forecast System (GFS) prognostic charts produced by the National Centers for Environmental Prediction (NCEP).

A primary source of evaporated water is the subtropical oceans. Some of this is transported into the tropics where it rains out in the intertropical convergence zone. Some of this is transported to higher latitudes, where precipitation exceeds evaporation, and the latent heat keeps the air much warmer than it would otherwise be. After precipitation, the drier air is then transported equatorward, where it picks up more water vapor and the cycle begins again. Typical values of vertically-integrated latent heat release are ~ 40 W m^{-2}, similar in magnitude to differences in radiative heating and cooling in Fig. 3.2.

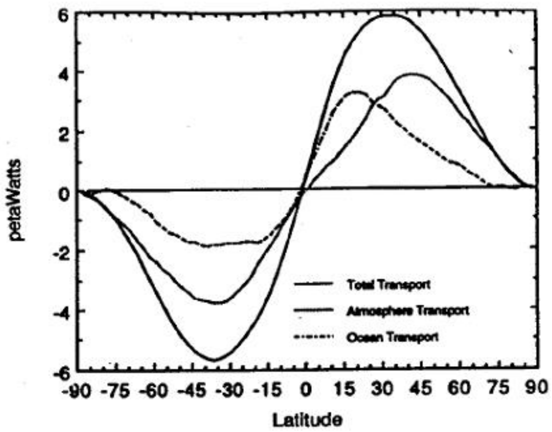


Figure 3.3. Annual and zonal mean meridional energy transport as a function of latitude (in units of petawatts or 10^{15} W) required by the radiative energy balance in Fig. 3.2, showing separate transport contributions from the atmosphere (observed) and the ocean (inferred) [Peixoto and Oort 1984].

A typical example of heat transport by a storm in the Midwestern U.S. is shown in Figs. 3.4 and 3.5, valid for 0000 UTC, February 6, 2008 (6 pm CST February 5). This storm has seen been referred to as the Super Tuesday storm. The radar reflectivity map (Fig. 3.4) shows where rain, hail, and snow (hydrometeors) have formed due to upward motion. Rising motion occurs along the cold front over Arkansas and the warm front over Northern Indiana. The cold front and the area just ahead of it in the warm sector is densely-beaded with red thunderstorm cells. These spawned more than 100 tornadoes which killed more than 50 people. Warm, moist air heading northward ahead of the cold front wraps counterclockwise around the low-pressure center toward Iowa, giving a comma shape to clouds and precipitation. In Southern Wisconsin snowfall from the storm ranged from 9 to 20 inches. More than 2000 cars were trapped on an 18 mile stretch of I-90 for almost a day.

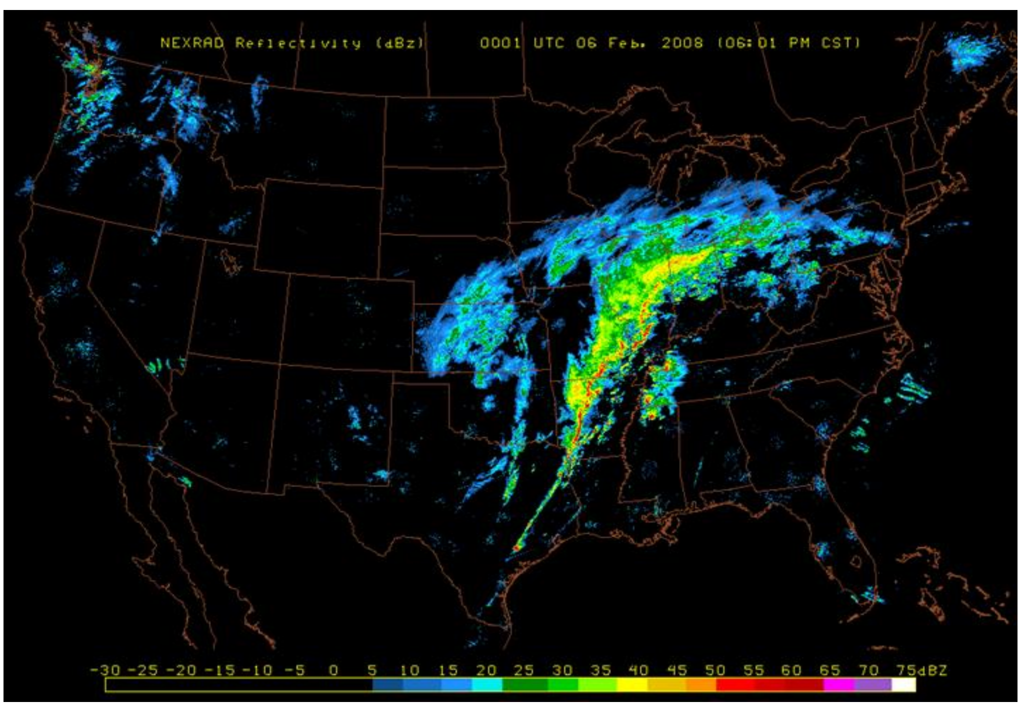


Figure 3.4. Composite radar reflectivity at 0000 UT February 6, 2008 (6 pm CST February 5). Reflected power (color) is proportional to the intensity of precipitation.

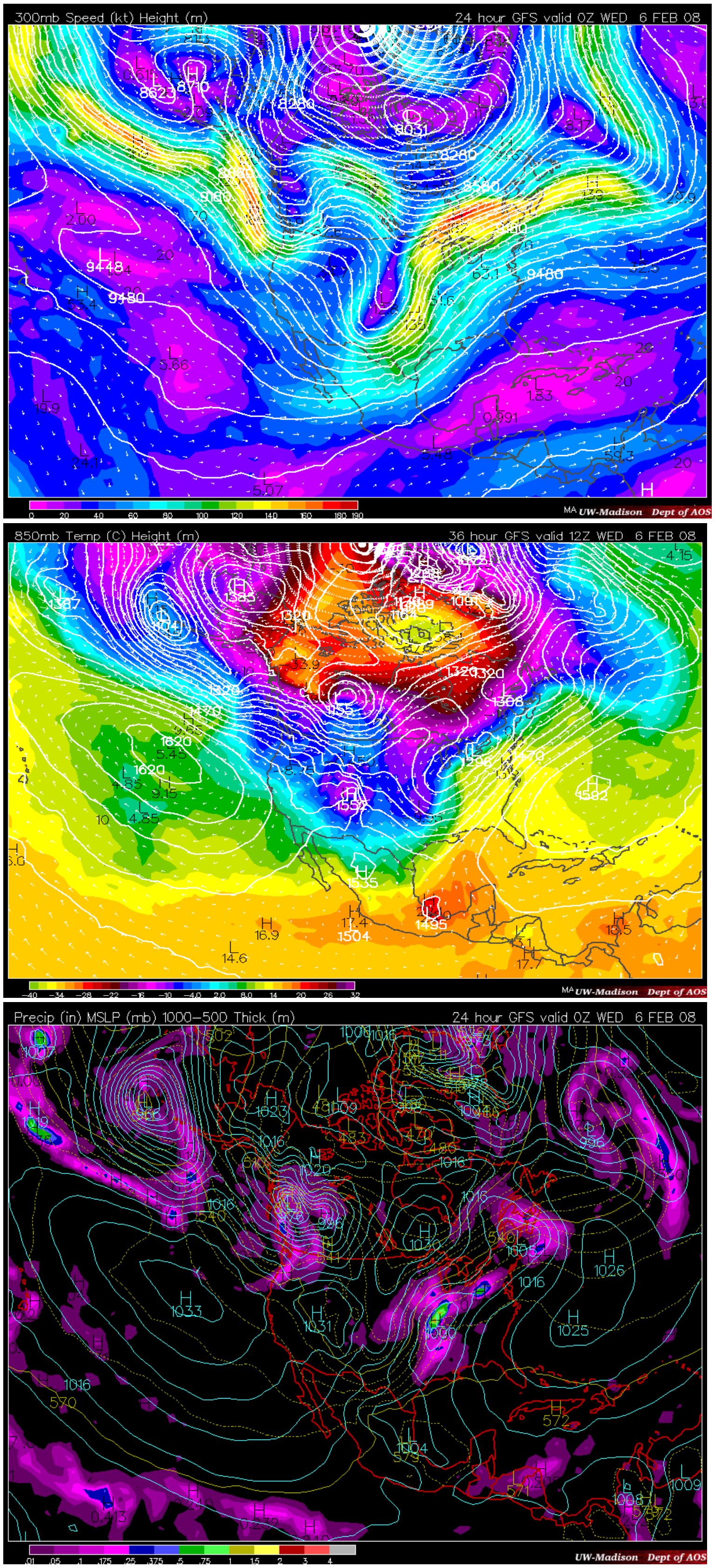


Figure 3.5. GFS 24 hour forecast valid at 0000 UT February 6, 2008 (6 pm CST February 5)

a) 300 hPa geopotential height (white contours every 60 m), and isotachs (color bar in knots; 1 knot = 0.544 m/s)

b) 850 hPa height (white contours, interval 30 m) and temperature (color bar, ^{o}C).

c) Sea level pressure (white contours, interval 4 hPa), 12-hour rainfall (color bar, inches), and 1000-500 hPa thickness (yellow contours, 60 m interval). Spatial variation in thickness is caused by the pattern of average temperature in the layer.

Focus: Synoptic-scale baroclinic waves

Figure 3.5 shows a 36 hour GFS forecast, including a) depiction of the jet stream in the upper troposphere (300 hPa), b) temperature pattern in the lower troposphere (850 hPa), and c) patterns of sea level pressure, 6-hour rainfall. The wavy pattern at 300 hPa features a 100-knot jet stream (~ 50 m/s) over Texas, which curves northward toward the Great Lakes, reaching 180 knots (~ 90 m/s) over Ontario, and extends eastward into the Atlantic (Fig. 3.5a). In this configuration, a developing surface low will track toward the northeast, consistent with flow at 500 hPa, which is often referred to as the "steering level".

The 850 hPa chart reveals a growing cyclone, with low pressure over the Mississippi valley. This cyclone is converting energy associated with the contrast between warm air coming up from the Gulf of Mexico toward the Great Lakes, and cold air heading southward toward Texas from Canada (Fig. 3.5b). Note the strong temperature gradients at the leading edge of the cold and warm air masses, the cold and warm frontal zones (Figs. 3.5b, 3.4). Precipitation and latent heat release occur in association with the fronts, where upward motion occurs. A common pathway for moist, rising air in the warm sector is to wrap cyclonically around the low-pressure center, resulting in a comma-shaped cloud and precipitation pattern (Fig. 3.5c).

One may observe that in the midlatitudes there are wavy temperature patterns associated with cyclones and anticyclones (Fig. 3.5b). Anticyclones are seen off the coast of California and Florida. An older, occluded cyclone is found near the Aleutian Islands. As the cyclones and anticyclones go through their life cycles, warm moist air moves poleward and rises ahead of an approaching cyclone, while cold dry air moves equatorward and sinks ahead of an approaching anticyclone, effectively transporting sensible and latent heat toward the poles. The warm moist air is lighter and rises up and over the cold dry air, which sinks equatorward. Since dense air sinks and light air rises, this *lowers the center of mass* of the air masses.

The air mass motions associated with a cyclone may be characterized as sloping buoyancy, whereby energy associated with the distribution of mass (geopotential energy) is converted into kinetic energy, causing the growth of a *synoptic-scale baroclinic wave*. The portion of energy that can be tapped is determined by the horizontal contrast in density. This process of wave growth is called *baroclinic instability*. The result of amplified air mass motions around a cyclone is to homogenize the horizontal variation in density in a process called occlusion, or Rossby wave breaking, thereby reducing the energy available for baroclinic instability. The end result of these waves going through their life cycles is to mix the atmosphere such that the difference in heat and moisture between the tropics and high latitudes is reduced. Synoptic baroclinic waves may be regarded as a response to differential heating. They make a primary contribution toward the general circulation by transporting heat, momentum, water, and other constituents.

3.3. A puzzle concerning land and sea

The large-scale wind and current patterns, which accomplish the necessary poleward heat transport, are controlled, in part, by the distribution of land and sea. The importance of this distribution can be brought out by examining a curious paradox about the earth's climate, which may be stated: *The globally-averaged temperature is colder in January than in July, but the earth is closer to the sun in January, receiving ~7% more radiation (~1418 W/m^2) than in July (~1322 W/m^2)!* This fact is rendered even more curious when it is noted that, in January, the southern hemisphere (SH) ocean absorbs more energy than does the more reflective northern hemisphere (NH) land surfaces in July. How can this be? The answer lends insight into how monsoons work and is an important aspect of the Milankovich theory of glacial / interglacial cycles.

The land is primarily located in the NH. Land heats up and cools off much more quickly than ocean, and can support snow and ice more readily. Sunlight is absorbed in a thin layer on land (< 1 cm thick) but penetrates much deeper into the ocean (~ 100 m). It takes 4 times as much heat to raise 1 kg of water 1 K compared to 1 kg of soil. The main reason why the land heats up more quickly than the ocean in the summer is that much of the solar energy reaching the ocean goes into evaporating water. This is also true of moist ecosystems on land. But wherever it is dry, sunlight quickly raises the surface temperature. Emission of infrared to space can quickly cool the land surface, but the ocean surface will stay more constant, since mixing of warmer water from below will keep the temperature mild. Ocean currents can also transport heat to where it is lost by infrared emission, keeping waters ice free as far north as Spitzbergen. All of these factors give the ocean a large thermal inertia, which cools off and heats up much more slowly than the land. Hence the seasonal cycle for the NH, which contains most of the land, exerts a strong control over the whole planet. Other consequences of this land/sea contrast for ecosystems and human habitation are that the diurnal and annual temperature variations are smaller near the ocean than in the middle of continents.

Even though the earth is closest to the sun in January, the NH land is tilted away from the sun, so it cools quickly. Snow can build up on land, reflecting sunlight, making the region cooler. This is an example of the ice albedo feedback, amplifying the ability of snow to fall on land. In July, the NH land is tilted toward the sun, so it heats up quickly, more than compensating for the fact that the earth is farther from the sun. Meanwhile, the SH oceans heat slowly in January and cool slowly in July. Applying similar reasoning, continents heat up and cool off much more quickly than the more equable oceans, leading to seasonally-reversing land-sea heating contrasts and monsoonal circulations. In Chapter 4 we will explore the role of NH land masses in amplifying tendencies from the Milankovich orbital parameters, causing the earth to go into and out of ice ages.

The distribution of the annual range in monthly averaged temperature is shown in Fig. 3.6. The interiors of continents are much colder in winter and much warmer in summer compared to oceans at a similar latitude, with the range in monthly-averaged temperature exceeding 60 K in northeastern Siberia, 40 K in Canada, 20 K in northwest Africa, and 15 K in Australia and Patagonia. In midlatitudes, the west coasts of continents are more like the oceans and the east coasts are more like the continents, because of the prevailing westerly winds. We will investigate the cause of these westerly winds shortly.

The tropics are not very noticeable in Fig. 3.6, with the annual range averaging < 2 K. This is partly due to the fact that the noon sun is high in all seasons. Other important factors include the efficient mixing of heat by air motions and trapping of infrared radiation by the large amounts of water vapor in the tropics. Nevertheless, air does get hotter over tropical land

(Amazonia, Africa, and Indonesia) than over the adjacent ocean, leading to a stronger tendency for rainfall over continents and groups of tropical islands.

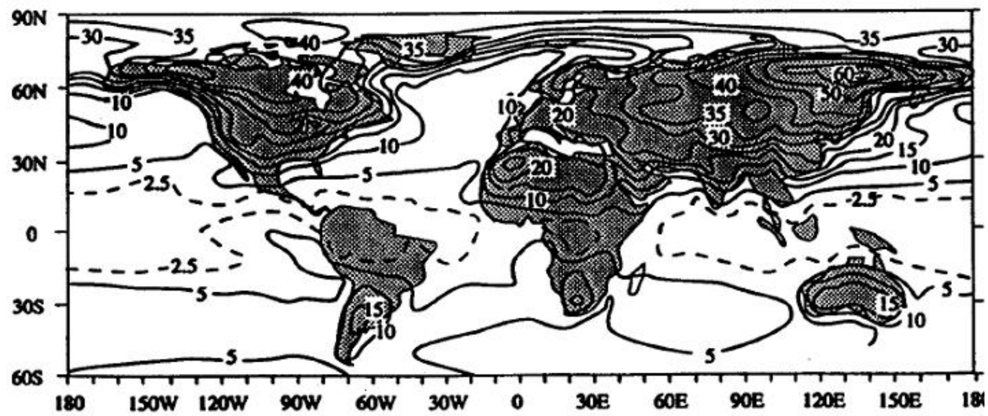


Figure 3.6. The annual range in monthly-averaged surface temperature, contour interval 5°C [Shea 1986].

3.4. Monsoon Circulations

Hot air rises and cold air sinks. If we burn some toast when it's cold outside and we open the door, the hot air with the smoke will go out the top and the cold air will come in along the floor and chill your feet, making tube socks seem desirable. You may also have noticed that air next to a window in winter chills, gets denser, and sinks along the floor, making your feet cold, and is replaced by air from the upper part of the room. These examples illustrate how the monsoons work, only on a larger scale. A monsoon is a seasonal reversal in the prevailing wind direction on a continental scale.

Figure 3.7 shows idealized cross-sections of monsoon circulations for summer and winter. In summer the air over the continent heats up quickly, expands, and rises, with molecules "spilling off" onto the cooler, contracted air column over the oceans. The export of molecules from the continents to the oceans implies lower pressure at the surface over the continent and higher pressure over the ocean. This pressure difference gives rise to a pressure gradient force, which causes air to move from the oceans to the continent, bringing moisture onshore. This air then rises, cools, condenses, and rains, hence the association of monsoon and summer rains.

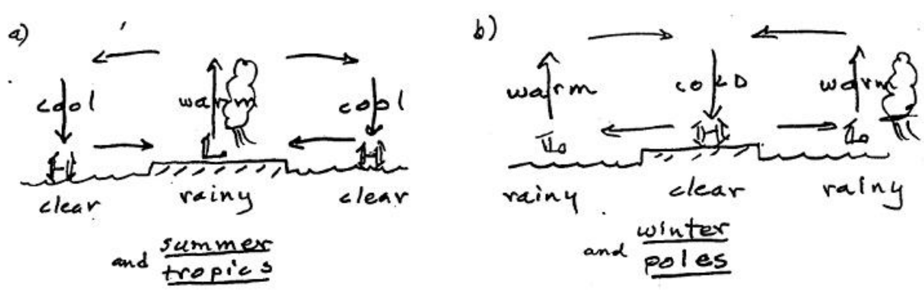


Figure 3.7. Idealized monsoon circulations corresponding to a) summer and the tropics, and b) winter and polar regions.

During winter the continents get much colder. The air over the continents becomes denser, more compact, and sinks, leaving room for air molecules to "fall off" of the expanded warm oceanic air columns onto the top of the contracted continental air columns. This increases the surface pressure over land and decreases it over the oceans. The resulting pressure difference causes the air to flow from the continents toward the oceans (offshore flow). The rising warm air over the oceans cools as it rises, leading to condensation and precipitation. The cold air over the continent warms somewhat as it sinks, which suppresses condensation and clouds.

Air converges into the warm low pressure regions and rains over the oceans during winter and over the continents during summer. In the subtropics and higher latitudes there is a seasonal monsoon circulation that strongly influences the general circulation. The winter circulation also applies to Antarctica most of the time, where high pressure dominates and katabatic flows descend the continent and rush out onto the ice shelves toward the warm low pressure areas surrounding Antarctica. The summer circulation also applies to the tropics, with preferred rising motion and rain over Indonesia, Africa, and Amazonia.

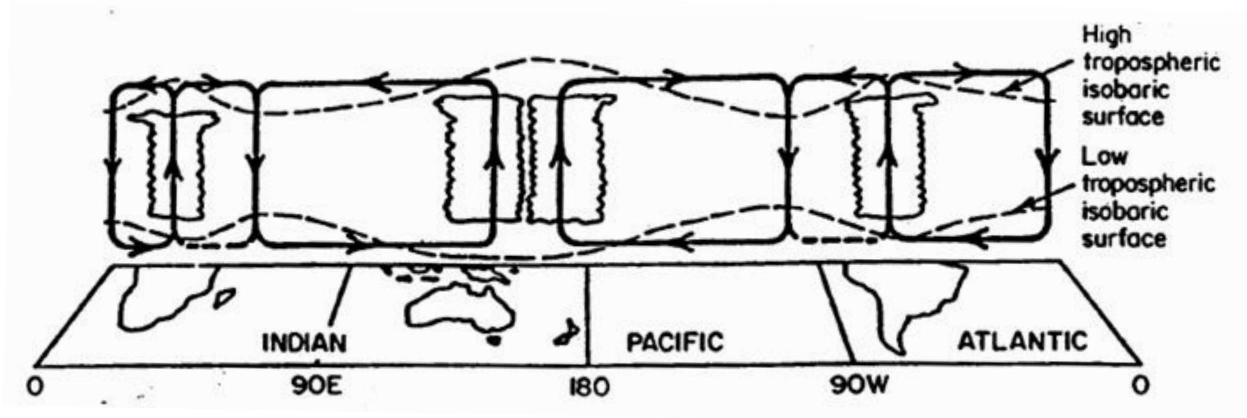


Figure 3.8. Schematic view of the atmospheric circulation in the tropics indicating convergence and rising motion in regions of convection [Webster 1983].

Figure 3.8 shows the strong east-west overturning in the Pacific that results from preferential heating over Amazonia, Africa, and Indonesia (which exhibits the thermal aspects of a "*Maritime Continent*"). This pattern of low pressure, rising motion, and rainfall over Indonesia and high pressure, sinking and clear skies in the East Pacific is part of the overturning *Walker circulation*, first identified by Gilbert Walker in the 1930s. This circulation varies between strong and weak every 3-7 years, giving rise to a *Southern Oscillation*, the atmospheric component of the *El Nino Southern Oscillation* (ENSO) phenomenon.

Differential heating gives rise to regions of high and low sea level pressure at all latitudes. In the tropics, air tends to flow straight from high to low pressure, such that spatial variation in sea level pressure is rather weak. In the extratropics, surface flow is also toward the warm ocean or continent, but with increasing latitude, the effects of rotation on a sphere are increasingly important (the Coriolis effect), causing the flow to have a primary tangential component around high and low pressure centers, with a smaller drift from high to low pressure.

3.5. Sea level pressure patterns and winds

The distribution of land and sea is directly related to the seasonal patterns of sea level pressure, winds, and gyre circulations in the upper layer of the oceans. The rotation of the earth leads to a surprising consequence for air trying to flow from high to low pressure. Since the earth rotates around once a day, the air doesn't flow simply from high to low pressure. This effect is more pronounced the farther away from the equator you get. To understand the world's large scale atmospheric and oceanic circulation patterns, we need to understand the Coriolis effect and the associated, wind-driven *Ekman transport* which exists in the upper layer of the ocean.

As observers sitting here on the earth, we are pulled by gravity toward the center of the earth and stuck to the earth's surface by the van der Wahl's forces that attract our shoes and clothes to objects that we walk and sit on. Since the earth rotates slowly enough, these frictional forces and the firmness of the earth cause us to move in a very peculiar path through space: ever curving (radially accelerating) toward the rotation axis but never getting there. In the NH, we are always curving to the left of straight-line motion. It is natural for us to express everything in a coordinate system that is not moving with respect to the earth's surface. But when we do so, straight line motion in the NH appears to curve to the right. This is the Coriolis effect, which is not a true force in the sense of a physical impulse to change direction or speed. Straight-line motion appears curved in a rotating coordinate system, causing air or water moving in a straight line to appear to be deflected to the right in the NH and to the left in the SH.

Imagine yourself inside a room and you have the ability to fly. If you took off and flew straight toward a spot on the wall on the other side of the room you would miss your target ever so slightly. That is because, during your flight, the room rotated slightly, counterclockwise around the north pole (or clockwise around the south pole), as seen from above. It is just the Coriolis effect.

A turntable normally rotates clockwise as seen from above. This is in the same sense that the SH rotates as seen from above. If you draw a chalk line on a long-play vinyl record from the spindle towards yourself, you would see a chalk mark (streak line) which curves to the left of the direction of motion of the chalk. It is just the Coriolis effect.

If you were to ride in a rocket flying straight from the North Pole toward the equator, you would find that the equator, moving eastward at 450 m/s, slipped off to the east, to your left, while you were moving straight. An observer in the rotating earth coordinate system would see you appearing to be deflected to the right and to appear to land to the right of your target. It is just the Coriolis effect. It is interesting to consider that a rocket launched eastward or westward at the equator will stay over the equator, because the Coriolis effect is zero there.

One day you may find yourself with a beautiful house, with a beautiful spouse, and a beautiful merry-go-round, trying to throw beautiful balls to each other, and you may ask yourself, well, why doesn't the ball get to my partner like I expect? The ball goes straight, but you and your partner are in a rotating coordinate system. It is just the Coriolis effect.

Figure 3.9 shows the patterns of sea level pressure and surface winds during January and July. During NH winter the oceans are warm and rainfall is prevalent in the Aleutian Low and Icelandic Low pressure systems. The continents are cold during NH winter, with the Canadian High and Siberian High pressure systems dominating the weather. During NH summer, the oceans are cooler and the North Pacific and Bermuda Highs expand to dominate the circulation, while lower pressure and thunderstorms dominate North America and Eurasia.

In the SH during summer (Fig. 3.9a) the oceans are cooler in the subtropics, so high pressure dominates over the eastern Pacific and Atlantic (cf. Fig. 3.7). Relatively lower pressure occurs over Australia, Africa, and South America. During SH winter the oceans dominate the climate, with synoptic storms travelling rapidly eastward in the "roaring 40s and 50s".

When air diverges out of a high-pressure region and converges into a low pressure region it is deflected to the right in the NH and to the left in the SH. During NH winter, air flowing outward from cold high pressure over Canada curves to the right, yielding northwesterly winds in central North America. During NH summer air flowing outward from the high-pressure region over Bermuda curves to the right, yielding southerly winds prevailing in central North America. This is the North American monsoon east of the Rockies. Note that in winter dry air sinks equatorward over us, while in summer moist warm air moves poleward over us, giving a poleward heat transport of sensible and latent heat in both seasons.

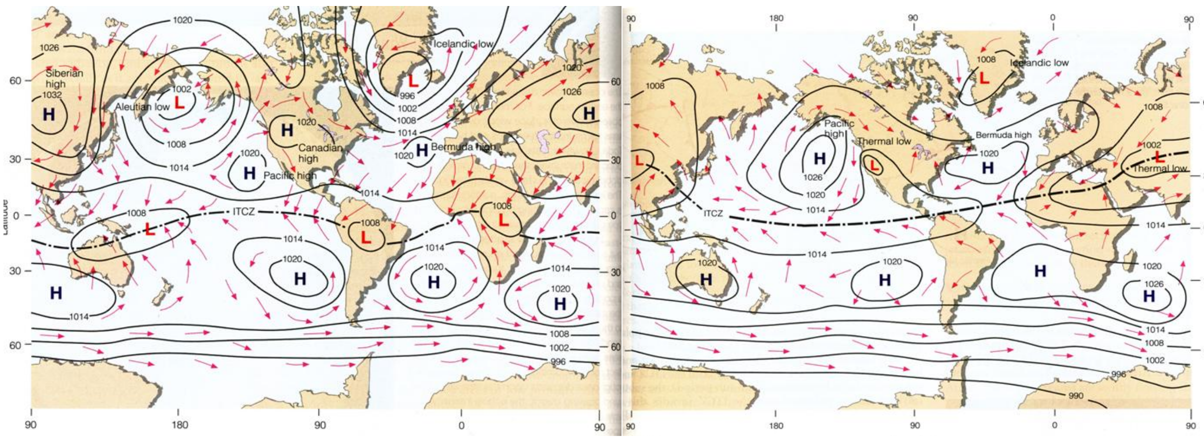


Figure 3.9. Monthly mean sea level pressure (contour interval 4 hPa), and idealized surface wind vectors for a) January and b) July [from Ahrens (2019)].

3.6. Midlatitude westerlies and subtropical easterlies

The ocean surface circulations are caused by wind pushing on the ocean surface. We need to understand why winds tend to blow from the east (easterly) in the subtropics and from the west (westerly) in the extratropics. The suffix -ly suggests the properties of the air from whence it came. We observe in Fig. 3.9 that the subtropical high pressure regions have westerly winds on their poleward flanks and easterly winds on their equatorward flanks. We can gain a deeper understanding of why this is so by considering the transport of angular momentum by the general circulation.

Angular momentum per unit mass is equal to the tangential speed of rotation times the distance to the rotation axis. The earth's surface at the equator is moving eastward at 450 m/s and is 6367 km from the rotation axis, so it has a lot of angular momentum, while the poles have zero angular momentum. This means that poleward motion brings larger angular momentum, while equatorward motion brings smaller angular momentum. Air diverges poleward out of tropical convection over Indonesia, Amazonia, and Central Africa in the upper troposphere. This poleward-moving air remembers its large angular momentum, which is greater than the midlatitude surface over which it is moving, so it travels eastward faster than the surface underneath. Poleward motion generates westerly winds. The surface air converging into the tropics will remember that it came from a latitude with lower angular momentum, and move less rapidly eastward than the surface it is moving over. Equatorward motion generates easterly winds. These trade easterlies converge into the tropics, where they rise again. The zonal average of this overturning meridional circulation is known as the *Hadley circulation*.

This meridional circulation varies around the equator and with season, being especially strong over the Indian Ocean, due the strong contrast between it and the Asian land mass in the NH. During NH summer, air converges into Southeast Asia, rises and heads across the equator into the southern Indian Ocean, while surface winds flow northward toward Southeast Asia. During the NH winter the land cools and the circulation reverses.

Subtropical jet streams are stronger in longitude bands where there is tropical convective outflow exporting high angular momentum. This creates the three regions of sharpened height gradients seen in Fig. 2.6, which indicate three preferred locations for enhanced jet streams near the East Coast of Asia, East Coast of North America, and the Middle East. The angular momentum transported by the local Hadley circulations feeds the entrance to the subtropical westerly jet streaks north of the Maritime Continent on the East Coast of Asia, north of Amazonia on the East Coast of North America, and in the Middle East, north of Africa. These constitute the NH wintertime mean storm tracks. During the SH winter, outflow from SE Asia leads to the beginning of a jet stream just SW of Australia, extending to South America.

These subtropical jet streams are unstable to small perturbations, meaning that synoptic scale cyclones and anticyclones will grow and break on them, transporting heat and angular momentum to the midlatitudes. The turbulent motions transport high angular momentum to the surface, so westerly winds prevail in the extratropics. Surface westerlies push the ocean and land surface eastward and the atmosphere loses angular momentum to the surface. As air flows toward the equator, the trade easterlies push on the surface from the east, picking up angular momentum from the surface, and pushing warm tropical waters toward the west, piling them up against the east shores of continents. In the Pacific, this vast gathering of warm surface waters toward Indonesia by the convergent trade easterlies creates the largest area of warm surface waters on the planet, it causes a downwelling of the thermocline near Indonesia, and creates a preferred region of deep convection, which accounts for the rising portion of the Walker Circulation (Fig. 3.8). The fundamental dominance of eastward wind stress in the midlatitudes and westward wind stress in the subtropics gives rise to the vast oceanic gyres in the ocean basins.

3.7. Ocean gyres

Most of the ocean is within 5°C of 0°C, but in the top 100 m or so sunlight can warm the ocean to over 30°C (Fig. 2.6). Wind tends to mix this heat downward to the *thermocline*, the zone of rapid transition to cold deep water. The heat content in a 1 m^2 column of the upper ocean is about 200 times the heat content of an atmospheric air column. Much of the excess energy emitted back to earth by anthropogenic greenhouse gases goes into heat storage in the upper layer of the ocean.

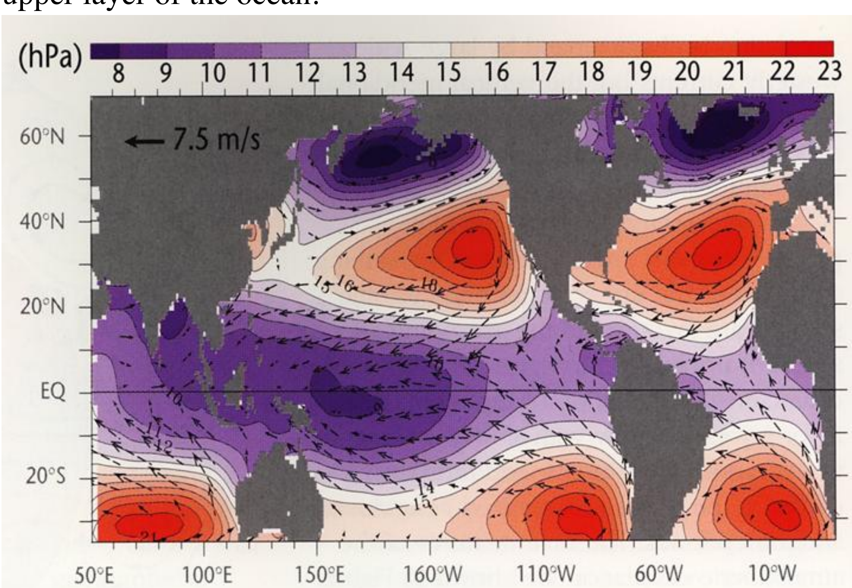


Figure 3.10. Annual mean sea level pressure anomaly and surface winds [www.cpc.noaa.gov].

The annually averaged sea level pressure anomalies and surface winds over the ocean are shown in Fig. 3.10. Subtropical highs dominate the eastern oceans, while low pressure areas dominate the North Pacific, North Atlantic and, the tropical western oceans. The trade easterlies in the tropics blow from high to low pressure, gathering warm waters toward Indonesia in the Pacific, depressing the thermocline. This is compatible with the anticyclones being located to the east, over colder water.

The midlatitudes experience westerly wind stress, while the tropics experience easterly wind stress. When the wind blows on the upper surface of the ocean and it starts to move, the Coriolis force will cause it to appear to curve to the right in the NH and to the left in the SH. This layer will then push on the layer below it, which will begin to move, deflected to the right of the uppermost layer. The next layer down is deflected still more, leading to a directional spiral with speed decreasing downward. This is called the Ekman spiral, and there is a counterpart in the boundary layer of the atmosphere. The net effect on the ocean is to cause its upper layer to move to the right of the wind in the NH and to the left of the wind in the SH, the *Ekman transport* (Fig. 3.11). Ekman transport tends to affect the layer above the thermocline, in a layer typically ~ 100 m thick. Large-scale gyres are a result of the combined effects of the midlatitude westerlies, subtropical easterlies, oceanic subtropical highs, continental boundaries, and Ekman transport (Fig. 3.12).

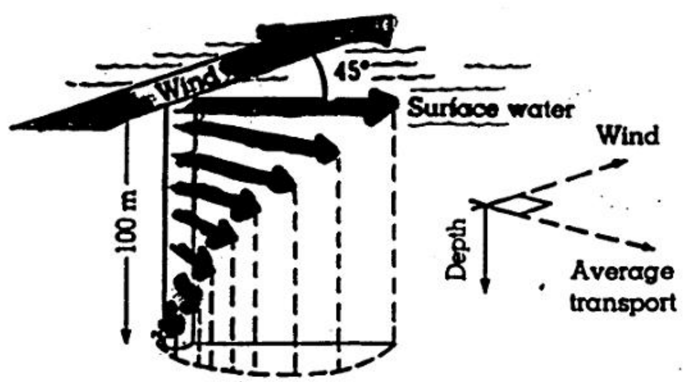


Figure 3.11. The Ekman spiral in the upper layer of the ocean for the Northern Hemisphere [Ahrens].

Since warm waters are gathered westward by the trade easterlies, when the equatorial currents hit continents they diverge poleward. So, warm water moves poleward along the western edges of the oceans, or near the east coasts of continents. High latitude cooling creates cold currents, which move equatorward along the eastern edges of the oceans, or near the west coasts of continents. Some of the most notable warm currents include the Kuroshio Current in the North Pacific, the Gulf Stream in the North Atlantic, Brazil Current in the South Atlantic, and the Agulhas Current in the South Indian Ocean. These currents keep the Bering Sea and far North Atlantic ice free most of the year. The Agulhas current, because it opposes the prevailing westerlies near the Cape of Good Hope, helps to create particularly dangerous ocean waves. Major cold currents include the California Current in the North Pacific, Canary Current in the North Atlantic, Peru or Humboldt Current in the South Pacific, and Benguela Current in the South Atlantic. The Peru current feeds the equatorial easterly current, which is a major cold current that extends westward across the tropical Pacific toward the Date Line, an important ingredient in ENSO. The westerly winds in the extratropical SH drive a Circumpolar Antarctic Current that goes around and around Antarctica.

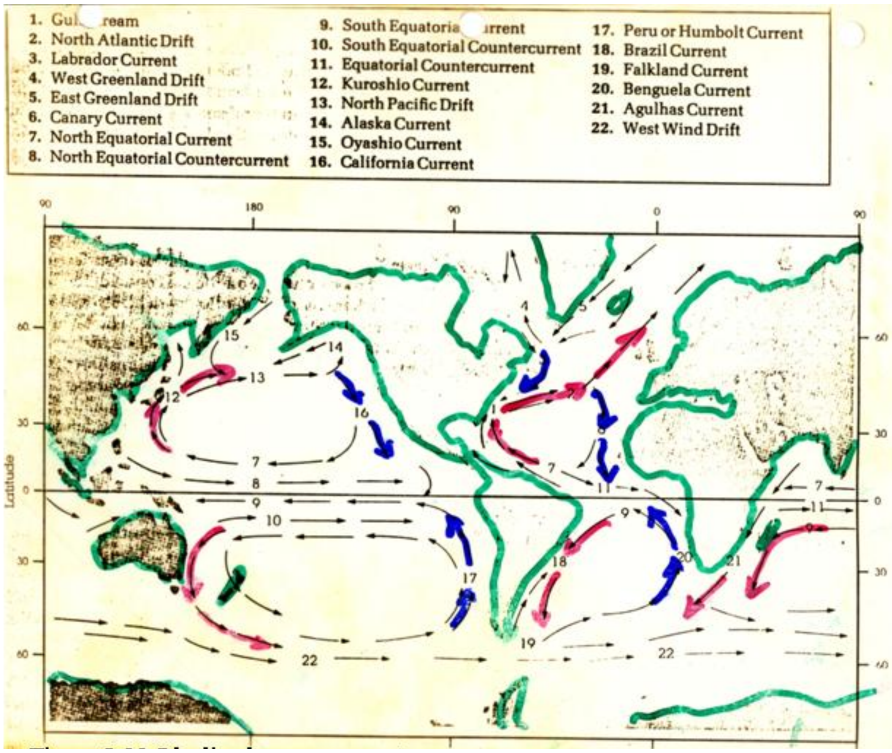


Figure 3.12. Idealized ocean currents [Ahrens].

One interesting effect of this distribution of warm and cold currents is that air near the east coasts of continents contains more moisture and there is more rainfall. Air near the west coasts of continents has less moisture near the cooler currents and consequently less rainfall. The water vapor pressure in July is 15 hPa near Los Angeles and 28 hPa in Miami. Los Angeles receives much less rain than Miami, Perth less than Sydney, Santiago less than Buenos Aires, Lisbon less than Tokyo. Even “rainy” Seattle receives only 37″ annual rainfall-equivalent precipitation compared to New York City’s 45″. Many of the world’s major deserts are located adjacent to the cold currents along the west coasts of North America, South America, Africa, and Australia.

Another important consequence of Ekman transport is that equatorward winds along the west coasts of continents push the upper layer of ocean offshore, causing upwelled water to replace it. This water is colder, so the air above it does not have as much water vapor in it. This augments the effect of the cold currents, helping to make the west coasts of continents dry. Upwelled water is also rich in nutrients, due to organic material settling down from the sunlit upper layer of the ocean and dissolving. When the high-pressure system off the coast of Peru is stronger, upwelling is stronger, and fisheries are better. Every few years this high pressure weakens, the upwelling weakens, and the coastal waters get warmer. Because the water is poor in nutrients, there is less primary productivity and the big fish swim away. South American fishermen first noticed this in the 1800s. This phenomenon often occurs in December, and was give the phrase “El Nino”, evoking the time of Jesus’ birth.

Figure 3.13 shows the typical temperature structure with depth across the equatorial Pacific from Indonesia to Peru. Normally the winds push the warmest waters westward, where the layer of warm water is deepest, bounded below by the thermocline. During an El Nino event, the water is warmer in the eastern Pacific and the thermocline slopes less steeply, with warm water found all the way to the coast of Peru. Even though there is some upwelling, it simply recirculates warm, nutrient-poor water. The associated redistribution of tropical convection can lead to significant changes in weather patterns over the globe. During the opposite phase, La Nina, the winds push the warm waters to the west, with cold upwelled waters near Peru.

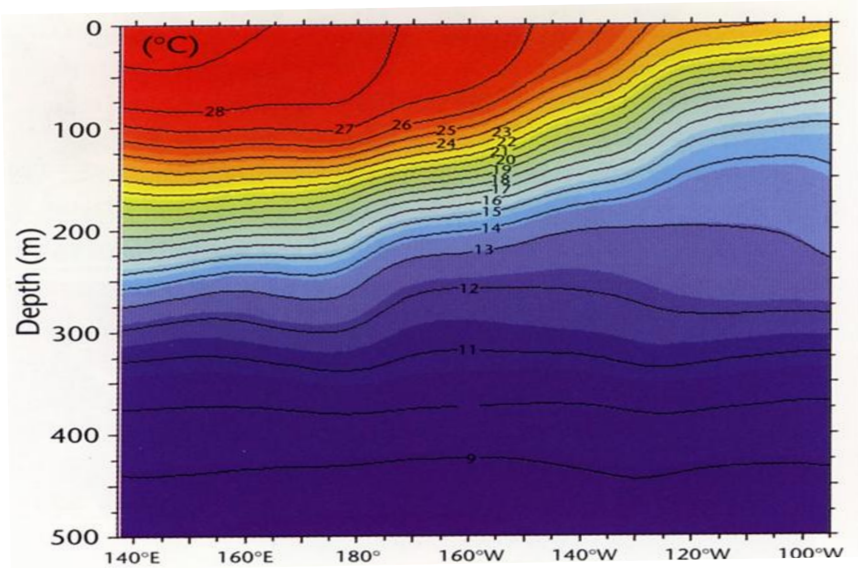


Figure 3.13. Vertical section along the equatorial Pacific showing the sloping thermocline, contour interval 1 K [www.cpc.noaa.gov].

Summary of primary aspects of the atmospheric general circulation

The features of the general circulation can be built up from a few basic principles:

1) Differential heating leads to differences in density, with light air rising, and cool air sinking.
2) Molecules will diverge out of warm, expanded air columns onto cold, contracted air columns, causing higher surface pressure under cold air and lower surface pressure under warm air.
3) Monsoons circulations arise due to continental-scale heating differences, with rising over hot land in the summer and sinking over the cold land in winter.
4) Rising motion creates clouds and rain, while sinking motion creates clear air.
5) In the tropics air flows from high to low pressure (the Walker Circulation).
6) In the extratropics, the Coriolis effect causes air to curve to the right in the NH and to the left in the SH. In the NH this causes counterclockwise flow into a low and clockwise flow out of a high.
7) Midlatitude westerlies and subtropical easterlies are a consequence of angular momentum transport in the Hadley circulation.
8) These chronic winds drive currents which close into gyres due to the presence of continents.
9) Over the cool eastern subtropical oceans, high pressure systems cause equatorward (along-shore) flow along the west coasts of continents. This leads to offshore Ekman transport and upwelling of nutrient-rich cold water from below.

3.8. Thermohaline Circulation

When longer climate variations are considered, the overturning of the deep ocean must be examined. Like the atmosphere, dense water tends to sink and light water tends to rise, although the variations in density are only a few kg m^{-3} out of 1000 kg m^{-3}. Density is controlled by temperature and salinity through the following physical processes. Cold water is more dense than warm water, so cooling favors sinking. Saltier water is more dense than fresh water, so evaporation and sea ice formation favor sinking, since the salt stays in the ocean instead of evaporating or freezing with the water. Precipitation and river runoff tend to dilute the saltiness, making ocean water less likely to sink.

Consider 1 m^3 of sea water with 1000 kg of water and 40 kg of salt. This can be obtained by putting 1 t salt into 1/2 c water (3 t = 1 T, 8 T = 1/2 c, so 1 t salt in 24 t water ~ 40/1000). Salt ions tend to fit between water molecules, but they also have a higher atomic or molecular weight than water molecules, so density increases with the added mass of salt ions with very little increase in volume. If 500 kg of water evaporated or became incorporated into surface ice, the salinity would be 40/500 = 80 ppt. If 1000 kg of water were added from precipitation or river runoff, the salinity would become 40/2000 = 20 ppt.

Figure 3.14 shows the average distribution of salinity for August. It is measured in parts per thousand (ppt). Salts include the ions Cl^-, Na^+, SO_4^{2-}, Mg^{2-}, Ca^{2+}, K^+, and HCO^{3-}. Surface salinity averages about 35 ppt, exceeding 40 ppt in the smaller seas near the Middle East, and being less than 30 ppt in the Chuckchi Sea. Rivers and rainfall tend to dilute the Siberian Arctic and North Pacific oceans.

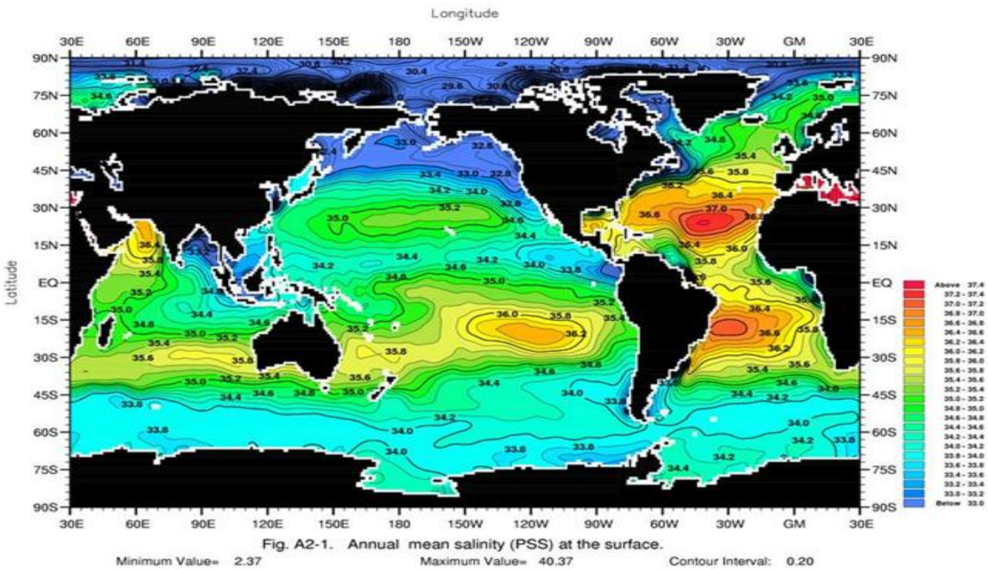


Figure 3.14. Average surface salinity during August, contour interval 0.2 ppt [World Ocean Atlas 2001].

The North Atlantic is a preferred site for the formation of downward-buoyant plumes that form bottom water. This is due to the strong evaporation in the Mediterranean Sea and subtropical Atlantic, making it the saltiest large ocean, followed by northward flow in the Gulf stream, cooling at high latitudes, and *brine rejection* upon ice formation. Another contributing factor is evaporation on the poleward journey along the east coasts of continents. Outflow of cold, dry air in the wake of cold fronts during fall, winter, and spring over the Gulf stream causes

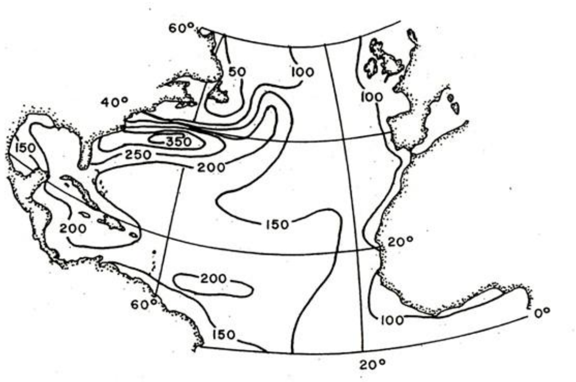


Figure 3.15. An estimate of the evaporation rate for the North Atlantic, contour interval 50 cm/yr [Bunker 1976].

strong evaporation (Fig. 3.15) and heat flux into the atmosphere. Another region for forming deep water is in the circumpolar Antarctic ocean.

Once North Atlantic bottom water forms, it gradually flows southward along the bottom of the Atlantic until it gets past Africa, where it flows eastward and fills the Indian and Pacific Ocean basins. There it gradually rises, aided by coastal upwelling, and returns at the surface to the North Atlantic. Along the way there is considerable commingling of water types, especially Antarctic bottom waters. This overturning circulation that is driven by density differences controlled by heat (thermo) and salt (haline) is called the *thermohaline circulation* (Fig. 3.16).

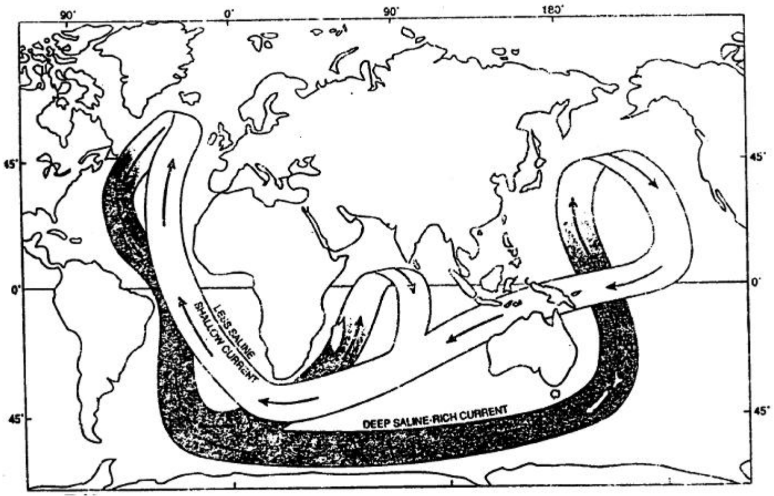


Figure 3.16. Idealized "conveyor belt" view of the thermohaline circulation, with sinking in the North Atlantic, spreading throughout the deep ocean, rising, and return at the surface.

The thermohaline circulation acts as a giant "conveyor belt", whereby surface water in the North Atlantic sink and spread throughout the deep ocean, gradually rising to the surface and returning to the North Atlantic. Atmospheric contaminants, such as radioactive debris, or anthropogenic CO_2 can thereby be transported throughout the deep ocean, where they can be sequestered for hundreds of years. The radiocarbon date of deep water in the North Pacific approaches 2000 years. The slowness of this circulation is readily appreciated by noting the arrival times in the deep ocean of radioactive particles from atmospheric nuclear tests in the 1950s and 1960s, which is still largely confined to the North Atlantic. Another useful tracer of the thermohaline circulation came from the rapid rise of CFCs in the 1970s.

From a wide variety of oceanic constituent distributions, it is known that the mean overturning time for this thermohaline circulation is on the order of 1000 years. The ocean has a long memory indeed. Experiments with coupled atmosphere / ocean models show that variations in the thermohaline circulation can cause significant changes in global surface temperatures and weather patterns. There is strong evidence that in the past this circulation has stopped and started again. It is part of an explanation for a remarkable climate oscillation that occurred ~ 10,600 ybp (years before present) called the Younger Dryas event to be described in Chapter 4. The North Atlantic is the seat for a powerful climate oscillator system.

Minor constituents can exert an amazing influence over large systems, such as water vapor in the atmosphere, salinity in the ocean, and humans in the earth system. It is interesting to compare the role of salinity at 40 ppt in the oceans to the role of water vapor in the atmosphere, which has a partial pressure of up to 40 hPa (40 ppt). These relatively minor constituents exert a powerful control over whether fluids rise or sink. Through its energy holding capacity and radiative properties, water vapor helps control where rising and sinking motion occurs in the atmosphere, while salinity helps control where water sinks in the ocean.

There is also an interesting interplay between the water vapor and salinity in the coupled atmosphere/ocean system. Evaporation in the subtropics enhances salinity and adds latent heat to the atmosphere. After water vapor is transported to higher latitudes and cools, the latent heat is released in the atmosphere during precipitation, which falls in the ocean and dilutes it. Meanwhile, the poleward-moving ocean water cools off. Thus, there is a delicate interplay among evaporation and precipitation along the path of poleward warm currents, with rate of cooling and brine rejection causing the density to be great enough to sink in the North Atlantic and Antarctic, but not in the North Pacific. Negatively buoyant plumes or "chimneys" tend to have small spatial and temporal scales, being a few kilometers across and lasting a few days. The small scale of processes in the ocean presents a significant challenge for ocean modeling of the climate system.

Carbon dioxide dissolves into sea water preferentially where it is colder and where it is depleted of nutrients. Figure 3.17, taken from Sabine et al. [2004], shows the amount of anthropogenic CO_2 in the ocean. Large values are seen in the North Atlantic and just equatorward of the Antarctic circumpolar current. These are the primary regions where surface waters sink into the deeper ocean. We will return to this idea when discussing the global carbon budget and future scenarios.

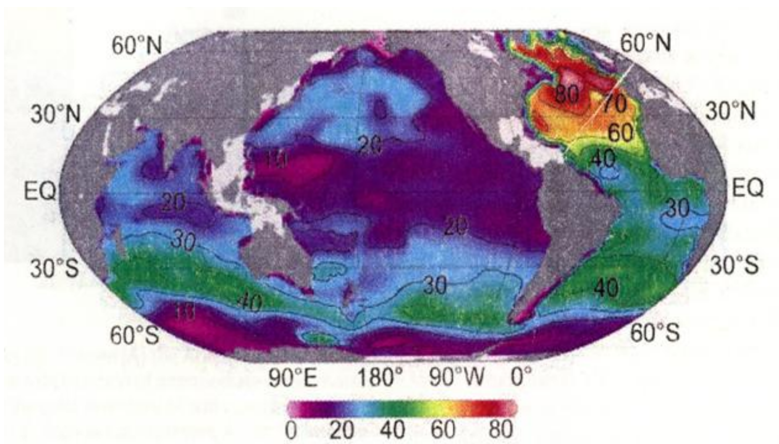


Figure 3.17. Column inventory of anthropogenic CO_2 in the ocean, in mol m^{-2} (color bar). High inventories are associated with deep water formation in the North Atlantic and intermediate water formation near 30-50°S. The total inventory is 106±17 Pg C. [Sabine et al. 2004].

Observations and theory suggest that the characteristic size of eddies that mix constituents is about 1000 km in the atmosphere but only 50 km in the ocean. The reason for this has its roots in the fact that the atmosphere is compressible and is therefore more stably stratified in the vertical than the ocean. This represents a significant challenge for ocean modelling, suggesting the need for 10 km grid spacing to capture ocean eddies. Simulations and observations reveal an incredibly rich suite of eddy motions in the ocean. Serendipitous spills of rubber duckies and tennis shoes from cargo vessels in storms have helped illuminate the details of ocean motion. Figure 3.18 [from Pazan 2004] show results from analyzing the path of a large number of drifting buoys.

Wherever a complex wind storm is creating large sea waves, especially when a current opposes the direction of wave motion, very large waves can occur. Superposition of several regular waves can lead to "rogue" waves exceeding 35 m. Being in a boat, at the interface of the air and sea, provides the most vivid view of the effects of wind on the ocean surface. In very large waves, if an extra-deep trough appears under a long cargo ship, part of it can slump under gravity, causing the hull to crack under its own weight. However, sailboats in the range 10-30 m can readily survive such waves if they have good hatches and if the passengers don't mind being occasionally dismasted.

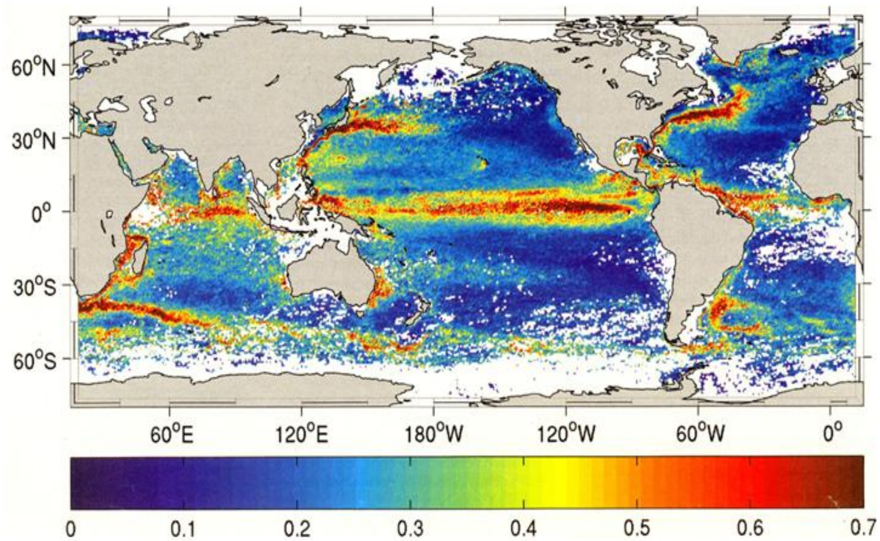


Figure 3.18. Variability of current velocity (standard deviation in m/s) as detected by global drifters [Pazan 2004].

The parable of Bernard Moitessier

The first single-handed circumnavigation of the world was by Joshua Slocum in 1898. Francis Chichester set a speed record with only one stop in Sydney for a solo circumnavigation in 1967. Since then a number of single-handed around the world races have sprung up, including the Grand Vendee, which has the simple rule of leaving Antarctica to starboard. The fastest racers employ 80′ trimarans and surf for 1000′ at a time on the great combing breakers of the southern ocean.

One famous sailor, Bernard Moitessier, pioneered the technique of taking large breakers not right over the stern, but at an angle, to avoid both pitch-poling and broaching. In one race, he found himself far in the lead approaching some reefs south of New Zealand, with malfunctioning navigational instruments and clouds overhead. Ten dolphins appeared, with a spotted one as their leader. They kept swimming past the boat and curving to the right, over and over again. When Moitessier decided to turn right, the dolphins broke up into riotous jumping and then swam away. When the stars came out and he got his bearings, he realized that he had just barely avoided hitting the reef. He attributed his survival to the dolphins' help. He decided to go all the way around Antarctica again and stop in Tahiti for a year, rather than collect the prize money in England.

The distribution of winds and currents and the geographical distribution of the continents relative to the ocean have played a central role in the evolution of civilization.

Focus on exploration by sea

The ocean still holds a deep attraction and mystery for us. Its noumenal essence shaped the course of civilization by facilitating or inhibiting exploration. The distribution of major wind systems and ocean currents has exerted a profound influence on the manner in which humans have colonized and explored the world. It was hard to get from Asia to North America, but some people travelled southward along the Pacific Northwest coast in small watercraft during the last ice age. The Greek historian Herodotus described the success of Egyptian seafarers in circumnavigating Africa in a clockwise sense in 650 B.C. and again by a Captain Hanno in 500 B.C. [Hermann 1954]. This would have been aided by the southwestward Agulhas current and the northward Benguela current (Fig. 3.12). The ancient Greeks also knew of the Canary Island, 1/3 of the way across the Atlantic.

Perhaps the most impressive explorations were carried out across the tropical Pacific by Polynesians during 0-1000 A.D in outriggers with unique sails, in which tacking was accomplished by putting the rudder at the other end of the boat [Lewis 1972]. Irish monks reached Iceland in the 600s [Severin 1978] and Vikings in the 900s [Prytz 1991] reached Iceland, Greenland, and Newfoundland. Several wrecks on the west coast of the U.S. contain ancient Chinese artifacts, suggesting that some Chinese made it to the New World, facilitated by the Kuroshio current. The Chinese did have an explicit period of extending their hegemony through huge fleets of enormous boats operating throughout the Indian Ocean basin during 1400-1430 [Dreyer 2007].

Prior to 1492, Portuguese fisherman regularly fished on the Grand Banks off of Newfoundland. Christopher Columbus travelled to Ireland and England to learn more about historic routes across the North Atlantic [Enterline 2002]. It was easier for Christopher Columbus to travel to the Caribbean in the trade easterlies. Spanish traders in the 1500s regularly made use of the easterlies in trade between the west coasts of the Americas and the Phillipines and other parts of Asia.

Ferdinand Magellan deduced correctly that the trade easterlies in the Pacific should behave somewhat similarly to those in the Atlantic, and was able to sail from Tierra del fuego to the Philipines in ~1520. Due to the dangers of the northwest Pacific, several expeditions disappeared in failed attempts to find the return route, or “vuelta”, from the Philipines northward to Japan and eastward to Acapulco until the African-Portuguese pilot Lope Martin survived the journey in 1565 [Resendez 2021].

Currents and winds were particularly challenging for exploring the west coast of North America past California, although several Spanish explorers did so. Sir Francis Drake, the hero/pirate/confidant of Queen Elizabeth I, may have documented the Olympic Mountains, Vancouver Island, Queen Charlotte Islands, and Prince of Wales Islands during a quest in the 1580s to find a Northwest Passage around North America [Bawlf 2003].

The brilliantly successful Fritjof Nansen made it close to the north pole by purposefully getting his boat, the Fram (forward), stuck in sea ice north of the Yenesei River, and drifting toward the east coast of Greenland [Nansen 1999]. Ernest Shackleton got his boat stuck in ice circulating in the Weddell Sea for over a year until it was crushed, with an amazing open boat escape from Elephant Island to a whaling community on South Georgia Island and noone died. Occasionally, passengers on boats crushed and sunk by ice have escaped to safety over sea ice [e.g., Albanov 2000]. It is hard to overestimate the role of winds and currents in shaping exploration and our view of the world and ourselves.

3.9. The El Nino Southern Oscillation (ENSO)

In order to detect an anthropogenic climate signal, it is important to understand natural modes of interannual variability. ENSO is a famous source of interannual variation in weather over most of the globe. The seat of ENSO's power is the coupled atmosphere-ocean system in the tropical Pacific. In the late 1700s people began to speculate about the nature of global synchronized droughts. In the late 1800s these droughts were linked to interhemispheric "see-saws" in sea level pressure, and the term El Nino was coined by Peruvian fisherman to refer to the warm waters that appeared every few years around Christmas. The variation in pressure and circulation in the tropical Pacific was described as a Southern Oscillation by Walker in the 1920s. Bjerknes unified El Nino and the Southern Oscillation conceptually in the 1960s, solidifying the phrase ENSO. Philander recognized La Nina as the extreme cold phase in the 1980s. The first successful predictive model was by Cane and Zebiak in 1986.

The annual mean pressure and wind patterns over the subtropical oceans were shown in Fig. 3.10. Air flows from the subtropical highs westward into tropical low pressure centers. The resulting easterly trade winds gather warm water across the vast tropical Pacific toward Indonesia and Northern South America. Heating in the Maritime Continent strongly accentuates this flow pattern. Note that sea level pressure is high at Tahiti and low at Darwin Australia. This largest tropical convective region affects the climate over the globe and drives the Walker circulation in the tropical Pacific (Fig. 3.8). Due to the complexity of atmospheric motions, it would be a rare occurrence for an air molecule to actually make a complete circuit through the Walker circulation. Rather, this represents the time-mean flow of molecules at each point. High pressure off the coast of Chile drives northward flow along the coast. This causes Ekman transport to the left, or offshore, with cold, nutrient rich water upwelling near Peru and extending westward across the equator. On average, sea surface temperatures across the equatorial Pacific vary from ~ 30°C near New Guinea to ~ 18°C near Peru (Fig. 3.19).

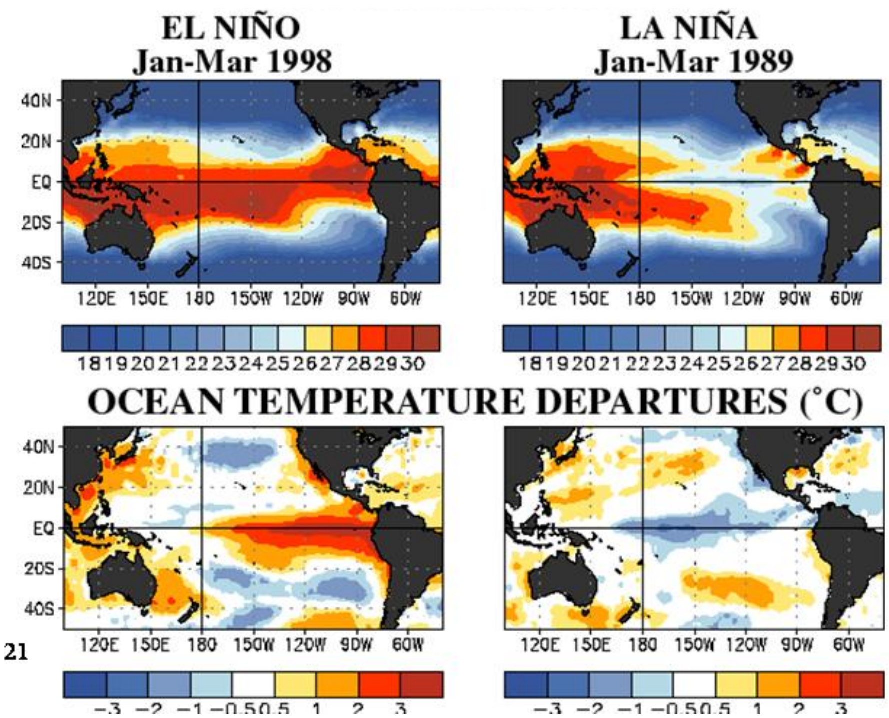


Figure 3.19. Sea surface temperatures and anomalies (in °C) for the 1998 El Nino and the 1989 La Nina [www.cpc.noaa.gov].

The location of tropical convection depends quite strongly on subtle variations in sea surface temperature. A 1°C temperature difference is enough to concentrate thunderstorms over the warmer water. The reason for this is that the amount of water vapor air can hold depends exponentially on temperature. An approximate fit to the dependence of saturation vapor pressure, e_s, in hPa, on temperature, T, in °C is

$$e_s = 7\, e^{0.06\,T} \,. \qquad (3.1)$$

At 30°C, e_s = 42 hPa, while at 31°C, e_s = 45 hPa, an increase of 7%. A 1% change from 303 K is 3K, which implies an increase of 21%, or a sensitivity of order 20, for the % response relative to the % change. Because of this sensitivity, clouds and rain are much more common over the warmer waters near Indonesia than in the Eastern Pacific.

The Walker circulation strengthens and weakens on time scales of 3-7 years, yielding a "Southern Oscillation". When high pressure off the coast of Peru weakens, the wind-driven offshore transport of ocean water weakens, so upwelling of cold, nutrient-rich water from the deep ocean ceases, and the water gets warmer (Fig. 3.19). With reduced trade easterlies, the cold upwelling at the equator ceases and the wind stress that piled up sea water in the west relaxes. These factors lead to warming of the tropical Pacific. Sometimes, this results in an identifiable eastward-moving pattern of increased sea surface temperatures and a deeper thermocline. This progression exhibits characteristics of an equatorial Kelvin wave, which ushers in an El Nino when it arrives on the coast of Peru. During the El Nino phase, water exceeding 28°C is found to the east of the Date Line. Note the wedge of anomalously warm water in the tropical Eastern Pacific during the El Nino of 1998 (Fig. 3.19). This encourages thunderstorms to develop farther eastward over the warmer water, displacing a major center of energy, thereby affecting weather patterns around the globe. During El Ninos the Walker circulation is weak and the thermocline is flatter, and the difference in pressure between Tahiti and Darwin is smaller than average (Fig. 3.20).

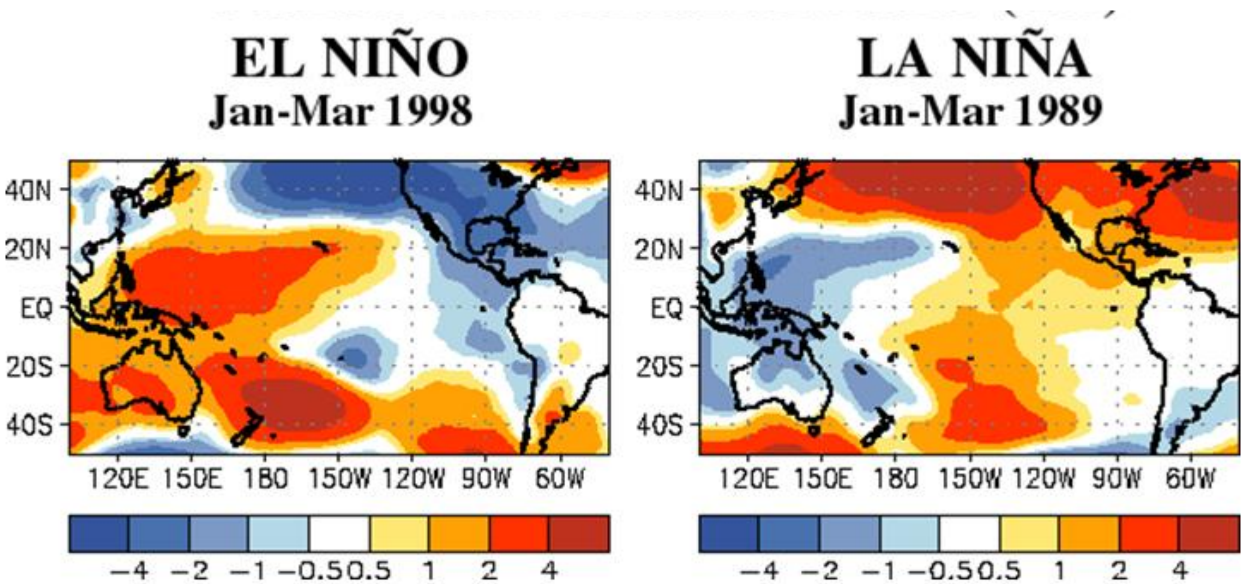
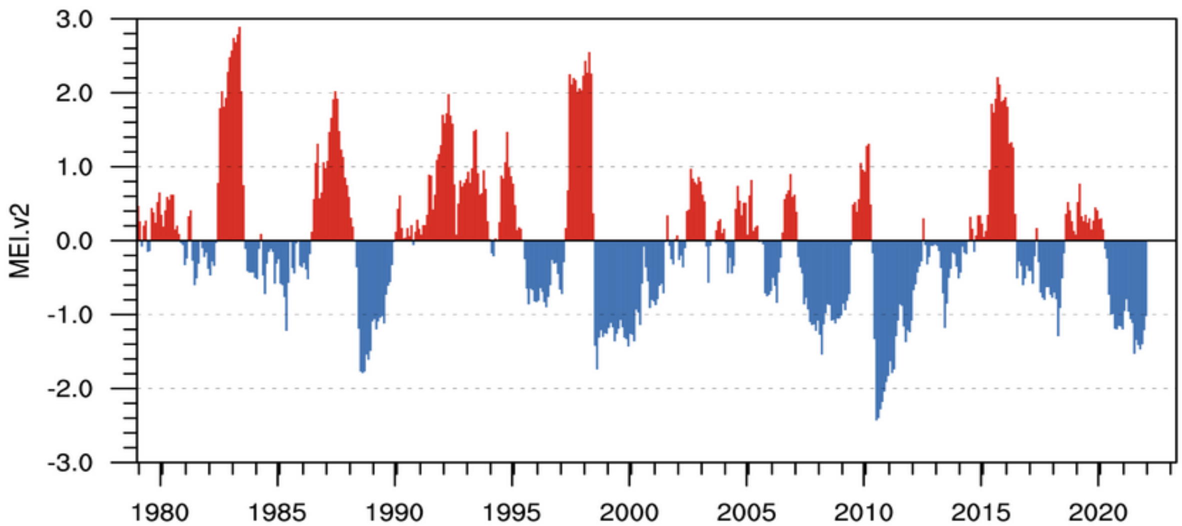


Figure 3.20. Sea level pressure anomalies (in hPa or mb) for the 1998 El Nino and the 1989 La Nina events [www.cpc.noaa.gov].

When Tahiti - Darwin sea level pressure differences are large, the Walker circulation is stronger, the higher pressure drives stronger winds and upwelling along the coast of Peru and the cold tongue extends far westward across the Pacific. Warm waters are gathered even more effectively to the west, with more thunderstorms and lower sea level pressure at Darwin (right side of Figs. 3.19 and 3.20). This strong circulation phase of ENSO has been dubbed La Nina. Note the anomalous cold water at the equator all the way to the Date Line in the La Nina of 1989. During La Ninas, and during northern winter the deepest thunderstorms and highest tropopause in the world are observed in Indonesia.   During El Ninos, thunderstorms are still common in the western Pacific. Tropical average sea surface temperatures and rainfall are both somewhat larger during El Nino.

An index has been developed to capture this combined El Nino Southern Oscillation phenomenon which includes Tahiti minus Darwin sea level pressure and tropical sea surface temperatures just west of the Date Line (Fig. 3.21). Some of the most notable recent El Ninos occurred in 1983, 1987, 1992, 1998, and 2002. Notable La Ninas occurred in 1989, 2000, and 2008.



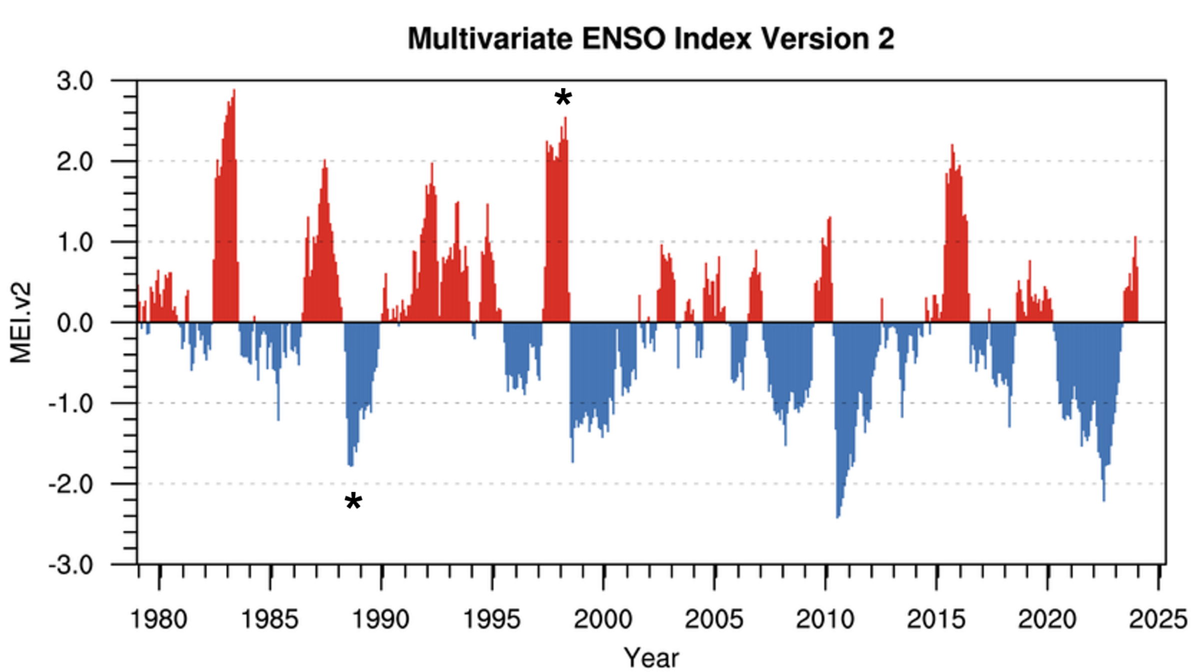


Figure 3.21. Normalized monthly departures of the multivariate El Nino Southern Oscillation index (MEI) version 2 during 1978 – 2024. Asterisks indicate the La Nina of 1989 and the El Nino of 1998 (Figs. 3.19, 3.20, and 3.22). Positive values correspond to El Nino conditions, with a reduced pressure difference between Tahiti and Darwin [www.cpc.noaa.gov].

During El Nino, phytoplankton near the coast of Peru are starved for nutrients, so the zooplankton that eat them fail to thrive, the small fish fail and the large fish swim away. The eastward-travelling oceanic Kelvin wave that ushered in the warm water off the coast of Peru may be thought of as having two halves with mirror symmetry across the equator. When the Kelvin wave hits the coast of South America, it splits, one going south toward Chile and one going north toward North America. As a result, sometimes warm water appears off the coast of Oregon, with tropical species such as sword fish. With warmer water off the coast of California, there is usually much more rainfall and associated landslides and flooding during El Nino events. ENSO involves the entire Pacific basin, with sea surface temperature patterns off the coast of California also changing due to large scale wind and heat transfer patterns.

During El Nino, it is more common to have rain on the west coast of Peru, making it easier to grow crops, compensating somewhat for the poor fishing. It is now possible to forecast ENSO a half a year or more in advance using numerical models (see the National Oceanic and Atmospheric Administration's Climate Diagnostics Center and Climate Prediction Center websites: www.cdc.noaa.gov and www.cpc.noaa.gov). This allows countries to plan for global food distribution. We can also better prepare ourselves for epidemics of diseases, which are more common with higher temperatures and warmer, wetter weather. During the 1800s yellow fever epidemics in the United States were linked to warmer, rainier weather and lower pressure over the Southeasten U.S. during El Nino events. While flooding can be a problem in Peru during El Nino, fires can be a bad problem in Indonesia, Australia, and Southeast Asia. The reduced uptake of carbon dioxide due to burning trees yields a strong source of CO_2 to the atmosphere during an El Nino.

Precipitation in the Pacific basin for the El Nino of 1998 is contrasted with the La Nina of 1989 in Fig. 3.22. During the 1998 El Nino, precipitation exceeding 800 mm in 3 months was found centered near the Date Line and near Equador (Fig. 3.22a). Rainfall exceeding 400 mm in 3 months was found across the Pacific just north of the equator. The anomaly plot shows that the equatorial Pacific was much more rainy than normal from the date line to Peru and much less than normal in Indonesia. Note also the enhanced rainfall in California and the Southeastern U.S. and reduced rainfall in Northeast Brazil. During the 1989 La Nina, precipitation exceeded 800 mm in 3 months over the Maritime Continent and the Amazon (Fig. 3.22b). Anomaly plots show much less rainfall than normal near the Date Line and across the Pacific just north of the equator. Note also the enhanced precipitation in Amazonia and in the upper Mississippi valley. Madison WI received a record amount of snow during 2007-2008, a La Nina year.

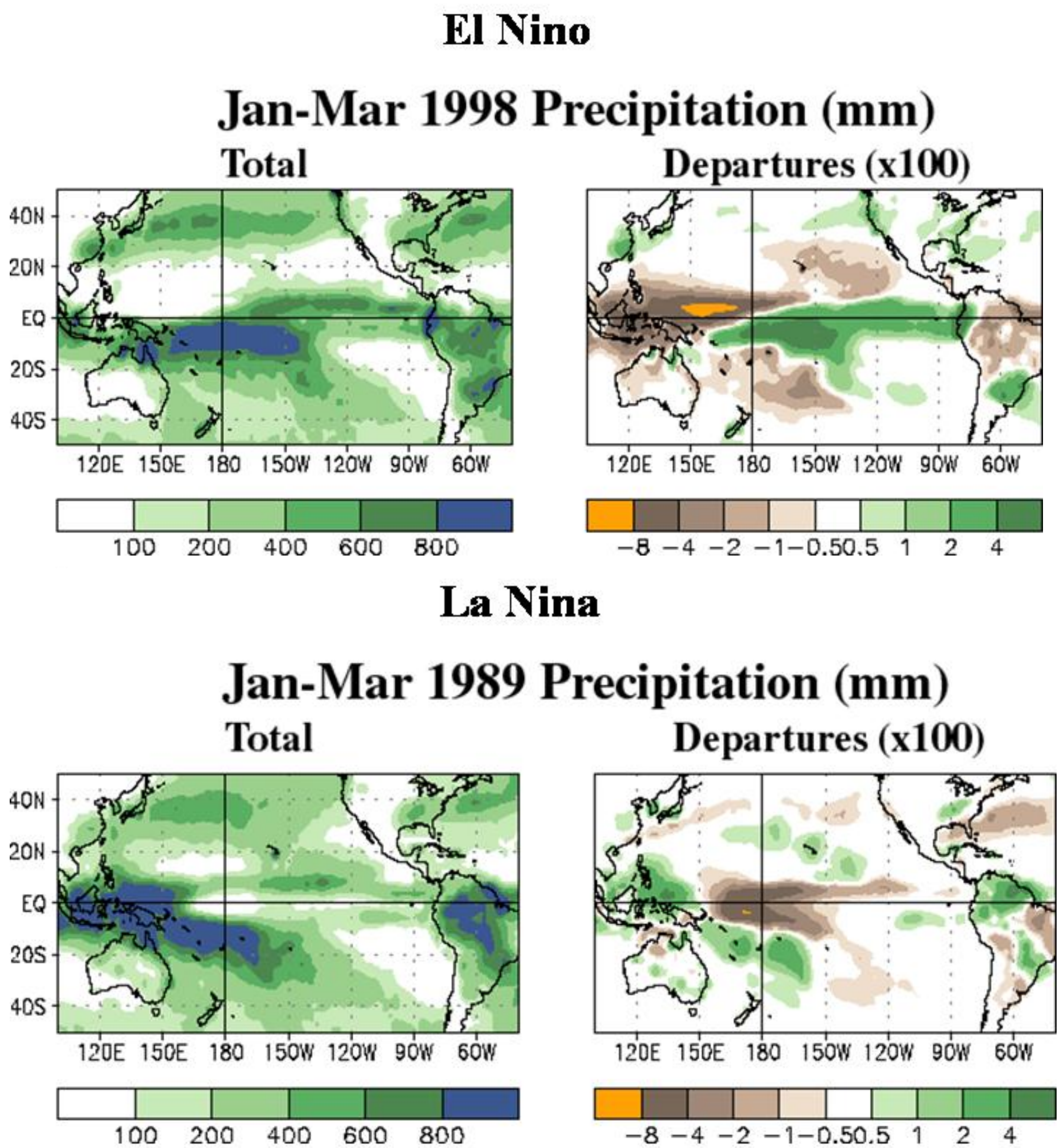


Figure 3.22. January-March rainfall (color bar, mm) and anomaly (values shown in hundreds of mm) during a) the 1998 El Nino and b) the 1989 La Nina.

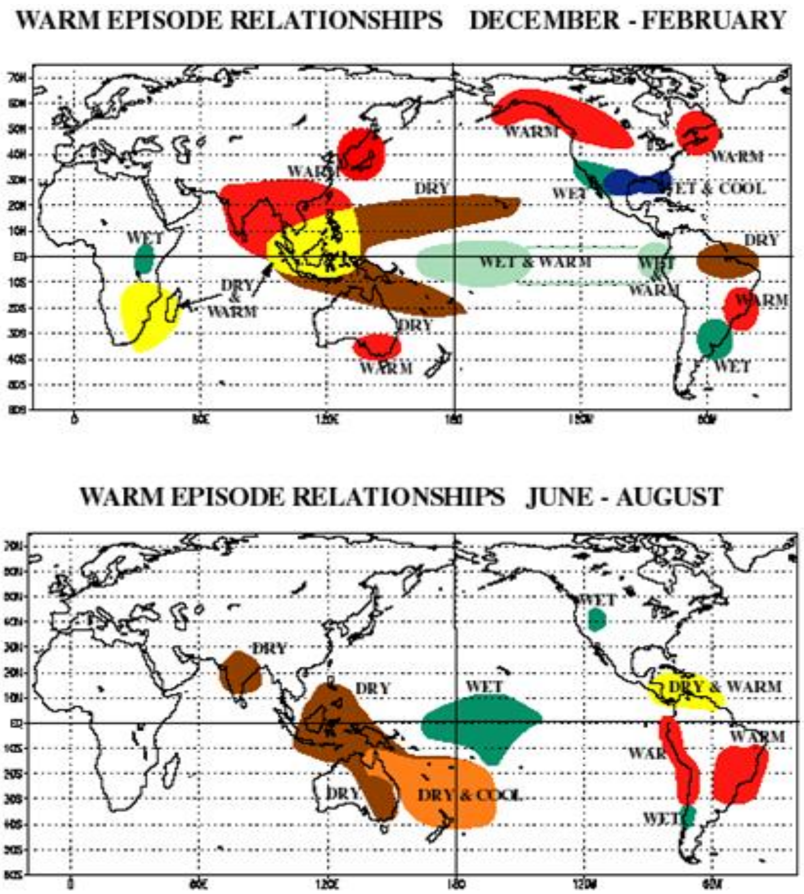


Figure 3.23a. Global weather relationships for DJF and JJA which tend to occur during El Nino [www.cpc.noaa.gov].

Each day brings a unique pattern in the tropical Pacific. No two El Ninos or La Ninas are ever identical. Yet certain global weather features are statistically associated with the ENSO index. These relationships are summarized in Fig. 3.23. During El Nino and boreal winter, Indonesia, Australia, South Africa, Southeast Asia, and Northeast Brazil tend to be unusually dry (Fig. 3.23a). California and Southeastern U.S. tend to be wetter than normal and Alaska is usually warmer than normal. During La Nina and boreal winter, Indonesia, Australia, South Africa, Southeast Asia, and Northeast Brazil tend to be unusually wet (Fig. 3.23b). The equatorial Pacific from the Date Line to Peru is unusually dry and cool, with dry weather in the southern U.S.

During El Nino (Fig. 23a), thunderstorm complexes form all across the tropical Pacific, feeding westerly momentum into the subtropics, extending the westerly jet into southern California and Southeastern U.S., bringing more storms and heavy rain. During La Nina (Fig. 23b), the jet stream tends to be more variable, bringing more moisture to the Pacific Northwest and the upper Midwest. Overall, ENSO explains about 15% of the interannual variability of winter weather over North America.

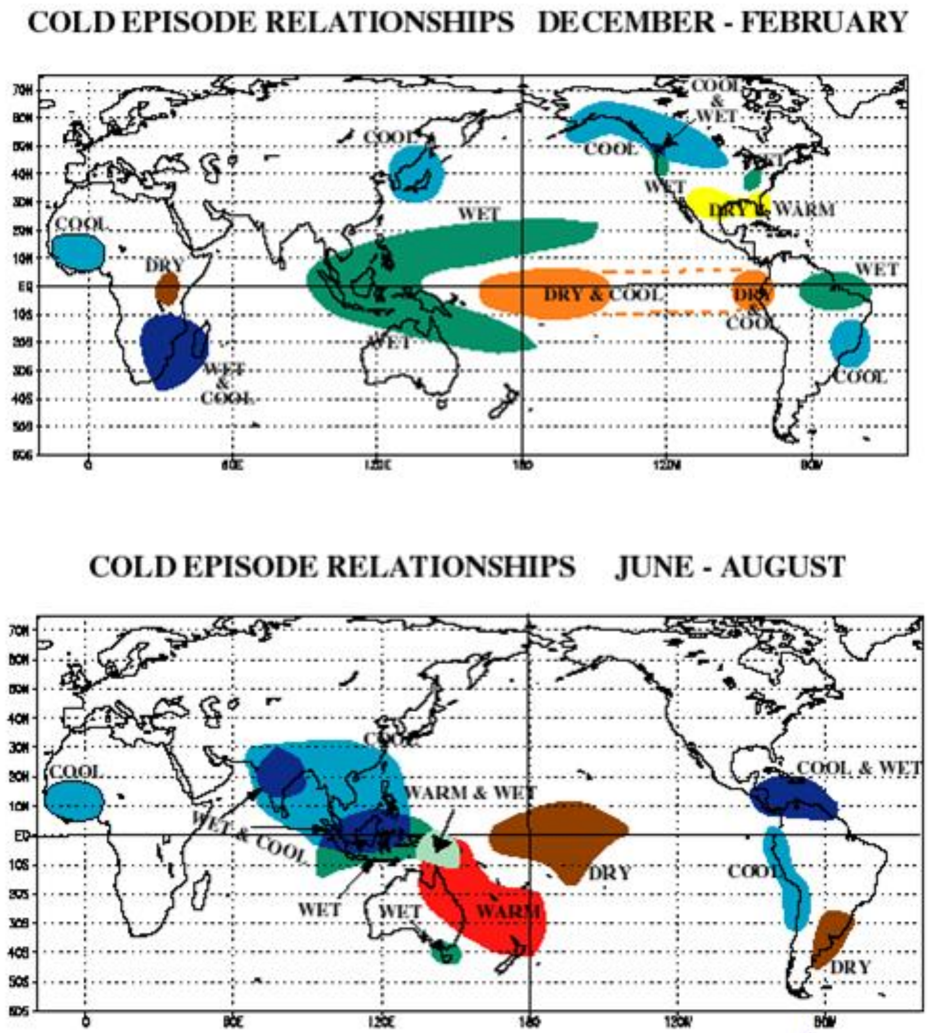


Figure 3.23b. Global weather relationships for DJF and JJA which tend to occur during La Nina [www.cpc.noaa.gov].

3.10. The northern annular mode (NAM)

In this section, we explore other natural modes of interannual variability in the climate system. Since the 1930s it has been known that there is an oscillation in sea level pressure centered in the North Atlantic. This North Atlantic Oscillation (NAO) is responsible for drastic changes in the distribution of rainfall between Northern Africa and Europe. With the recognition that the NAO pattern is intimately connected to the stratospheric polar vortex and much of the northern hemisphere, a broader name was sought to describe this phenomenon: the Northern Annular Mode (NAM). A similar phenomenon of interannual variability in the distribution of pressure, with an oscillation between polar and subpolar regions, also occurs in the southern hemisphere and is known as the SAM. The NAM and SAM are vertically coherent westerly vortices from the surface to the upper stratosphere.

When the NAM index is high, sea level pressure near Iceland is lower and the pressure off of Portugal is higher than normal, with a stronger jet stream and storm track toward Northern Europe (Fig. 3.24b). When the NAM index is low, sea level pressure anomalies are weaker, and the jet stream is directed more toward North Africa (Fig. 3.24d).

High NAM index northern European winters are warmer and wetter, and there is less rain in Northern Africa (Fig. 3.24b). Low NAM index winter temperatures are colder in Europe and there is more rain in North Africa and the Iberian peninsula (Fig. 3.24d). Interesting weather changes also occur over North America in association with the NAM. A high NAM index favors a warmer Eastern U.S. (Fig. 3.24a), while a low NAM index favors a colder Eastern U.S. (Fig. 3.24c).

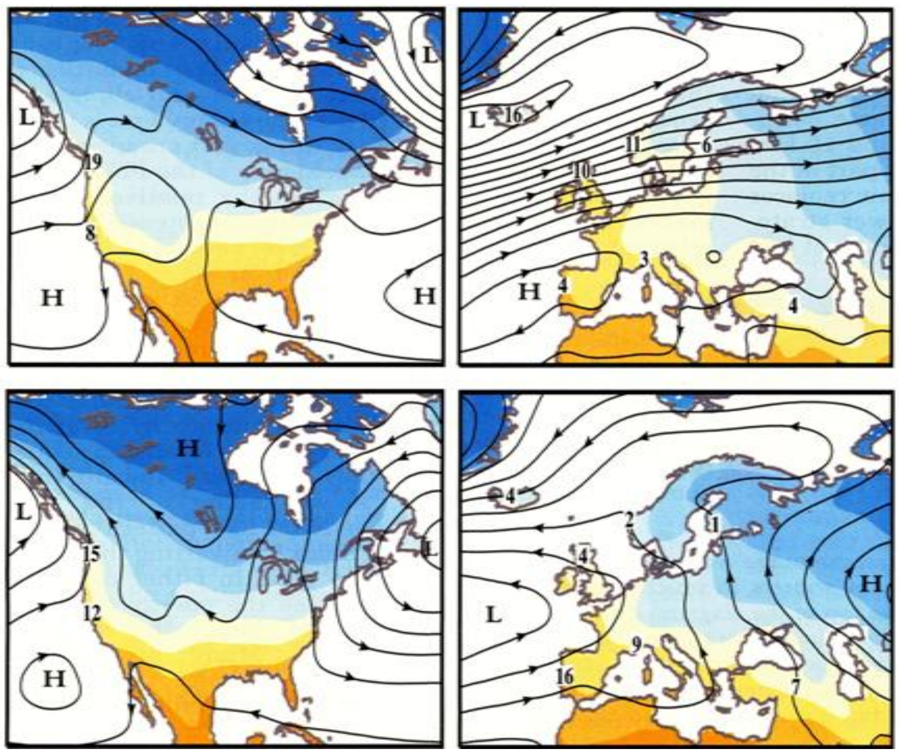


Figure 3.24. Composite maps of surface air temperature (shading every 5°C), sea level pressure (contours every 3 hPa) and precipitation (cm/mo) for (top) high NAM index days and (bottom) low NAM index days [Wallace and Thompson 2002].

The surface air temperature anomaly over land for high index NAM days is shown in Fig. 3.25. When the subpolar jet is stronger it advects warm air from the Pacific into the interior of North America and warm air from the Atlantic into the interior of Eurasia. This pattern is also very similar to the temperature anomalies in the winters following 11 out of 12 of the major volcanic eruptions in the 1900s. Volcanic eruptions can lead to a stronger polar vortex by affecting radiative heating patterns [Robock 1991], evidently exciting a high index NAM flow pattern.

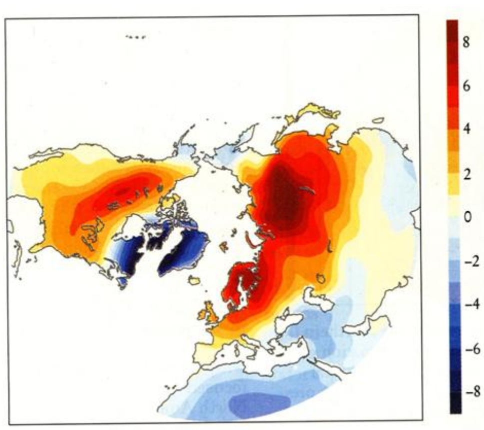


Figure 3.25. Air temperature anomaly (°C) on high minus low-index days for the Northern Annular Mode [Thompson and Wallace 2001].

The NAM is particularly of interest in attempting to discern a geographical fingerprint for global warming. The 30-year trend in sea level pressure closely resembles the high NAM index pressure anomaly pattern [Wallace and Thompson 2002]. The 30-year trend in high latitude temperature also resembles Fig. 3.25. Figure 3.26 shows that the NAM has exhibited significant interdecadal variability over the past 150 years. The NAM index strengthened from 1965 to 1990 and then declined again to the present. Although the spatial pattern of temperature trend and NAM temperature anomaly are very similar, the temporal signal for the NAM index is not the same as the trend in temperature increase, which has continued to increase since 1990.

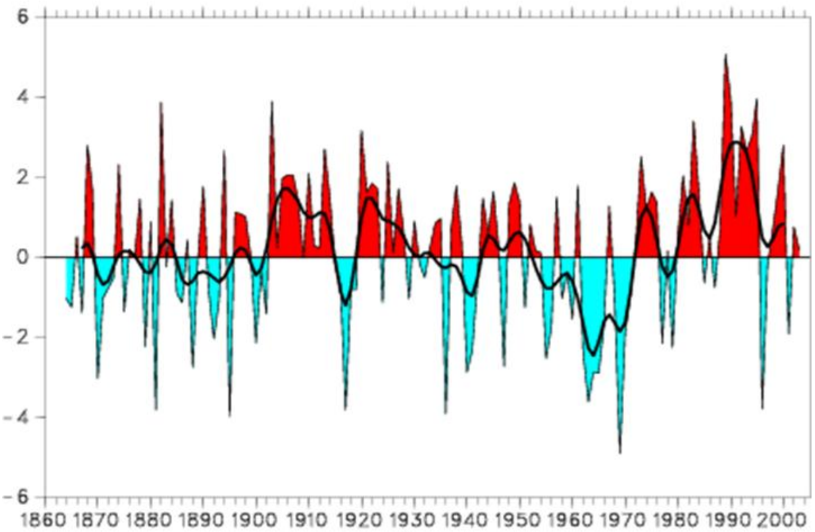


Figure 3.26. Northern Annular Mode index during DJFM for the period 1864-2003 [Thompson].

It may be the case that global warming tends to favor the positive phase of the NAM. If this is true, then Northern Eurasia would tend to be warmer and wetter and Northern Africa would tend to have droughts. It is further consistent with a stronger stratospheric polar vortex and reduced ozone over the North Pole. The strength and position of the storm track across the North Atlantic is intimately related to the wind stress on the ocean and where the Gulf Stream goes. A positive NAM favors a robust Gulf Stream extending to high latitudes. This relationship plays a significant role in explanations of climate oscillation such as the Younger Dryas Event. Over the past 10,000 years the Indian monsoon has been stronger when northern Europe is warmer and wetter, suggesting that the link between North Atlantic Climate and the Asian monsoon is a persistent aspect of global climate [Gupta et al. 2003].

A salient feature of a low-index NAM day is that it implies a much more variable jet stream, hence greater likelihood of cold outbreak events [Thompson and Wallace 2001]. Baldwin and Dunkerton [2001] found that the state of the stratospheric polar vortex at 10 hPa is a good predictor of the sea level pressure anomalies over the subsequent 5-6 weeks. Figure 3.27 shows composites of weak vortex and strong vortex regimes during northern winter. When the stratospheric vortex is weak, there is a greater weather variability in the troposphere for the next few months. When the stratospheric vortex is strong, weather patterns tend to be more stable and westerly in the troposphere over the next few months.

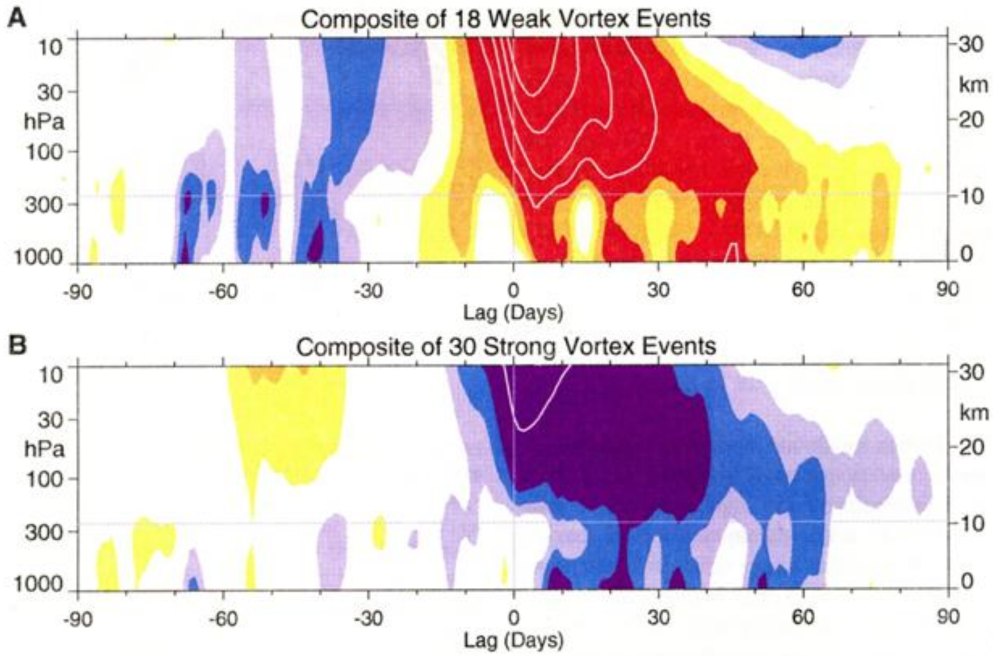


Figure 3.27. Time-altitude development of the NAM for composites of a) weak and b) strong vortex events at 10 hPa [Baldwin and Dunkerton 2001].

The south polar circumpolar vortex is stronger when the SAM index is high. Over the past 20 years, the SAM index has been increasing as surface temperatures have fallen over the Antarctic plateau, especially during austral spring and summer. Thompson and Solomon [2002] attribute this trend to the deepening ozone hole which occurs every spring, with increasing lingering effects in the summer. Reduced ozone implies reduced absorption of solar ultraviolet and of upwelling infrared radiation, hence cooling, and a stronger westerly vortex. The effect of this is to make Patagonia and the Palmer Peninsula warmer. But it is interesting that the ozone hole may be counteracting global warming by keeping most of Antarctica cool.

3.10. The stratospheric quasi-biennial oscillation (QBO)

The stratosphere is also the home of the unusual geophysical oscillator known as the stratospheric quasi-biennial oscillation (QBO). In 1883, it was noticed that volcanic aerosol from the eruption of Krakatoa travelled rapidly westward in the tropical stratosphere and peopple spoke of “Krakatoa easterlies”. Yet, when Arthur Berson measured lower stratospheric winds over East Africa by rawinsonde in 1908, he found a thin layer of eastward flow, or “Berson westerlies”. By 1960, time series of tropical rawindsondes revealed that there is an oscillation in winds in the tropical stratosphere, where a layer of westerlies forms near the stratopause, descends at a rate of about 1 km/mo to the tropopause. Meanwhile the westerlies near the stratopause are replaced by easterlies, which descend toward the tropopause, replacing the westerlies. This cycle varies in length from 22 to 34 months. The QBO in equatorial zonal wind is shown in Figs. 3.28 and 3.29. It is driven by tropical convection, which excites a range of waves that travel upward into the stratosphere [Holton and Hakim 2012].

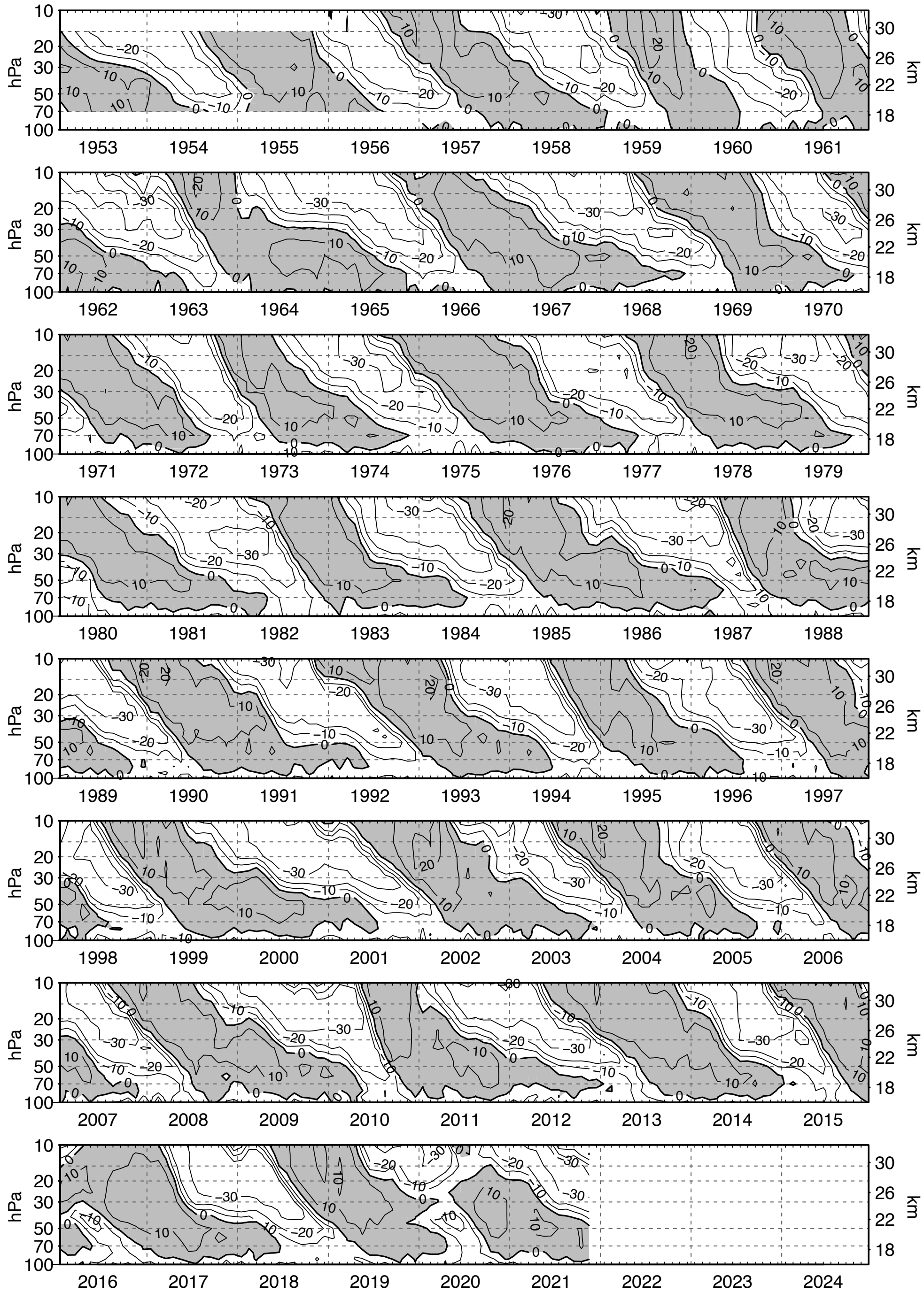


Figure 3.28. Time-height section of monthly mean zonal winds (m/s) at equatorial stations: Canton Island, 3°S/172°W (Jan 1953 - Aug 1967), Gan/Maledive Islands, 1°S/73°E (Sep 1967 - Dec 1975) and Singapore, 1°N/104°E (since Jan 1976). Isopleths are at 10 m/s intervals; westerlies are shaded (updated from Naujokat, 1986).

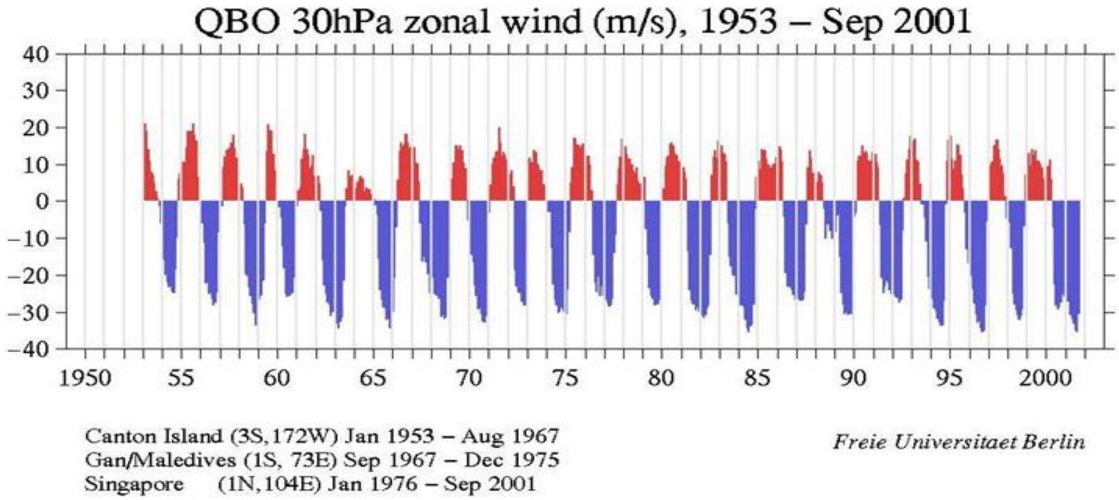


Figure 3.29. Time series of zonal wind over the equator at 30 hPa (~25 km altitude) during 1958-2001, indicating the appearance of alternating descending layers of westerlies (red) and easterlies (blue) at this level [Naujokat, FUB].

Volcanic aerosol and ozone tend to stay in the tropical stratosphere during QBO easterlies and to spread poleward during QBO westerlies [Hitchman et al. 1994]. When QBO westerlies reach the tropopause, they tend to inhibit tropical convection in Indonesia, Africa, and Amazonia, especially during boreal winter when the tropopause is highest, thereby altering rainfall patterns [Collimore et al. 2003]. The QBO also modulates the winter extratropical stratosphere, with significant effects on tropospheric weather. The QBO is much more predictable than ENSO or the NAM, making it a desirable candidate for exploring its relationship with global weather.

Question for Thought

Since the density of water is 1000 kg m^{-3} and the global average solar intensity is 240 W m^{-2}, how long would it take to evaporate 1 m of sea water if all of the solar energy went into evaporating water?

Key Terms

angular momentum per unit mass – distance to rotation axis times tangential speed

baroclinic instability – warm moist air rises, while cold dry air sinks, lowering the center of gravity, releasing energy for the growth of midlatitude storms

brine rejection – when sea ice forms, salt ions are not taken up into the ice crystal lattice and are left in the water, making the water more dense

Ekman transport – wind stress on the upper layer of water causes it to move to the right (left) of the wind in the NH (SH), causing coastal upwelling on the west coasts of continents

El Nino Southern Oscillation (ENSO) – A 3-7 year cycle seated in the equatorial Pacific basin with variations in sea level pressure, sea surface temperature, rainfall, strength of the Walker Circulation, and tilt of the thermocline

general circulation – the totality of motions in the atmosphere and ocean which transport moisture, heat, momentum, and constituents *gyres* – closed current circulations in the upper layer of the ocean driven by wind westerly wind stress in the midlatitudes, easterly wind stress in the subtropics, and bounded by continents

Hadley circulation – rising in the tropics, poleward motion (causing the midlatitude westerlies), sinking in the subtropics, then equatorward motion (causing the trade easterlies)

latent heat – the energy required to evaporate water that is "released" upon condensation

latent heat transport – moist air is transported generally upward and poleward, while dry air is generally transported downward and equatorward

Maritime Continent – the predominance of islands in and near Indonesia makes the region act as if it were a continental land mass, in comparison to the Pacific and Indian Oceans

meridional circulation – a north-south overturning, such as the Hadley circulation

midlatitude westerlies – due to export of high angular momentum from the tropics by the Hadley Circulation, the wind in midlatitudes tends to come from the west

monsoon - a seasonal reversal in the prevailing wind direction on a continental scale

North Atlantic Oscillation (NAO) – The component of NAM seated in the North Atlantic which describes the variation between a strong westerly

Northern Annular Mode (NAM) – vertical coupling between the stratospheric polar night jet and tropospheric jet stream which varies between strong westerly flow and blocking highs with a disturbed polar vortex

Quasibiennial Oscillation (QBO) – mode of atmospheric variation seated in the tropical stratosphere where alternating layers of westerly winds and easterly winds descend with time, with a period varying from 22-34 months and averaging 28 months

sensible heat transport – warm air is transported generally upward and poleward, while cold air is generally transported downward and equatorward

Southern Oscillation – the atmospheric component of ENSO which involves variation in the difference in sea level pressure between Darwin, Australia and Tahiti

subtropical easterlies – air returning to the equator brings low angular momentum, acquiring easterly flow relative to the ground, allowing for easy ship travel in the "trade easterlies"

synoptic scale baroclinic waves – waves which grow from the energy associated with differences in temperature between air or water masses

thermocline – the depth at which the warm sunlit surface layer of the ocean transitions to the cold, deep ocean

thermohaline circulation – slow overturning circulation in the ocean driven by differences in temperature (*thermo*) and salinity (*haline*)

Walker Circulation – east-west overturning circulation in the tropics, with rising motion over Africa, Indonesia, and South America and sinking over the oceans; component of ENSO

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