# Climate Science

# INTER-ANNUAL TO DECADAL CLIMATE VARIABILITY/COASTAL UPWELLING AND COASTAL CLIMATES

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## MONITORING EL NIÑO and LA NIÑA

### Background:

Before 1982, few Americans had ever heard of the term *El Niño*, when exceptionally stormy weather conditions were reported along the West Coast. Much media and public attention was focused upon this large-scale anomalous atmospheric and oceanic condition again during the 1997-98 winter when numerous Pacific storms battered the West Coast and Southeast, while the northern tier of states remained exceptionally mild. Briefly, El Niño, named after "the Christ child" by Peruvians some 200 years ago, is associated with a noticeable warming of the equatorial Pacific Ocean waters along the South American Coast in December. This phenomenon that occurs every three to five years had been long known to produce disastrous effects upon the local South American economy. Warming of the coastal Pacific waters causes a reduction in the upwelling of nutrient-rich cold water reducing the fish population and hence the income from the fishing industry. Studying these El Niño events, some researchers had found a correlation between these episodes and the Southern Oscillation, a quasi-periodic variation in the atmospheric pressure across the tropical Pacific Ocean. The term ENSO, a contraction for ***E***l ***N***iño and ***S***outhern ***O***scillation, has been used to describe the combined effects of these two phenomena.

Notably in 1998, the opposite condition, called *La Niña* appeared. The term La Niña had been proposed about 1988 to identify an event associated with anomalously cold ocean waters in the eastern Pacific. The reason attention has been paid to these warming and cooling events in the equatorial Pacific is that atmospheric and oceanic scientists have seen a relationship between El Niño/La Niña events in the eastern Pacific and unusual weather conditions in many other areas of the world. Research continues to predict future El Niño and La Niña events and to explain the causes in an effort to understand these "teleconnections." In fact, the terms El Niño and La Niña now refer to the larger scale anomalous atmospheric and oceanic patterns seen across the globe.

Following the significant 1982-83 El Niño event, a major international effort called *TOGA* (Tropical Oceans, Global Atmosphere) was launched. Between 1985 and 1994, the weather and near-surface ocean conditions in the tropical Pacific were closely monitored by investigators using moored ocean buoys, drifting buoys, ship measurements, and satellites in both geosynchronous and polar orbits. Infrared radiation (IR) sensors onboard these satellites provide a continuous worldwide estimate of the sea surface temperatures (SST). The buoy network and the satellite surveillance, continued under the administration of NOAA, provided the scientific community with the first indications of the major 1997-98 El Niño or "warm-phase ENSO" and the 1998 "cold phase" La Niña events.

### WIDESPREAD EFFECTS OF El NIÑO and LA NIÑA

The Climate Prediction Center has a website entitled ENSO Temperature and Precipitation Composites, where a suite of maps can be viewed that show how the temperature, precipitation and snow patterns over three-month "seasons" across the coterminous United States are affected by El Niño and La Niña conditions. The data were collected from 1950 through the present and are plotted as departures from 1981-2010 mean values, grouped on six separate pages (e.g., El Niño temperature, El Niño precipitation, etc.) accessed from separate tabs. Eighteen El Niño cases (listed below the maps) and 16 La Niña cases were considered. Considering the top row ("composite"), the left panel represents the average temperature, precipitation or snow departures from normal for a given three-month season, while the right panel shows the frequency of occurrence of above or below average conditions as a percentage for the set of all individual El Niño or La Niña years. For example, take the case of temperature for the late meteorological winter and early meteorological spring (JFM). For an El Niño situation, the Southern States extending from Arizona eastward to the Carolinas would have below average temperatures, with Florida experiencing temperature departures that would be at least one Celsius degree below average. The frequency of occurrence of below average temperatures would be in excess of 60 percent, or approximately eleven years out of the 18 El Niño cases. On the other hand, the nation's northern tier of states would have above average JFM temperatures in an El Niño case. Such a positive temperature anomaly situation across the northern Rockies and adjacent high Plains occurred little more than 40 percent of all El Niño years. For the same set of months (JFM) in a La Niña year, the Northwest, the northern Rockies and the northern Plains would most likely experience below average temperature conditions.

## KEEPING TRACK OF CURRENT El NIÑO/ LA NIÑA INDICATORS

Several Web sites focusing on the El Niño and La Niña provide up-to-date information concerning the SST and other El Niño indicators. You can use these sources to monitor the present conditions across the tropical Pacific, compare a recent El Niño event with other historic predecessors, and learn how these events may affect the weather and climate elsewhere on the planet. A special El Niño theme page produced by the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (PMEL) in Seattle, WA contains background information and various types of current information sources. One such source is the set of real time plots of sea surface temperature and wind observations provided by an array of moored ocean buoys in the Pacific Ocean. Other links from this page provide El Niño forecasts and information in a question and answer format. A NOAA La Niña theme page is also available that describes La Niña episodes.

Another site, the Ocean Surface Topography from Space homepage, provides global sea level data obtained from NASA's Jason satellite. From this altimeter information, current El Niño and La Niña conditions can be monitored and displayed.

The National Weather Service's Climate Prediction Center (CPC) issues an *El Niño* or *La Niña Watch* when conditions are favorable for the development of El Niño or La Niña conditions within the next six months.

As of this writing, borderline ENSO-neutral were continuing as observed surface temperatures were close to the long-term averages across most of the equatorial Pacific, with "SST anomalies" (differences between observed surface temperatures and the long-term averages) generally being less than 0.5 Celsius degrees above or below average. While slightly cooler than average waters were found across the eastern equatorial Pacific, "positive SST anomalies" (observed surface temperatures above the long-term averages) amounting to nearly 1.0 Celsius degrees above average were found across small areas in the far western Pacific near Oceania. Scientists at NASA's Jet Propulsion Laboratory reported that based upon global sea level data from the Jason-2 satellite a "'La Nada' climate pattern lingers over the Pacific" following two years of strong, cool-water La Niña events. ("La Nada" is a term that is used by some sources to describe ENSO-neutral conditions.) Recently, scientists at CPC indicated that ENSO-neutral conditions would appear to be favored through the spring 2014 in the Northern Hemisphere. Therefore, the ENSO Alert System Status is considered "Not Active."

# INTER-ANNUAL TO DECADAL CLIMATE VARIABILITY

**Driving Questions:** *How do interactions between the ocean, atmosphere, and Earth's surface produce inter-annual and longer climate variability? What are examples of such short-term climate variability on local, regional, and global scales?*

**Educational Outcomes:** To describe the origins and characteristics of inter-annual and decadal variability. To explain their impacts on local, regional and global weather and climate.

**Objectives:** After completing this investigation, you should be able to:

- Describe fundamental concepts concerning climate fluctuations that have been observed lasting beyond a year to decades.
- Explain inter-annual climate variability as exemplified by El Niño — Southern Oscillation (ENSO).
- Describe local, regional, and global impacts or teleconnections of inter-annual climate variability phenomena.

## Variability in Earth's Climate System

Earth's climate system shows considerable variability on all time scales. As stated previously, the primary drivers of climate are the direct impacts of (a) incident solar radiation, (b) Earth's rotation and revolution, (c) the character of Earth's surface, and (d) atmospheric composition. These boundary conditions underlie cycles of climate components (e.g., temperature, precipitation) that adhere strictly to diurnal and annual time periods. These essentially determine the multi-year mean state of the climate system (including annual and seasonal mean values of climatic components).

But there are fluctuations that occur in the climate system with time scales lasting greater than a year (inter-annual) to decades and longer. They manifest conditions, or modes, with distinctive life times and spatial patterns. These are departures from the mean state of the climate system that are related to variations in the general circulations of the atmosphere and ocean, and the conditions at Earth's surface such as sea surface temperatures (SST) and snow and ice cover. These modes arise from the forcings and responses, including feedbacks, in the system and the extent to which the slower acting components (e.g., ice, deep ocean, and vegetation) become entrained with the more rapid variations of the atmosphere and ocean surface.

The ocean, because of its attributes, including its great mass, huge heat capacity, fluidity, and thermal inertia, is a crucial participant in producing climate fluctuations that run their course on inter-annual and longer time scales. These fluctuations are significant to societies and ecosystems through their impacts on water resources, food supply, energy demand, human health, biological systems, and national security, among other issues.

**El Niño — Southern Oscillation (ENSO):** Perhaps the best known and most readily detected inter-annual climate variability phenomenon is **El Niño — Southern Oscillation (ENSO**), a large-scale, persistent disturbance of ocean and atmosphere in the tropical Pacific Ocean. ENSO is governed by large-scale ocean dynamics and coupled ocean-atmosphere interactions which result in periods of anomalously warm and cold conditions (or phases) in the tropical Pacific Ocean on a quasi-periodic basis. While its different phases have major impacts on the tropical Pacific and bordering land environments, there are also impacts worldwide. Globally, ENSO is the largest single contributor to inter-annual climate variability.

The term ***El Niño*** originally described a short-term, weak warming of ocean water that ran southward along the coast of Peru and Ecuador around Christmas resulting in poor fishing. Now, the term is incorporated into the more comprehensive general term El Niño - Southern Oscillation (ENSO), which exhibits a warm phase (traditional El Niño), a cold phase (termed La Niña) and a neutral or long-term average phase. The "SO" in ENSO refers to the Southern Oscillation, an interannual see-saw in  tropical sea level pressure between the eastern and western portions of the tropical Pacific. In general, the terms El Niño and La Niña may be used for particular phase occurrences.

El Niño modes last an average of 12 to 18 months and occur about once every two to seven years. Ten occurred during a recent 42-year period, with one of the most intense on record in 1997-98. Sometimes El Niño is followed by La Niña, a period of unusually strong trade winds and vigorous upwelling in the eastern tropical Pacific. During La Niña, changes in SST and extremes in weather are typically opposite those observed during El Niño.

A persistent ENSO phase can be accompanied by major shifts in planetary-scale atmospheric and oceanic circulations and weather extremes. Because of the importance of ENSO, the tropical Pacific Ocean is now monitored continuously via about 70 tethered (anchored) buoys in NOAA's Tropical Atmosphere Ocean (TAO) Project. Operational definitions of ENSO phases have been agreed to by the World Meteorological Organization (WMO) Commission for Climatology. They are defined based on three-month averages of SST departures from normal for a critical region (ENSO 3.4 region: 120W-170W, 5 N-5S) of the equatorial Pacific as follows:

**El Niño** (the warm phase) is characterized by a positive SST departure from normal, equal to or greater than 0.5 Celsius degrees, averaged over three consecutive months.

**La Niña** (the cold phase) is characterized by a negative SST departure from normal, equal to or greater than 0.5 Celsius degrees, averaged over three consecutive months.

**Figure 1** displays the average SST and wind patterns for December 2011 based on observations from NOAA's TAO/Triton equatorial Pacific buoy array.

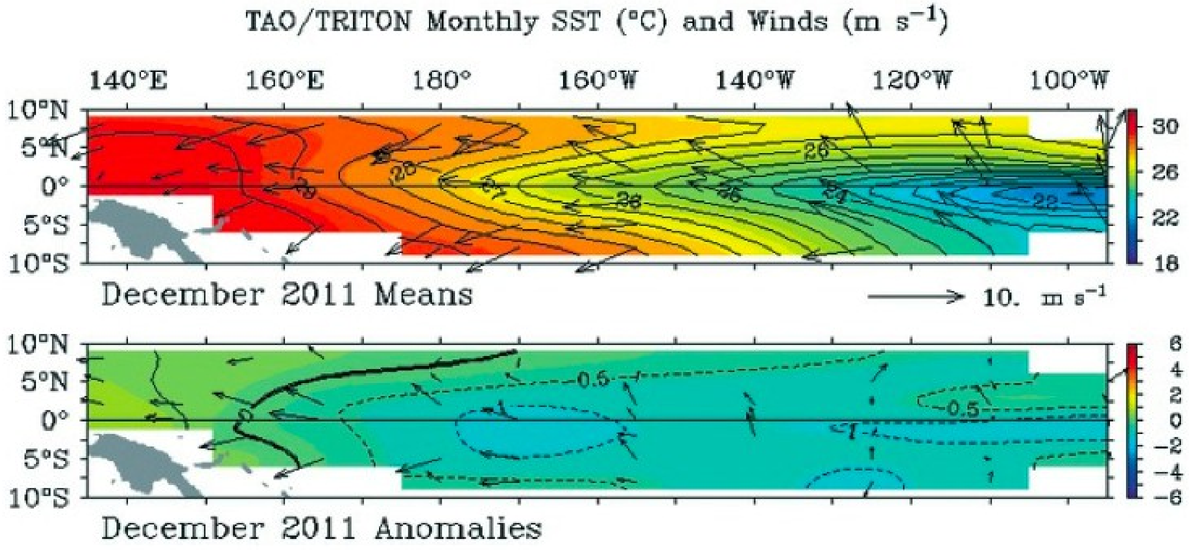


Figure 1.
Tropical Pacific monthly SST and winds during December 2011.

1. The upper panel in Figure 1 depicts SST and winds across the tropical Pacific, and shows the temperature patterns as averaged over the month of December 2011. Isotherms are drawn at a 0.5 C° interval to show the temperature pattern. Temperatures range from above 29.5 °C in the far western Pacific to less than **[(*25.5*)(*24.0*)(*22.0*)]** °C along the equator near 100 deg W.

2. Average wind directions are indicated by arrows with their lengths proportional to the wind speeds. The prevailing surface winds across most of the tropical Pacific during December 2011 were towards the **[(*east*)(*west*)]**.

The lower panel in Figure 1 denotes anomalies. An **anomaly** is a departure from the longterm average condition. Anomaly patterns are depicted with lines also drawn with half-degree intervals. Positive (warmer than normal) anomalies are analyzed with solid lines and negative (colder than normal) anomalies with dashed lines. The heavy solid black line, labeled “0”, denotes locations where SST values were the same as the long-term averages.

3. With a pencil and a straight edge, mark off the ENSO 3.4 region (120W-170W, 5 N-5S). The average anomaly in the region is **[(*warmer than +0.5*)(*between 0 and −0.5*)(*colder than −0.5)*]** Celsius degrees.

4. Anomalies in the ENSO 3.4 region similar to those in December 2011 had persisted for at least three months. Based on the definitions stated earlier, **[(*El Niño*)(*La Niña*)]** conditions existed in the tropical Pacific in December 2011. [Note: Tropical Pacific conditions made a transition towards ENSO-neutral during April 2012.]

**Figure 2** and **Figure 3** are presented to demonstrate especially strong El Niño and La Niña episodes, respectively, from recent years.

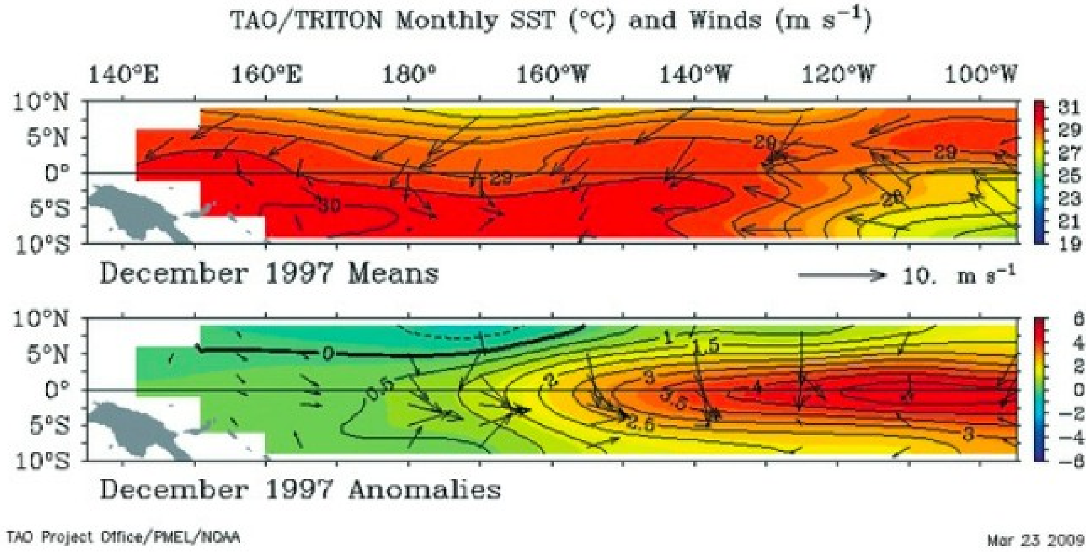


Figure 2.

Monthly SST and winds during a significant El Niño (warm phase) episode.

5. Figure 2 shows tropical Pacific conditions midway through a strong El Niño (warm phase) episode in 1997-98. The upper panel shows warm temperatures generally across the Pacific, with the lower panel showing anomalies in the ENSO 3.4 region which are **[(*warmer than +0.5*) (*between 0 and −0.5*)(*colder than −0.5*)]** Celsius degrees.

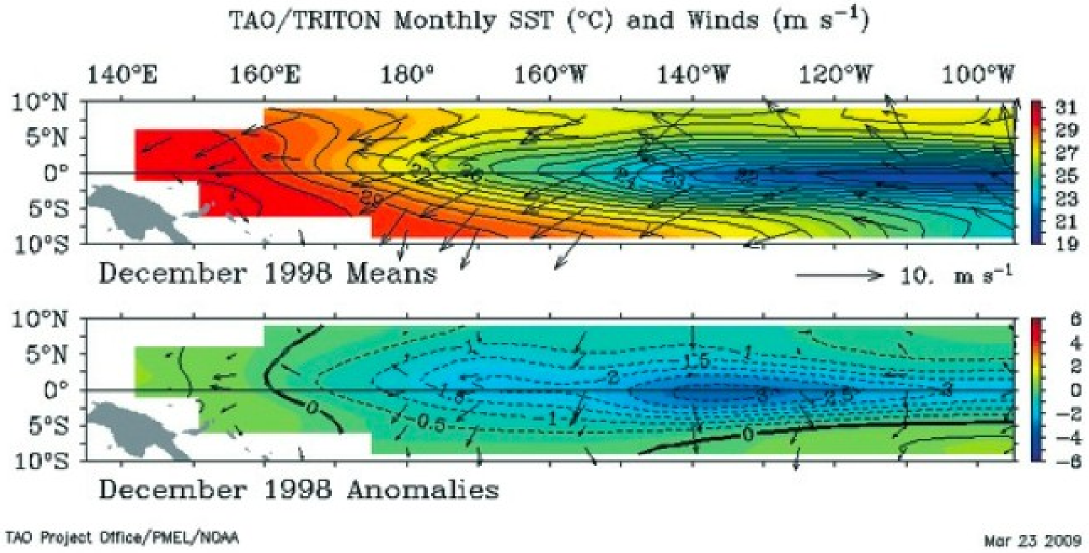


Figure 3.
Monthly SST and winds during significant La Niña (cold phase) episode.

6. Figure 3 shows tropical Pacific conditions midway through a strong La Niña (cold phase) episode during 1998-99. The upper panel shows warm temperatures in the western Pacific and colder temperatures along the equator to the east. The lower panel shows anomalies in the ENSO 3.4 region which are **[(*warmer than +0.5*)(*between 0 and −0.5*)(*colder than −0.5*)]** Celsius degrees.

7. Compare the wind arrows in the upper panels of Figures 2 and 3. They show that during **[(*El Niño*) (*La Niña*)]** episodes the wind blows more strongly towards the west across all or most of the tropical Pacific.

For the most recent monthly SST and Winds TAO depiction, go to: *http://www.pmel.noaa.gov/tao/jsdisplay/*. There, click on “Lat Lon plots”. On the new page, click on “Monthly” and then, “Make plot!”. Click on image to enlarge it. You can also get the latest 5-day average depiction at the same website.

**Teleconnections: Teleconnection** is the name given to statistically significant correlations between weather events that occur at different places around the globe. There are a number of such correlations that appear during ENSO episodes. They result from the changing position of the major heat source (identified by high SST) in the tropical Pacific. These interactions between ocean and atmosphere have a ripple effect on climatic conditions in far flung regions. Shifts in tropical rainfall affect wind patterns over much of the globe. Waves in the air flow pattern determine the positions of the monsoons, storms tracks, and belts of strong upper-air winds (jet streams) which overlie borders between warm and cold air masses at Earth's surface.

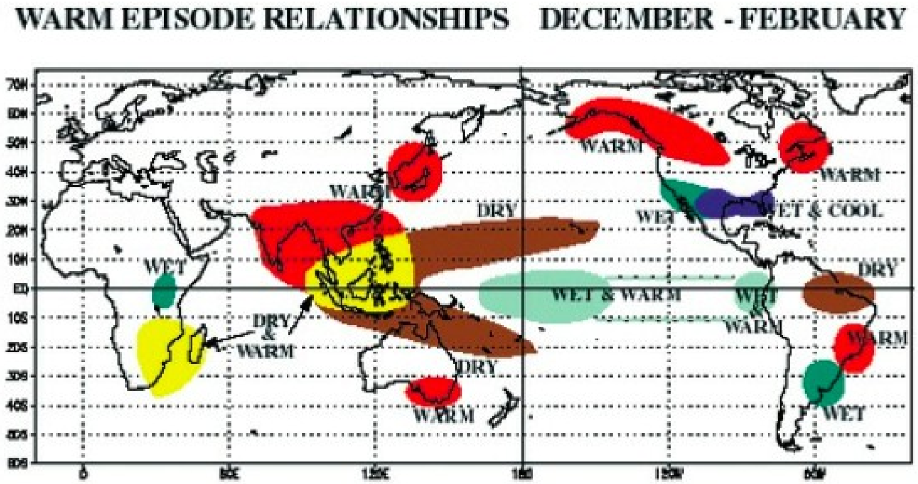
El Niño (warm phase) and La Niña (cold phase) teleconnections are summarized in **Figure 4** and **Figure 5**, respectively.

8. According to Figures 4 and 5, ENSO-related teleconnections in North America are more extensive during the Northern Hemisphere **[(*summer*)(*winter*)]**.

9. El Niño (warm phase) related teleconnections are typically stronger, more frequent, and longer lasting than those during La Niña (cold phase) episodes because El Niño events themselves are typically stronger, more frequent, and longer lasting. The teleconnections are also different. If the U.S. southeastern states were experiencing drought, the onset of a Northern Hemisphere winter-season **[(*El Niño*)(*La Niña*)]** might be welcomed.

10. One part of the coterminous U.S. which appears least likely to be impacted by ENSO events is the **[(*northwestern*)(*southwestern*)(*central*)]** states.

11. One country that is most impacted by teleconnections to some extent by all El Niño (warm phase) and La Niña (cold phase) episodes is **[(*Brazil*)(*Indonesia*)(*Japan*)]**.



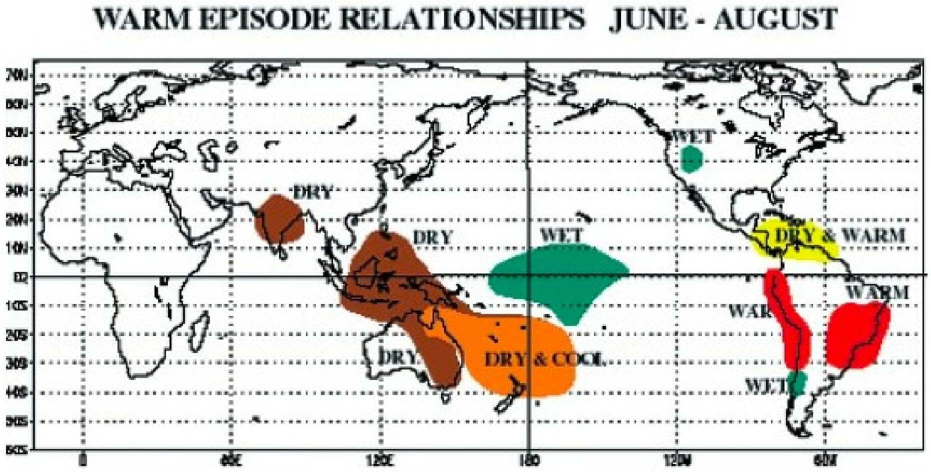


Figure 4.
December-February and June-August El Niño (warm phase) typical teleconnections.

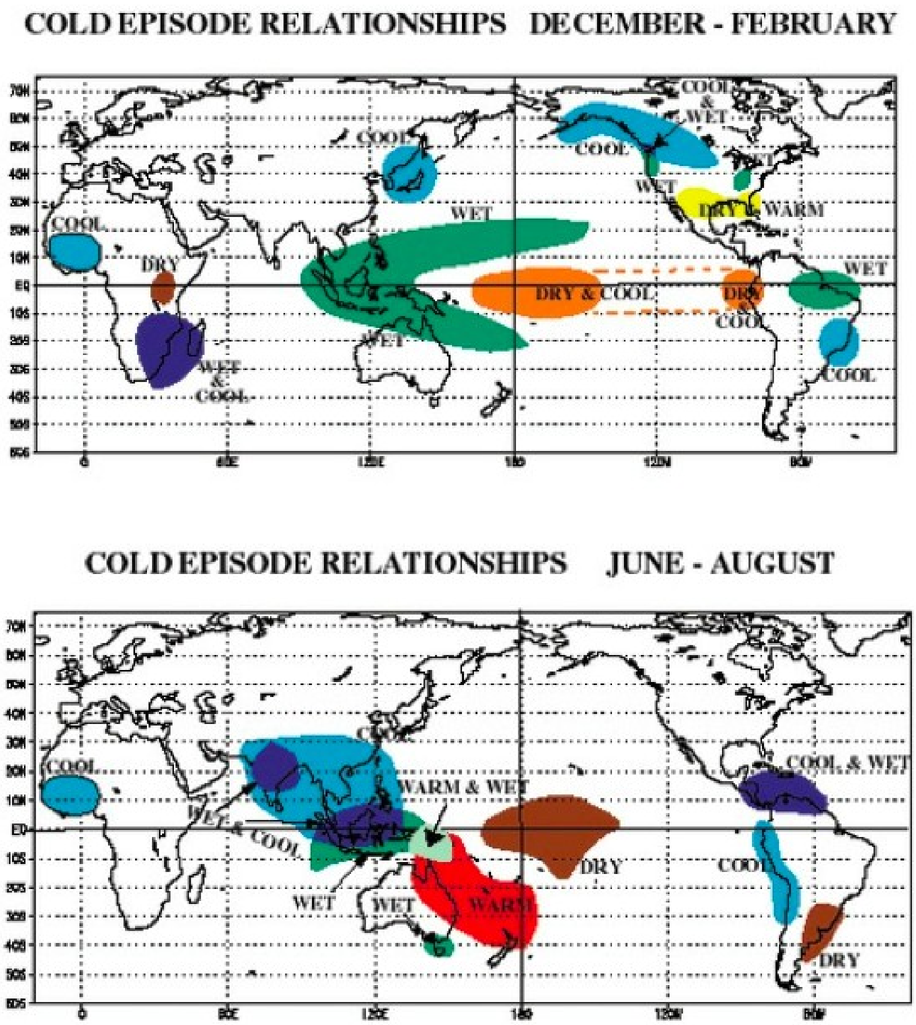


Figure 5.
December-February and June-August La Niña (cold phase) typical teleconnections.

**ENSO Impacts on the U.S.:** Detailed statistical analyses have been made by NOAA's Climate Prediction Center to describe strong ENSO temperature and precipitation teleconnections. These are available in map forms at: *http://www.cpc.ncep.noaa.gov/products/predictions/threats2/enso/elnino/index.shtml*. As an optional activity, we suggest that you examine maps to determine what, if any, ENSO-related teleconnections have been detected in your geographical area.

**Decadal Variability:** Additional variabilities in the climate system in certain regions over time frames of several decades have been identified. These periodicities are just beginning to be documented and understood. Regional differentials in sea-level air pressure and/or sea surface temperatures have been associated with upper atmospheric wind patterns or surface ocean conditions in the North Atlantic, North Pacific, Arctic and Antarctic areas.

**Summary:** Fluctuations occur in the climate system with time scales on the order of more than a year (inter-annual) to decades and longer. Ocean-atmosphere interactions play major roles in causing these climate modes with distinctive life times and spatial patterns. The El Niño — Southern Oscillation is the most significant inter-annual climate variability phenomenon. While the climates of the locations where these fluctuations take place are directly impacted, they can also impact weather and climate in far flung places. These distant impacts are referred to as teleconnections.
These fluctuations are significant to societies and ecosystems through impacts on water resources, food supply, energy demand, human health, biological systems, and national security.

# COASTAL UPWELLING AND COASTAL CLIMATES

**Driving Questions:** *How do winds produce upwelling and downwelling in the ocean? What is the significance of upwelling for marine productivity? What are possible impacts on local climate?*

**Educational Outcomes:** To describe upwelling and downwelling in coastal areas. To describe relationships between upwelling and marine productivity. To describe the impacts of upwelling and downwelling on California coastal climates.

**Objectives:** After completing this investigation, you should be able to:

- Demonstrate the causes of coastal upwelling and downwelling.
- Describe the influence of the prevailing wind and Coriolis Effect on upwelling and downwelling.
- Describe the impacts of upwelling and downwelling on coastal climates.

**Introduction:** In some near-shore areas of the ocean, coastal orientation, prevailing wind, and Earth's rotation combine to influence vertical ocean circulation. In these regions, the wind sometimes transports water in the upper 10 to 100 m (33 to 330 ft) away from the coast, to be replaced by cooler water from below. This process, called **coastal upwelling**, brings to the sunlit surface nutrient-rich water, spurring biological productivity. At other times and places, the wind transports near-surface water towards the coast, causing warm surface waters to pile up and sink. This process, known as **coastal downwelling**, thickens the layer of nutrient-deficient water, reducing biological productivity.

Upwelling and downwelling can be accompanied by dramatic changes in the local weather and climate. Upwelling and downwelling are also associated with broad-scale atmosphere/ ocean interactions (e.g., El Niño and La Niño) that have regional and even global impacts on precipitation patterns and other components of the water cycle.

In this investigation, we examine coastal upwelling and downwelling by looking at the contribution of coastline orientation, prevailing winds, and Earth rotation. We also describe the impacts on California coastal areas.

**Materials:** Scissors and paper brad or a paper clip with its inside end bent at a right angle to the rest of the clip.

**Figure 1** (last page of this Investigation) provides a **Model Ocean Basin** manipulative. Use scissors to separate the top and bottom diagrams along the dashed line and to remove the "cut out" areas in the top diagram along the dashed lines. The top block diagram represents the ocean surface with a vertical cross-section through a model ocean basin.

1. According to the cardinal direction arrows in the upper left hand corner of the top block diagram, the east boundary of any ocean basin is the land's **[(*eastern*)(*western*)]** coast.

Use a pencil point to poke a small hole through the centers (each marked with a ) of the two diagrams. Lay the top diagram (Model Ocean Basin) directly over the bottom diagram (arrows) so the center points of the two coincide. To hold the two together and to provide an axis for rotation, place a paper brad pin through the holes you made on the diagrams. [If you are using a bent paper clip, lay the device flat on a table or desk so the clip doesn't fall out.]

2. While holding the top diagram stationary, rotate the bottom diagram through all 4 positions. Note that there are two different hemispheres, North (***N***) and South (***S***), each with two different wind directions and two different coasts possible. Hence, the total number of different combinations of hemispheres, wind directions, and coasts possible in our model is **[(*2*)(*6*)(*8*)]**.

3. Everywhere except at the equator, surface ocean water set in motion by the wind will be deflected by Earth's rotation. This deflection is called the **Coriolis Effect**. Turn the bottom diagram until a Northern Hemisphere combination appears, that is, when "N" appears in the upper right window. Compare the wind direction and the direction of the near-surface flow of water. (This is best seen by imagining yourself on the tail of the wind arrow and facing forward.) The near-surface flow of water is about 90 degrees to the **[(*right*)(*left*)]** of the wind direction.

4. Predict the flow direction of near-surface water produced by wind blowing from the opposite direction in the same hemisphere. Your prediction is that the near-surface flow will be about 90 degrees to the **[(*right*)(*left*)]** of the wind direction.

5. To check your prediction, rotate the bottom diagram until the other "N" appears in the window. From what you have learned so far in this investigation, wind-driven flow of near-surface water in the Northern Hemisphere is about 90 degrees to the **[(*right*)(*left*)]** of the wind direction.

6. Repeat the last three steps for the Southern Hemisphere. Again predict and note the difference between the wind direction and the direction of flow of near-surface water. The wind-driven flow of near-surface water in the Southern Hemisphere is about 90 degrees to the **[(*right*)(*left*)]** of the wind direction.

7. Near-surface water transported away from the coast tends to be replaced by cooler water from below in a process called upwelling. Rotate the bottom diagram to a position showing the wind blowing from south to north in the Southern Hemisphere. This combination will produce upwelling along the land's **[(*east*)(*west*)]** coast.

8. Coastal upwelling of nutrient-rich water stimulates the growth of marine plants which support fisheries. Now rotate the underlay to determine that in the Northern Hemisphere on the west

coast of Africa, upwelling and increased productivity will be generated by a wind blowing from **[(*south to north*)(*north to south*)]**.

9. When the wind transports near-surface water towards a coast, the warm surface layer thickens, decreasing biological productivity. This process is called downwelling. Rotate the underlay to a position showing the wind blowing from south to north in the Northern Hemisphere. This combination will produce downwelling along the land's **[(*eastern*) (*western*)]** coast.

10. Along the coast of central and northern California, surface winds generally blow from north to south in the summer and from south to north in the winter. The season of warm water transport towards the California coast and downwelling for this region is **[(*summer*)(*winter*)]**.

11. The season when cold coastal upwelling water along the California coast cools the overlying air to saturation and produces frequent fog is **[(*summer*)(*winter*)]**.

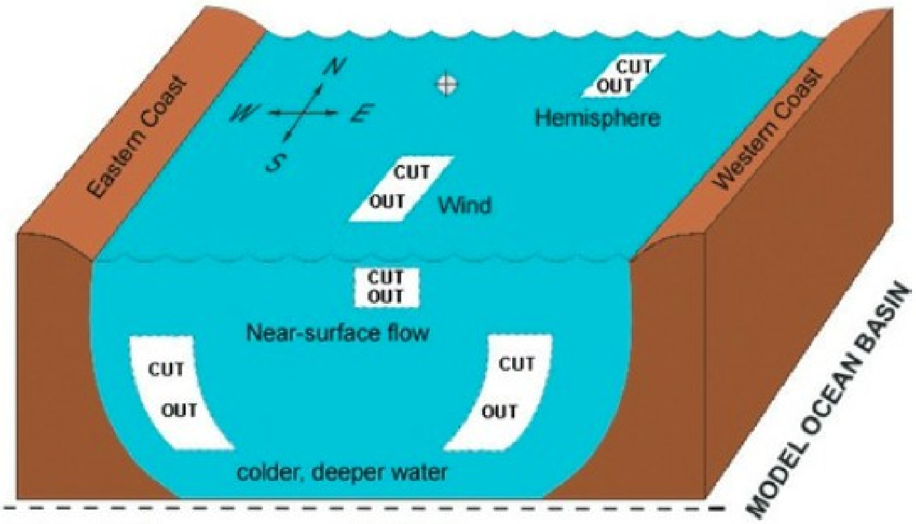
12. The Southern Hemisphere's trade winds, between the equator and 30 degrees S, have a strong component blowing from south to north. This causes upwelling, high biological productivity, and abundant fish harvests along the **[(*western*)(*eastern*)]** coasts of Africa and South America.

**Coastal Upwelling from a Different Perspective:** As part of its NASA-sponsored **Satellite Observations in Science Education**, the University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS) leads an effort to improve the teaching and learning of the Earth system through quality educational resources that make use of satellite observations.

To learn more about coastal upwelling via a learning activity developed in the Satellite Observations in Science Education Program, go to: *http://www.ssec.wisc.edu/sose*. Under the "Learning Activities" heading, scroll down to and click on "5) Coastal Upwelling". Proceed as directed through Module A entitled, "The Biological Pump and the Significance of Upwelling".

Optional: After completing this CIMSS module, consider clicking "Main Menu" on the screen at the lower left, then on "5) Coastal Upwelling", and complete Modules B and C.

**Summary:** Coastal upwelling and downwelling of ocean water have significant effects on coastal weather and climates.



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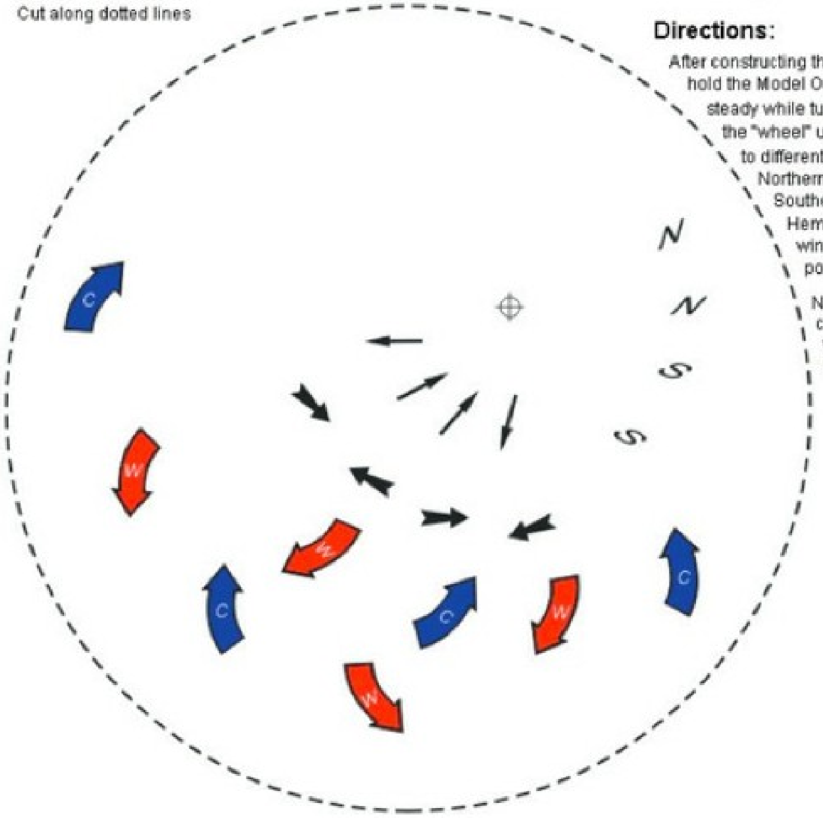

## Directions:

After constructing this device, hold the Model Ocean Basin steady while turning the "wheel" underneath to different Northern and Southern Hemisphere wind-direction positions.

Note changes in water flow.