

**AIR - SEA
INTERACTION**

TEACHER'S GUIDE

Project ATMOSPHERE

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Foreword

This guide has been prepared to introduce fundamental understandings about the guide topic. This guide is organized as follows:

Introduction

This is a narrative summary of background information to introduce the topic.

Basic Understandings

Basic understandings are statements of principles, concepts, and information. The basic understandings represent material to be mastered by the learner, and can be especially helpful in devising learning activities in writing learning objectives and test items. They are numbered so they can be keyed with activities, objectives and test items.

Activities

These are related investigations. Each activity typically provides learning objectives, directions useful for presenting and completing the activity and questions designed to reinforce the learning objectives.

Information Sources

A brief list of references related to the guide topic is given for further study.

Introduction: Air-Sea Interaction

Weather is the current state of the atmosphere at a location. The atmosphere is in constant motion on many scales ranging from the weakest wind gust to the great wind belts that encircle the globe. The energy that sustains these motions comes from the Sun via the surface of the Earth. About 71% of that surface is ocean water so that it is not surprising that the ocean strongly influences the circulation of the atmosphere and weather everywhere on Earth.

The interface or boundary between the ocean and the atmosphere is dynamic. Matter and energy are continually being transferred across the air-sea interface in both directions. The coupling of the wind with the water surface creates ocean waves and currents. Air either gains heat from or loses heat to the ocean depending on the temperature difference between the sea-surface and the overlying air. Ocean water evaporates into the atmosphere and atmospheric water vapor condenses forming fog, clouds, and possibly precipitation that returns water to the ocean.

Water is a unique substance that has an unusually high specific heat and latent heat. *Specific heat* is the quantity of heat needed to change the temperature of one unit of a substance's mass by one degree. Relatively large amounts of heat are required to change the temperature of water compared to other substances. *Latent heat* is the amount of heat needed to change the phase of a substance, for water to evaporate, for example. These thermal properties of water have important implications for sea-surface temperatures, the temperature of air overlying ocean water, heat transfer between ocean and atmosphere, and the circulation of the atmosphere.

This module deals with one aspect of air-sea interaction, the effect of sea-surface temperature on the weather in coastal regions influenced by wind-driven upwelling and downwelling of ocean water. In some coastal areas, the combination of persistent winds, Earth's rotation, and shoreline orientation can produce vertical circulation of ocean water. At locations where winds transport near-surface water (the surface layer to a depth of about 100 meters) away from the coast, it is replaced by relatively cold water that wells-up from below. This process is called *upwelling*. In other regions, where the winds transport near-surface water toward the coast, water sinks and sea-surface temperatures are higher. This process is called *downwelling*.

The Earth's rotation deflects water and air motions everywhere except at the equator; this deflection is called the *Coriolis effect*. The Coriolis effect combined with the coupling of the wind with water causes a net transport of near-surface water. This transport of water is directed about 90 degrees to the right of the wind direction in the Northern Hemisphere and about 90 degrees to the left of the wind direction in the Southern Hemisphere. Persistent winds blowing along the

coast drive near-surface water away from or toward land, resulting in upwelling or downwelling, respectively.

Coastal upwelling and downwelling influence weather and climate by affecting sea-surface temperatures. Along the northern and central California coast, for example, upwelling cold water contributes to frequent summer fogs. Cold water inhibits development of showers and thunderstorms as well as formation of tropical storms and hurricanes. Upwelling in the eastern Pacific off Ecuador and Peru contributes to the desert conditions in the coastal plains. Weakening of the upwelling associated with atmospheric and oceanic circulations on a three to seven year time span is known as El Niño. Warmer sea surface temperatures lead to enhanced precipitation along the coastal plain.

Upwelling and downwelling areas are of major research interest in the search for global links among wind-driven surface currents, density-driven deep ocean circulation, and the atmosphere. It is possible that small changes in upwelling and downwelling may influence not only the ocean, but weather and climate variability on a planetary scale.

Basic Understandings

Thermal Properties of Water

1. Water is 1000 times more dense than air. (The density of water is about 1000 kilograms per cubic meter whereas the density of air is about 1 kilogram per cubic meter.) Hence, there is more matter per volume of water to absorb and emit energy.
2. Compared to other naturally occurring substances, the specific heat of water is exceptionally high. About six times more heat energy is required to raise the temperature of one kilogram of water one Celsius degree than to raise the temperature of one kilogram of air one Celsius degree. For equal volumes of air and water, about 6000 times more heat energy is required to bring about the same temperature change in water as in air.
3. Solar radiational energy that enters the ocean is largely absorbed (converted to heat) in the near-surface water layer. Wind-driven ocean circulation distributes that heat through several hundred meters of depth so that the ocean is a vast reservoir of stored heat.
4. Water changes phase within the Earth-atmosphere system. A change in phase of water is brought about by either an input of heat (that is, for melting, evaporation, and sublimation) or a release of heat to the environment (that is, freezing, condensation, and deposition). Heat involved in phase changes of any substance is known as *latent heat*. Compared to other naturally-occurring substances, water has unusually high latent heat values.
5. Evaporation of ocean water followed by condensation within the atmosphere is the major heat-transfer mechanism operating between the ocean and atmosphere. Evaporation of one kilogram of water requires the input of almost 600 times more heat energy than it takes to warm one kilogram of water by one Celsius degree. Heat required to evaporate water subsequently is released to the atmosphere when water vapor condenses forming clouds.

Implications for Weather and Climate

6. The relatively large specific heat of water compared to land and air is the main reason why the ocean warms more slowly than land or air and also cools more slowly. Compared to adjacent land masses, the ocean surface does not heat up as much during the day and in the summer and cools down less at night and in the winter.

7. The temperature of a mass of air is largely governed by the surfaces over which the air resides and travels. Air over the ocean exhibits less seasonal and day-to-night temperature changes than does air over the continents. Air over the ocean is also more humid.
8. Coastal communities with prevailing winds from the ocean have moderate climates, with cooler summers and milder winters than might be expected based on their latitude alone.
9. Storms that form over the ocean, such as hurricanes, are powered by the latent heat released to the atmosphere when water vapor condenses. That water vapor is derived mostly from evaporation of ocean water and the rate of evaporation is chiefly governed by sea-surface temperature. The higher the sea-surface temperature, the greater the rate of evaporation, and the more latent heat that is delivered to the atmosphere.
10. In response to differences in temperature over distance (called a *temperature gradient*), heat is transferred from where it is warmer to where it is colder. Hence, warmer air is chilled as it travels over colder ocean water and colder air is heated as it travels over warmer ocean water.
11. Cooling air from below reduces the likelihood of strong vertical motion of air necessary for the development of showers and thunderstorms. Where the sea-surface temperature is lower than the air temperature, showers and thunderstorms are infrequent over the ocean and downwind coastal localities.
12. Heating air from below increases the likelihood of strong vertical motion of air that can lead to the development of showers and thunderstorms. Where the sea-surface temperature is higher than the air temperature, showers and thunderstorms are more frequent over the ocean and downwind coastal localities.
13. The water vapor concentration of air over the ocean surface is increased by evaporation. Warm humid air moving across a relatively cold ocean surface may be chilled to saturation. Water vapor condenses and sea fog forms. (*Fog is a cloud in contact with a water or land surface.*) Fog may also form when very cold air passes over relatively warm ocean water. In that case, evaporation into the cold air produces saturation and fog appears as rising steam-like streamers. That type of fog is common over the North Atlantic in winter and is called steam fog (or *Arctic sea smoke*).

Role of Wind and Earth's Rotation

14. Friction between wind and the ocean surface helps produce the broad-scale horizontal water movements of the ocean's surface, called surface currents. These currents tend to resemble the patterns of the prevailing surface winds.
15. If Earth did not rotate, friction between the wind and the ocean surface would push a thin layer of water in the same direction as the wind, but at a fraction of the wind's speed. This layer, in turn, would drag the layer beneath it and put it into motion. This interaction would continue downward through successive ocean layers, like individual cards in a deck of cards, each moving forward at a slower speed than that of the layer above.
16. Because Earth does rotate, the shallow layer of surface water set in motion by the wind is deflected to the right of the wind direction in the Northern Hemisphere and to the left of the wind direction in the Southern Hemisphere. This deflection is called the *Coriolis effect*. The Coriolis effect depends on latitude, being zero at the equator and greatest at the poles.
17. Earth's rotation causes a change in direction of each layer of water that is put into motion by the layer above. Viewed from above, changes in the direction of horizontal water motion (and decreased speed) with increasing depth form a spiral known as the *Ekman spiral*.
18. Although the motion of the surface-water layer can be up to 45 degrees to the right (Northern Hemisphere) or left (Southern Hemisphere) of the wind direction, the Ekman spiral causes the net transport of water in the top 100 meters or so of the ocean to be approximately 90 degrees to the wind direction.

Upwelling

19. Ocean winds can result in the transport of near-surface water away from a coastal area. Colder water then wells up from below to replace it. Upward movement of cold bottom water is called *upwelling*.
20. In coastal regions, upwelling can occur when winds blow more or less parallel to the shoreline. In the Northern Hemisphere, net transport of surface water is to the right of the wind direction. Along the west coast, upwelling occurs when the wind blows from the north because the net transport of near-surface water is away from shore. Along the east coast, upwelling occurs when the wind blows from the south.
21. In the Southern Hemisphere, net transport of surface water is to the left of the wind direction. Upwelling occurs along west coasts in the Southern

Hemisphere with winds blowing from the south because the net transport of near-surface water is away from shore. Winds from the north cause upwelling along east coasts of the Southern Hemisphere.

22. Sea-surface temperatures are relatively low in regions of upwelling.

Downwelling

23. There are regions of the ocean where winds result in the transport of near-surface water towards a coastal area, causing surface water to pile up. In response, near surface waters sink. This downward movement is called *downwelling*.

24. In coastal regions, downwelling can result from the transport of water towards the coast when winds blow more or less parallel to the shore. In the Northern Hemisphere, net transport of surface water is to the right of the wind direction. Hence, downwelling occurs when winds blow from the south along the west coast and when winds blow from the north along the east coast.

25. In the Southern Hemisphere, net transport of near-surface water is to the left of the wind direction. Hence, downwelling occurs when winds blow from the north along the west coast and when winds blow from the south along the east coast.

26. Sea-surface temperatures are relatively high in regions of downwelling.

Impacts of Upwelling and Downwelling

27. Prevailing summer winds blow from the north along the California coast. This causes coastal upwelling and relatively low sea-surface temperatures. Warm, humid summer air may be cooled to saturation producing frequent fog along the northern and central California coasts. Thunderstorms are also relatively rare along the California coast.

28. Upwelling along portions of the west coasts of the African and American continents leads to colder water in the eastern Atlantic and Pacific Oceans inhibiting development of tropical storms and hurricanes because of relatively low sea-surface temperatures.

Activity: Sea-Surface Temperatures

Introduction

In some near-shore areas of the ocean, coastal orientation, prevailing winds, and rotation of Earth combine to influence vertical ocean circulation. In these regions, the wind sometimes transports the upper 10 to 100 meters of water away from a coast, to be replaced by cooler water welling up from below. This process, called coastal upwelling, brings to the surface relatively cold bottom water which can chill the air immediately above the ocean surface. At other times and places, the prevailing wind transports near-surface water towards a coast, causing warm surface waters to pile up and sink. This process, called coastal downwelling, produces relatively warm ocean surface-water near the coast.

This activity investigates coastal upwelling and downwelling by looking at the combinations of coastline orientation, prevailing wind direction, and Earth rotation that produce them. From this, you can predict the general sea-surface temperature pattern and possible influences on weather and climate.

Materials

Photocopies of Model Ocean Basin page and Global Ocean Basin Chart, scissors, paper brad.

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 the Coriolis effect on upwelling and downwelling.
- Describe the influence of upwelling and downwelling on sea-surface temperatures.

Investigations

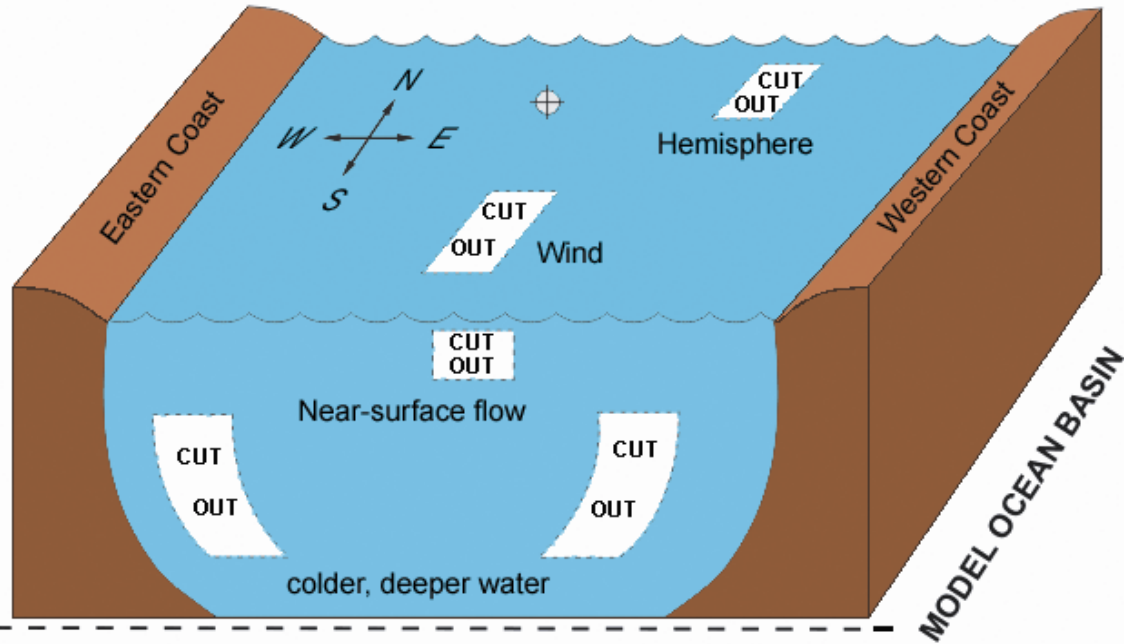
Use the scissors to separate the top and bottom diagrams along the dashed line and cut out the windows from the top diagram as indicated. The top block diagram represents the ocean surface with a vertical cross-section through a model ocean basin. If desired, this can be better seen by folding the diagram along the intersection of the ocean surface and the vertical cross-section and placing it so the vertical cross-section is hanging off the edge of a table.

Use a pencil point to poke a small hole through the rotational centers (each marked with a \oplus) of the two diagrams. Lay the top diagram (Model Ocean Basin) directly over the bottom diagram (arrows) so the rotational centers of the two coincide. To hold the two together, place a paper brad down through the holes you punched in the diagrams.

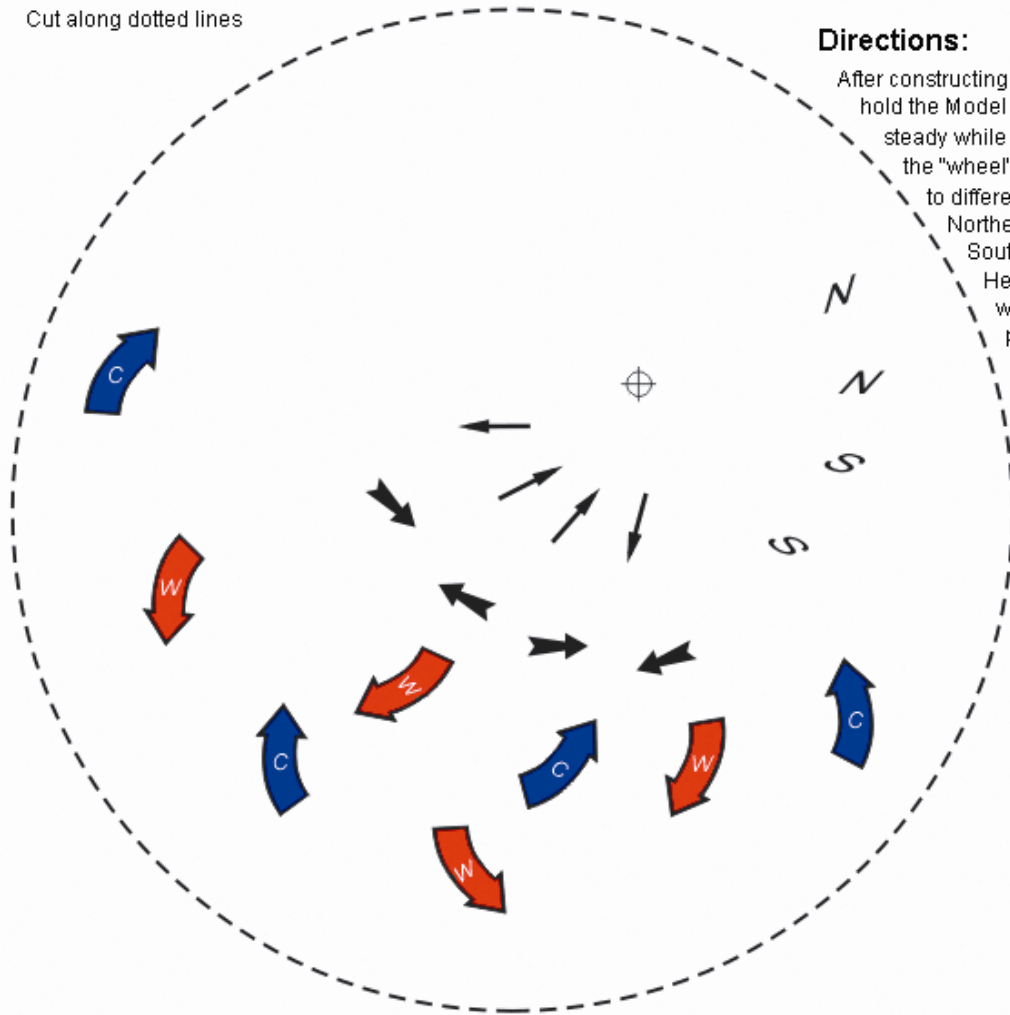
The global Basin Chart is provided for reference as you proceed through the following investigations.

1. According to the cardinal direction arrows in the upper left hand corner of the top block diagram, the west boundary of any ocean basin is the land's **[(eastern)(western)]** coast and the east boundary of any ocean basin is the land's **[(eastern)(western)]** coast.
2. On Earth, away from the equator, surface 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, an "N" appears in the upper right window. Compare the wind direction and the direction of the near-surface water motion. If desired, this can be better seen by orienting yourself so that you are on the tail of the wind arrow facing its head. The near-surface water motion is about 90 degrees to the **[(right)(left)]** of the wind direction.
3. Predict the direction of the near-surface water motion produced by winds blowing from the opposite direction in the same hemisphere. Your prediction is that the near-surface water motion will be about 90 degrees to the **[(right)(left)]** of the wind direction.
4. 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 activity, wind-driven near-surface water motion in the Northern Hemisphere is about 90 degrees to the **[(right)(left)]** of the wind direction.
5. Repeat the last three steps, but this time for the Southern Hemisphere. Again predict and note the direction of the near-surface water motion relative to the wind direction. The wind-driven near-surface water motion in the Southern Hemisphere is about 90 degrees to the **[(right)(left)]** of the wind direction.
6. When wind transports near-surface water away from a coast, it 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 Northern Hemisphere. This combination will produce upwelling along the land's **[(eastern)(western)]** coast.

7. Upwelling of colder ocean water would tend to produce relatively **[(high)(low)]** sea-surface temperatures compared to regions not affected by the upwelling. Warmer air moving over this ocean surface would be **[(chilled)(heated)]** from below.
8. Chilling of air by a relatively cold ocean surface would likely **[(enhance)(inhibit)]** development of clouds, showers, and thunderstorms. Also sea fog **[(would likely)(would be unlikely to)]** form.
9. When wind transports near-surface water towards a coast, the warm surface layer thickens and water is forced downward. 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, prevailing surface winds blow from north to south in the summer and from south to north in the winter. The season of warm water movement towards the coast and downwelling for this region is **[(summer)(winter)]**. The season for cold-water upwelling and frequent fog is **[(summer)(winter)]**.
11. Rotate the underlay to a position showing the wind blowing from north to south in the Northern Hemisphere. Along the land's eastern coast, this combination will produce **[(upwelling)(downwelling)]** and relatively **[(cool)(warm)]** surface waters. This surface temperature pattern would tend to **[(enhance)(suppress)]** cloud formation.
12. In view of the latent heat requirements of tropical storms and hurricanes, those weather systems are not likely to develop over a(n) **[(upwelling)(downwelling)]** zone. A hurricane that moves over an upwelling area of a tropical ocean is likely to **[(intensify)(weaken)]**.



Cut along dotted lines



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.

Real World Applications

The U.S. West Coast shows the effects of these wind and water interactions and their influences on the coast areas. **Figure 1** is the comparison of the annual average air pressure patterns off the U.S. West Coast. Note that, although there is north-south movement of the center of highest pressure seasonally, the clockwise and outward atmospheric flow about the center of a High means that there would generally be a fairly steady wind directed toward the southeast the majority of the year.

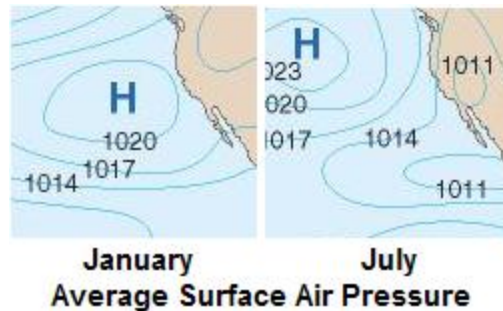


Figure 1. Atmospheric pressure patterns off the U.S. West Coast. (Adapted from *AMS Weather Studies*.)

Figure 2 is a composite of three California regional weather maps for the twenty-four hour period from 00Z 11 October to 00Z 12 October 2011. The maps show the persistent wind flow toward the southeast along the California coast over that period.

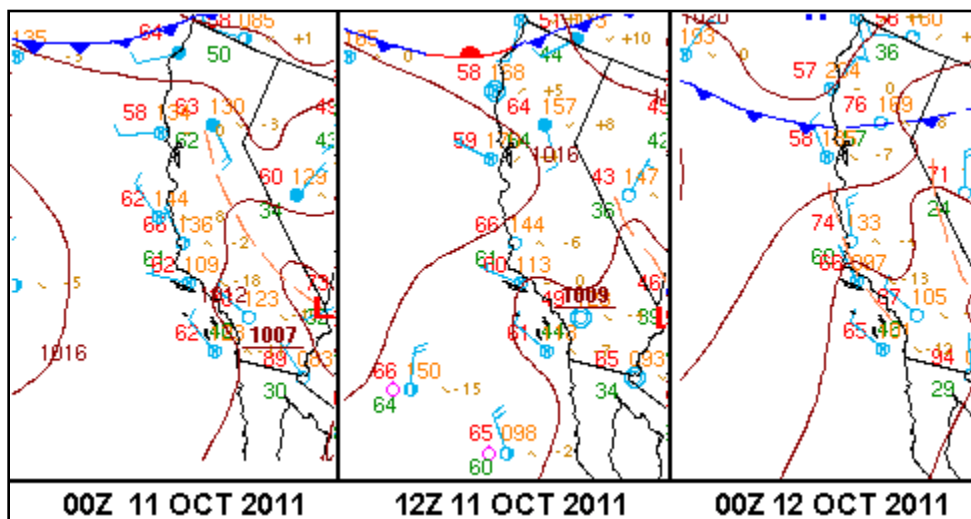


Figure 2. California regional weather maps for the twenty-four hour period of 11 October 2011. [HPC – NCEP, NOAA]

1. The coastal wind directions seen in the Figure 2 map segments **[(are)(are not)]** consistent with the southerly flow to the east side of the persistent High seen in Figure 1.

Set your Model Ocean Basin device to the combination of the **Northern Hemisphere** position with a wind directed toward the **south**. Consider the water movements in the ocean in relation to the “Western Coast”.

2. This Model Ocean Basin configuration **[(is)(is not)]** the same as the California weather map configuration seen in Figure 2.
3. The Model Ocean Basin device indicates that the Near-surface flow of water along the California coastal region would be directed **[(onshore)(offshore)]**.
4. The Model Ocean Basin device also indicates that the flow of colder, deeper water would be **[(upwards)(downwards)]**.
5. This condition would be a case of **[(upwelling)(downwelling)]**.
6. With this vertical movement of the deeper water, surface water temperatures in the region affected would be relatively **[(lower)(higher)]** than surrounding temperatures.

Figure 3 is a composite of MODIS satellite views on 12 October 2011 showing the California region in visible conditions where clouds are to the west and north in the left image. The center image displays ocean “color”, a measure of chlorophyll concentration in surface waters. Higher biological productivity produces more chlorophyll as shown by the yellow and red shadings. The image on the right shows sea surface temperatures as shades of green. Black is where the clouds caused missing data. Darker shades of green are warmer temperatures. Blues and light greens represent cooler temperatures.

7. The color shadings of sea surface temperatures along the Southern California coast **[(are)(are not)]** consistent with your answer to Question 6.
8. The associated existence of upwelling in coastal waters **[(would)(would not)]** bring nutrients to surface layers to enhance biological productivity.
9. The likelihood of upwelling and increased biological productivity in the Southern California coastal waters **[(is)(is not)]** consistent with the center image in Figure 3 of chlorophyll concentrations.

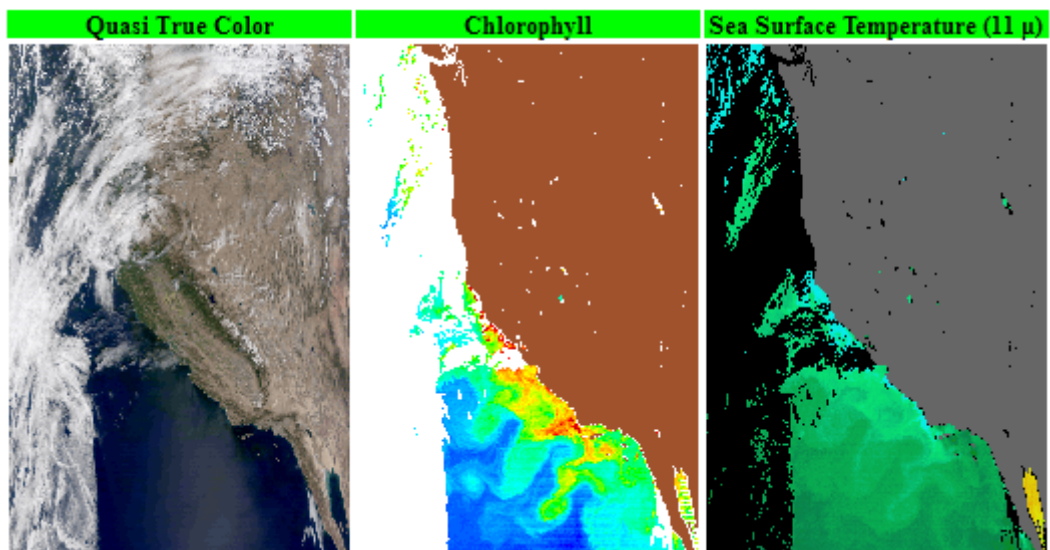


Figure 3. MODIS images of visible, chlorophyll, and sea surface temperature from left to right, respectively, on 12 October 2011. [SeaWiFS]

Information Sources

Books

Moran, Joseph M. Weather Studies: Introduction to Atmospheric Science, 5th Ed. Boston, MA: American Meteorological Society, 2012.

Periodicals

Weatherwise. Bimonthly magazine written in association with the American Meteorological Society for the layperson. Weatherwise, 1319 Eighteenth St., NW, Washington, DC 20036.

USA Today. National newspaper with extensive weather page. Available at local newsstands and by subscription.

Radio and Television

NOAA Weather Radio. The voice of the National Weather Service and All Hazards Emergency Alert System. Local continuous broadcasts from over 1000 transmitting stations nationwide.

The Weather Channel. A continuous cable television program devoted to reporting weather. Includes frequent broadcast of local official National Weather Service forecasts.

Internet

DataStreme Atmosphere (www.ametsoc.org/amsedu/dstreme/). Atmospheric education distance-learning website of the AMS Education Program.

JetStream – Online School for Weather (www.srh.noaa.gov/jetstream/). Background weather information site from the National Weather Service.