Patterns of

Ocean Energy Balance

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Gulf Stream, in yellow and orange, revealed through Sea Surface Temperature data (SST)

Lesson Objectives:

• To understand the need for measurement protocols and ways to compute statistical measures of data.

• To use the human body as a model to understand energy balance in the Earth system.

• To demonstrate an understanding of patterns of the diurnal heating and cooling cycle of the atmosphere.

• To investigate fluctuations of solar energy received on Earth.

• To understand important patterns of sea surface temperatures and ocean surface currents.

Glossary: conduction, convection, global warming, mean, median, sea surface temperature

Introduction: Energy Flow in the Earth System

Reflected Solar Radiation (W/m²) 0 — 700

Emitted Heat Radiation (W/m²) 85 — 350
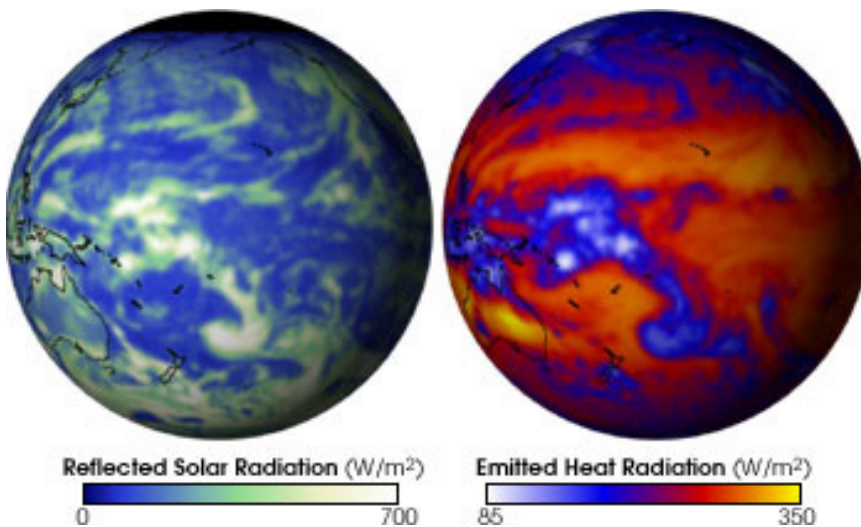
Scientists are concerned about global warming due to changes in the flows of energy through the Earth system. The ocean plays an important role in determining and moderating the effects of an energy imbalance. The physical properties, large-scale movements and global distribution of the ocean make it a key indicator of changes in Earth's temperature and energy balance. The ocean is not a passive thermometer. Instead it manages and distributes stored solar energy to all regions of the planet. It is essential that scientists look for evidence of stability, change and variability not only in ocean surface temperatures but also in the major currents that redistribute the energy.

The top 3-5 meters of ocean surface water has the same heat capacity as the entire atmosphere above it. It takes 3.7 times as much energy to heat one kilogram of seawater by one degree Celsius than to heat one kilogram of air by the same amount. In addition, one kilogram of air (at standard temperature and pressure) occupies 795 times more volume than 1 kilogram of seawater. So a given amount of heat energy will raise the temperature of 2,940 cubic meters of air and one cubic meter of seawater by the same amount. Because the ocean surface is always in contact with the atmosphere, the ocean surface can act as a very effective heat storage medium for the atmosphere. *Small changes in ocean surface temperature can indicate large exchanges of energy with the atmosphere.*

Learn how scientists measure heat energy on the surface of Earth and how ocean surface currents transport heat energy when you interact with satellite data visualizers in the following investigation.

Data Image and description: http://www.nasa.gov/vision/earth/environment/earth_energy.html

What do you know?

Before beginning this lesson is it helpful to learn how much you already know about the patterns of energy flow in the ocean. A simple survey has been created for you to assess your prior knowledge.

1. Click on the blue **Quiz** button below.
2. Take the quiz
3. Submit your responses online and they will be automatically scored.
4. Return to this guide and begin your exploration of ocean warming.

Quiz

Gathering and Manipulating Data
Basic Data Gathering and Processing

When studying the ocean, scientists use automated instruments such as buoys and satellites to collect data. These measuring tools are very accurate and stable, but they also can be as prone to error and uncertainty as the thermometer you hang outside your window.

Scientists realize they can never make perfect measurements. Instead they try to be as accurate as possible within the limitations of their measuring instruments and their protocols (i.e., the set of procedures scientists follow for every measurement). They consider a measurement that is close to the true value an accurate measurement. Random uncertainties can cause these measurements either to be too high or too low. Such uncertainties must not be systematic. In other words, the measurements should not be consistently higher or lower than the true values. Scientists therefore must constantly reevaluate the uncertainties that affect their measurements and the conditions under which the measurements are made. Following measurement protocols insures as much accuracy and reproducibility as possible.

1. Students may form teams (or work individually) and use a thermometer to measure the temperature of water in a cup or deep bowl. Each student (or team of students) should record their name(s), the temperatures they measure and any comments they may have about their measurements (scientists call these comments *metadata*) on a board or poster for all to see. Copy the results of the measurements along with any student comments in the table below:

| Name	Temperature Value	Comments/Metadata

2. Compare the measurements of the water temperature. Are all the measurements the same or nearly the same?
3. List some of the factors that might cause the temperature measurements to differ?

4. Create a protocol (or procedure) to measure the temperature of water in a nearby pond, lake or ocean. The protocol should have enough detail so that any student following the protocol will measure the same (or very nearly the same) value.


Joyful Data Graphing and Finding the Mean

Assume that 15 water temperatures were collected with a calibrated thermometer. Each of the following five processing steps may help to better understand characteristics of the data collected.

Graph the Data: The temperature data points make a pattern that seems to be level – not slanted up or down. If the points showed a systematic trend rising or falling from left to right, it would suggest that the "true" value being measured was systematically changing during the measurements. In this case, the measurement protocol should be re-examined and revised.
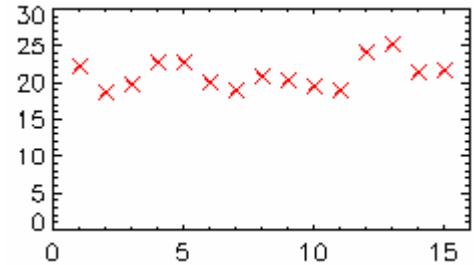
Expand the Graph Scale: To see the variations in the data more clearly, expand (magnify) the data scale. The data points look different but correspond to the same values.
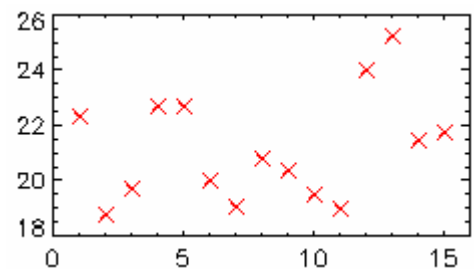
Compute the Mean: Add all temperature measurements and divide by the number of points (15) to compute the mean value of the data. The red line in the figure shows the mean value. Its value is just above 21°. The mean value line does not exactly intersect any of the temperature data points but it lies in the middle of the data points (7 above the line, 8 below).
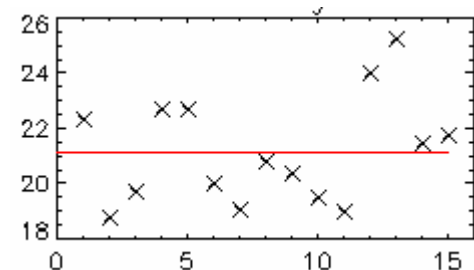
Compute the Differences from the Mean: Compute the difference between each data point and the mean value. This will be used to estimate the variation in this set of measurements.
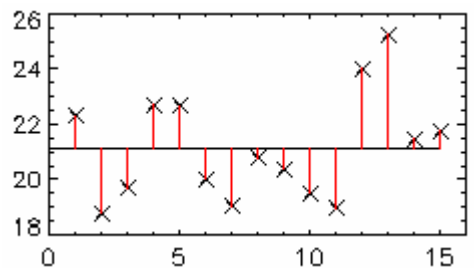
Compute the Standard Deviation: Use all the differences to compute the standard deviation (σ) of the data set. The red lines show the limits of the [mean + σ] and [mean – σ]. Note that 10 data points lie between these limits and 5 lie outside:
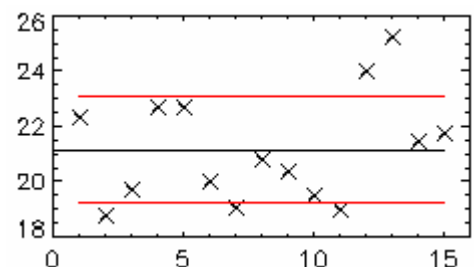
Within limits: 10/15 = 2/3 = 67% of the data set
Outside limits: 5/15 = 1/3 = 33% of the data set

The method for calculating the standard deviation is discussed on the next page.

Standard Deviation For The Courageous
Level 2, More Challenging

Here is an exercise where you will practice calculating the mean and standard deviation of data values. Imagine that you have measured the following temperatures 27.4°C, 26.5°C, 28.1°C, 27.6°C, 26.9°C and you wish to compute the mean and standard deviation of your data. Organize the data into a table (Column A) and perform calculations as discussed in the steps below. Follow the flow and method of this example and then you will practice the calculations yourself:

	Column A **Data**	**Column B** **Difference**	**Column C** **Squared Difference**
	X_I	X_I-X_M	$(X_I$-$X_M)^2$
1	27.4	(27.4-27.3)=0.1	$(0.1)^2$=0.01
2	26.5	(26.5-27.3)=-0.8	$(-0.8)^2$=0.64
3	28.1	(28.1-27.3)=0.8	$(0.8)^2$=0.64
4	27.6	(27.6-27.3)=0.3	$(0.3)^2$=0.09
5	26.9	(26.9-27.3)=-0.4	$(-0.4)^2$=0.16
SUM	Sum of Data $\sum_{I=1}^{5} X_I = 136.5$		Sum of Squares $\sum_{I=1}^{5}(X_I - X_M)^2 = 1.54$
MSD	Mean Value $X_M = \dfrac{\sum_{I=1}^{5} X_I}{N} = \dfrac{136.5}{5} = 27.3$		Standard Deviation $\sigma = \sqrt{\dfrac{\sum_{I=1}^{5}(X_I - X_M)^2}{N-1}} = \sqrt{\dfrac{1.54}{4}} = 0.62$

• List the data as in Column A

• Add all the data values and record the sum in the SUM row of Column A.

$$\sum_{I=1}^{5} X_I = 27.4 + 26.5 + 28.1 + 27.6 + 26.9 = 136.5$$

• Compute the mean by dividing the sum (from Step 2) by the number of measurements (N=5). Record this result in the MSD (**M**ean and **S**tandard **D**eviation) row of Column A.

• Subtract the mean value (Step 3) from each data value as shown in Column B.

• Compute the square of each difference value from Column B and record it in Column C.

• Add all the squared differences from Column C (Step 5) and record the sum in the SUM row of Column C.

$$\sum_{I=1}^{5}(X_I - X_M)^2 = 0.01 + 0.64 + 0.64 + 0.09 + 0.16 = 1.54$$

• Compute the standard deviation by taking the square root of the sum of the squared differences (Step 6) divided by one less that the number of measurements (N-1 = 5-1 = 4). Record this result in the MSD row of Column C.

The mean and the standard deviation are related in a very important way. For a given data set, *the mean is the single value that minimizes the standard deviation of the data.* Choosing any value other than the mean for calculating the standard deviation yields a larger standard deviation. If, for example, you replace the mean value 27.3 with 28.0 everywhere in the above calculation, you will find that the standard deviation increases. In this sense, choosing the mean value as the best value to represent a dataset is justified by the fact that *it deviates (differs) least from the other numbers in the dataset*.

5. Your Turn: The following is a new dataset. Practice the calculation of mean and standard deviation values:

	Column A Data	Column B Difference	Column C Squared Difference
	X_I	$X_I - X_M$	$(X_I - X_M)^2$
1	4.73		
2	4.65		
3	4.82		
4	4.70		
5	4.69		
6	4.83		
7	4.77		
SUM	Sum of Data $\sum_{I=1}^{5} X_I = $ _____		Sum of Squares $\sum_{I=1}^{5} (X_I - X_M)^2 = $ _____
MSD	Mean Value $X_M = \dfrac{\sum_{I=1}^{7} X_I}{N} = $ _____		Standard Deviation $\sigma = \sqrt{\dfrac{\sum_{I=1}^{7} (X_I - X_M)^2}{N-1}} = $ _____

The sun rises over Europe and Northern Africa.

By The Living Earth http://www.fourmilab.ch/ear thview/

Energy In = Energy Out

How can a model of the human body be used to better understand energy in the Earth system?

What comes down must go back up!
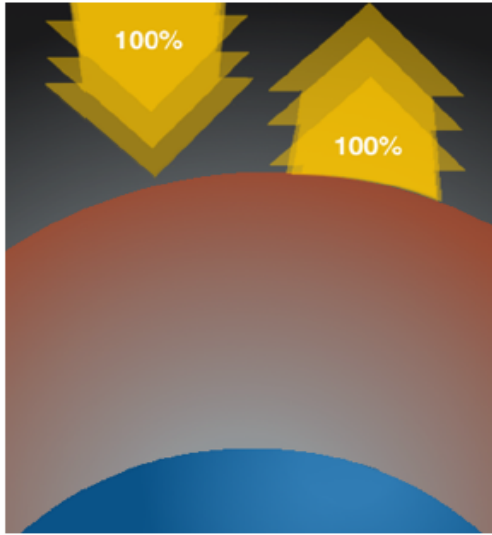
Energy absorbed by Earth = energy emitted by Earth

Energy balance is a familiar topic to most people because it relates directly to their health. Your body maintains an energy balance:

Energy In = Energy Out + Energy Stored

The above formula illustrates energy conservation—all the energy has to "go" somewhere. It cannot just disappear. Humans eat food that provides energy for biochemical processes necessary for life and for heat that the body sheds through various processes (radiation, conduction, convection and evaporation). The unit of energy found on food package labels is the Calorie (1 Calorie = 1000 calories = 4186 Joules). The body regulates blood flow to increase or decrease body heat. If too many calories are consumed, the body stores the excess energy as fat.

6. In the chart below, complete the following analogies that compare the energy balance of the body to that of the Earth.

| Energy	Human Body	Atmosphere/Ocean
Primary energy source	Food	
Ways the energy is expended	Exercise, work, internal body functions	
Ways the energy is stored	Fat accumulation, chemical energy	
Ways to transfer energy	Evaporation (sweat), conduction, convection (blood circulation)(hmm. The blood is pumped through the body, carrying heat), radiation	

Air Temperature Investigations
What do data reveal about daily energy cycles in the Earth system?

To investigate energy cycles, begin by examining air temperature data collected in Washington, DC on July 4–5, 2005 – a calm, clear summer day in the nation's capital. On July 3, the Earth is farthest from the sun— 94,500,000 miles (in the first week of January, Earth is closest—91,400,00 miles). Many of the details that you will learn about this daily energy cycle will apply to the yearly cycle of ocean surface temperatures as well. The daily cycle occurs because Earth rotates once on its axis every 24 hours. The yearly seasonal cycle occurs because the Earth's axis is tilted 23° relative to the plane of its orbit. As Earth orbits the Sun, this tilt remains constant, so the United States experiences winter when the Northern Hemisphere tilts away from the Sun and summer when it tilts towards the Sun.

Sun rise over North America.
http://www.fourmilab.ch/earthview/

The graph below represents outside air temperatures for July 4–5, 2005 in Washington, D.C. For this investigation, we have selected a calm, clear day with no precipitation or significant movement of air masses. Examine the graph and answer the following three questions.
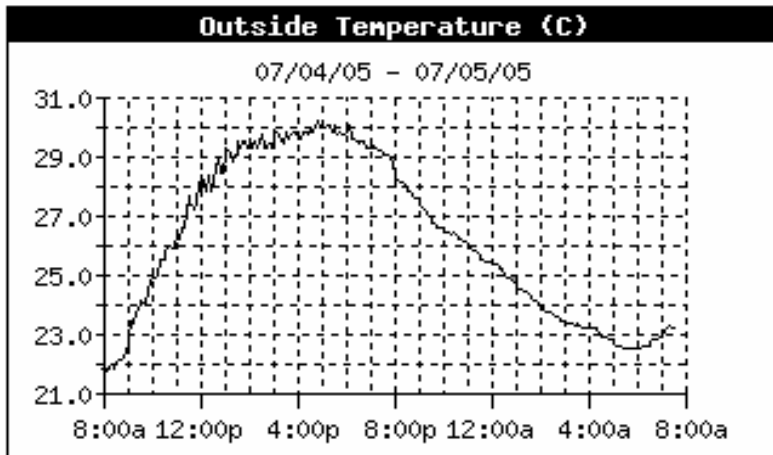
7. Determine the maximum temperature and the time and date it occurred.

Max Temp:
Time:
Date:

8. Determine the minimum temperature and the time and date it occurred.

Min Temp:
Time:
Date:

9. What is the temperature range shown in the graph?

During the entire 24-hour interval, the Kelvin (absolute) air temperature was *relatively* constant:

30.2°C (max temp) = 30.2 + 273.15 = 303.35°K

21.9°C (min temp) = 21.9 + 273.15 = 295.05°K.

Measured on this scale, the Kelvin temperature of the air changed by less than 3% over 24 hours:

$$\frac{303.35 - 295.05}{295.05} \times 100\% = 2.8\%$$

The energy radiated by a substance or object depends directly on its Kelvin temperature. Objects with a higher temperature radiate more. Assuming that the nearby ground surfaces have temperatures similar to the air temperatures, it can be concluded that during the 24-hour period, the electromagnetic energy radiated around the site of this Washington, D.C. weather station site was fairly constant.

The following graph shows the intensity of solar radiation measured in Watts per square meter received at the Washington, D.C., weather station. A Watt is a unit of power that measures energy used or generated per second: 1 Watt = 1 Joule/1 second = (1/746) horsepower. A typical light bulb in the home is rated at 75 Watts. As shown by the graph, solar intensity varies significantly throughout the day. The intensity reaches its peak near noon and is zero between 8:30 pm and 6 am when Washington, D.C., is not receiving direct light from the Sun).
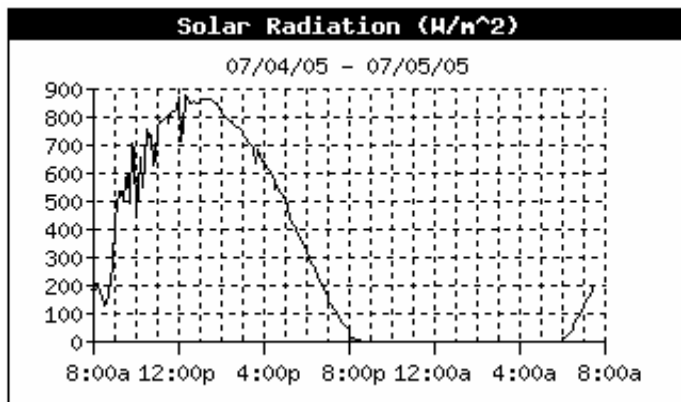
10. Compare the two graphs Outside Temperature, (page 8), and Solar Radiation, (page 9). Describe what happened to the air temperature and solar radiation during the afternoon and early evening between 2 pm and 8 pm.

11. Why was the solar radiation zero between 8:30 pm and 6 am? Examine the Outside Temperature data and describe what happened to the air temperature during this time interval.

Why Is There a Time Delay? Based on the graphs, there is a delay in the temperature response to the Sun's energy. Air temperatures continue to rise and remain steady for hours after the solar radiation reaches its peak. *Why?*

To investigate this question, you will use a simple daily energy balance model that receives incoming energy that peaks around Noon and that emits energy at a steady rate (the same amount of energy is lost during each hour). The following table lists information about the model:

• Column A: Time of day (starting at 1 AM)
• Column B: Incoming (incident solar) Energy (IE) is zero at night and peaks near Noon.
• Column C: Emitted (radiated infrared) Energy (EE). This remains constant at all hours, reflecting the relatively constant temperature of the environment.
• Column D: Total (thermal) Energy (TE). The total energy is the amount of thermal energy that accumulates throughout the day. Incoming Energy makes it higher. Emitted Energy makes it lower.

The model starts with 9 units of energy (Total Energy in Column D) in the air and environment at 1 am. Between 1 AM and 2 AM, no incoming energy is added; however 1 unit is emitted, leaving 8 units of energy:
TE (2 AM) = TE (1 AM) + IE (1 AM) − EE (1 AM) = __8__

Fill in the remaining TE values using this same iterative method of calculation:
12. TE (3 AM) = TE (2 AM) + IE (2 AM) − EE (2 AM

Daily Energy Balance Model			Column B Incoming Energy (IE)	Column C Emitted Energy (EE)	Column D Total Energy (TE)
Column A Time of Day			**Column B Incoming Energy (IE)**	**Column C Emitted Energy (EE)**	**Column D Total Energy (TE)**
AM	1		0	1	9
	2		0	1	8
	3		0	1	
	4		0	1	
	5		0	1	
	6		0	1	
	7		1	1	
	8		1	1	
	9		2	1	
	10		3	1	
	11		3	1	
Noon			4	1	
PM	1		3	1	
	2		3	1	
	3		2	1	
	4		1	1	
	5		1	1	
	6		0	1	
	7		0	1	
	8		0	1	
	9		0	1	
	10		0	1	
	11		0	1	
Midnight			0	1	

By 1 AM, total energy (TE) will be back to 9 units and the same energy cycle will repeat for this ideal, balanced case. For any one location and date on Earth, the energy flows do not have to always be in balance. Balance applies to the entire Earth over an extended period of

time. In our example, if the incoming energy (IE) increases significantly, then Earth's surface temperatures will rise and the emitted energy (EE) will increase. The amount of emitted energy will naturally adjust to compensate for increases (or decreases) in incident energy.

13. Look at the energy values in the table above. When does *incoming energy* (column B) reach its minimum, its maximum? Does the emitted energy (column C) show a maximum or minimum value? When does *total energy* (column D) reach its minimum and its maximum?

| Daily Energy Balance	Time	
	Minimum Energy	Maximum Energy
Incoming Energy (IE)		
Total Emitted Energy (TE)		

14. Compare this model to the Washington DC data of July 4, 2005. How is the behavior shown by this model similar to, or different from, the air temperature situation?
• Incoming Energy compared to the Solar Radiation
• Total Energy compared to Outside Temperature

Air temperature continues to rise as long as the incoming energy (IE) exceeds emitted energy (EE).

The Annual Energy Cycle
How does solar energy received by Earth change throughout the course of a year?

JUL 4   Solar Declination: 22

Daily Energy Intensity (10^7 J/m²)
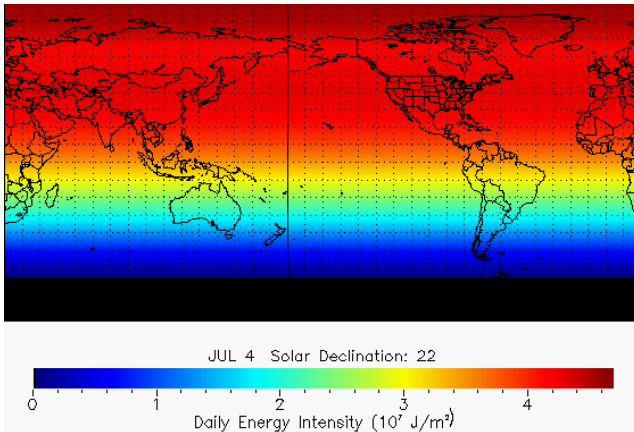
Extend your study of the yearly solar energy cycle with an online solar energy animation. As you cycle through a year, changes in incident above-the-atmosphere solar daily energy intensity (Joules/day/meter^2) are shown as color changes on a world map. Typically 30% of this energy is reflected and 70% is absorbed. Overall, ½% of this incident energy drives atmosphere and ocean circulation – winds and ocean currents.

The image on the left shows the daily incident solar energy intensity on July 4. The highest values of energy intensity (dark red) are in the arctic region due in part to the 24 hour day above the Arctic Circle while the Earth's Northern Hemisphere is tilted towards the Sun. Because of cloud and ice cover, a high fraction of this energy will be reflected back to space and will not heat the surface of the Earth. On this date, the South Pole region experiences 24-hour darkness and is shown in black.

Make a Prediction: Before you view the solar energy animation, guess in which month the solar intensity will be greatest and in which month it will be the least for your hometown.

15. In what town and state do you live?

16. During which month do you think solar intensity is greatest at your home?

17. During which month do you think solar intensity is least at your home?

Click the Solar Energy Animation link. (Note: Because of the file size, give the web page time to download its images.) Manipulate the computer model until you feel comfortable with it. Then return to page 12 for further instructions.

18. Use the computer model to determine the daily energy values for your home and for the Equator at the beginning of each month. Use the drop-down menu to select the months January through December. Look at the color changes on the map and use the legend below the map to determine energy values.

Location	Jan 1	Feb 1	Mar 1	Apr 1	May 1	Jun 1	Jul 1	Aug 1	Sep 1	Oct 1	Nov 1	Dec 1
Your Home												
Equator												

Use the values you recorded in the table to answer the following three questions:

19. In which month was *solar intensity the greatest* in the following locations?

Your home?

Equator?

20. In which month was *solar intensity the lowest* in the following locations?

Your home?

Equator?

21. How accurate were your earlier predictions of times of the year when solar intensity is highest and lowest at your home?

Sea Surface Temperatures

How does solar radiation affect sea surface temperatures?

Examine sea surface environment data that are superimposed on a map and incorporated into a computer model that can be manipulated. Click the Sea Surface Environment visualizer.
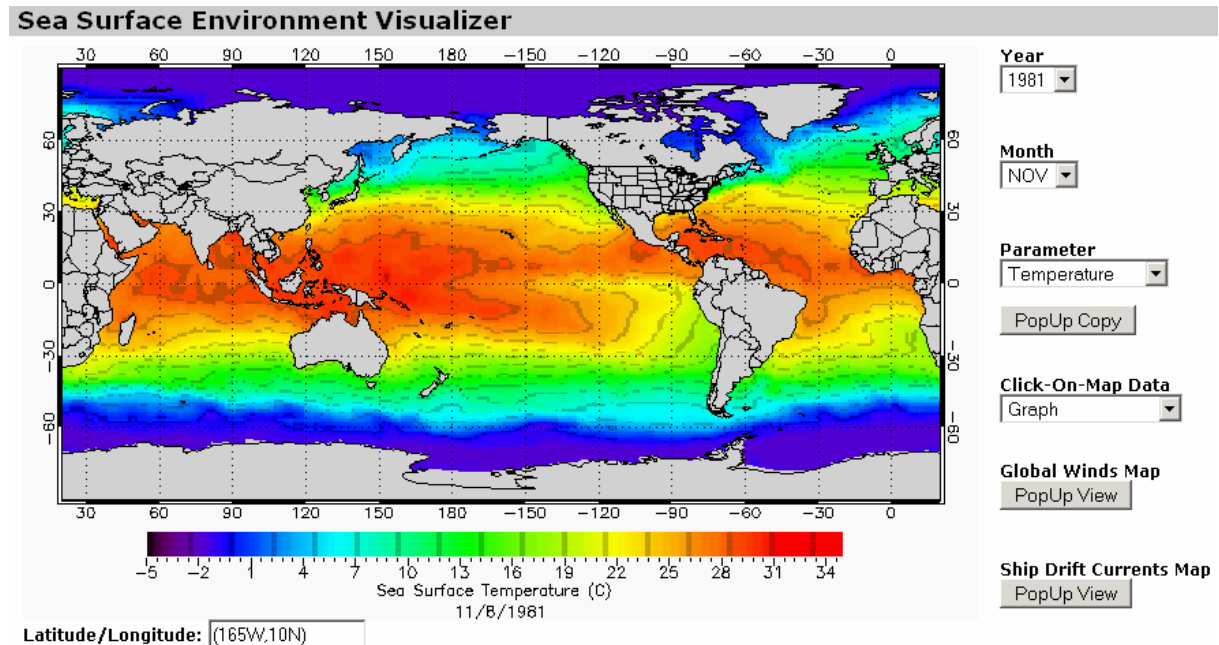*Set the visualizer controls to,*
Year: **1981**
*Month:* **November**
Parameter: **Temperature.**

Observe the map generated and answer the following questions.

22. Describe information provided by the colored image. What does the image depict? What do the colors represent? What do the numbers along the sides of the image represent?

23. What patterns do you see in the November 1981 Sea Surface Temperature data (SST)?

24. Where are the water surface temperatures coldest?

25. Where are the water surface temperatures warmest?

26. Do you see regions where cool surface water moves into latitudes where warm surface water dominates?

27. Do you see regions where warm surface water moves into latitudes where cool surface water dominates?

Next, return to Sea Surface Environment data visualizer.

• The Click-On-Map Data selector determines the type of data displayed when you click on any 5° x 5° ocean site on the map. You can select a graph or a table of median parameter data for each site and each available year.
• Set the Click-On-Map Data option to **Graph** and click an ocean region near the Equator. A time series graph will appear showing you how the sea surface temperature at that site varied over the years. For example:
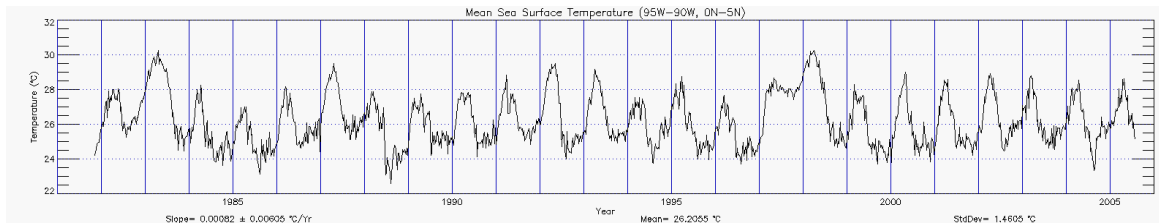

The graph above shows sea surface temperatures at a selected site near the Galapagos Islands. Before interpreting any graph, including this one, make certain that you understand what the x- and y-axes represent. Answering the following questions correctly is critical to reading this graph accurately.

28. What is measured on the x-axis?

29. What does each vertical line (blue) on the graph represent?

30. What is the range of the entire graph?

31. What does each horizontal dot on the graph represent?
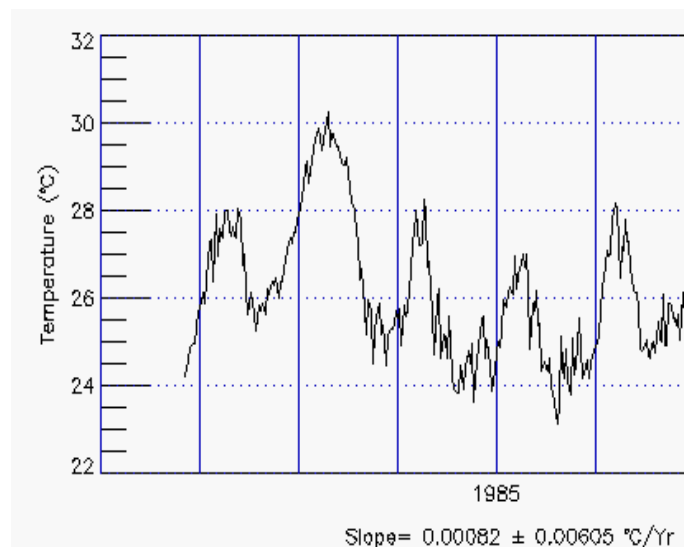
32. What is the month and year that data were first shown on this graph?

33. What is measured on the y-axis?

34. What does each graduation on the y-axis represent?

Ocean Motion Student Guide   **Lesson 5**   14

35. The graph shows data that vary considerably from year to year. Complete the following chart by identifying three years when sea surface temperature was highest and three years when it was lowest.

Mean Sea Surface Data (95W – 90W, 0N – 5N)						
	Highest Temperatures			Lowest Temperatures		
Year						
Month						
Temp °C						

36. If during a certain year, many widespread sites experience the same unusually high or low temperatures, there is good reason to look for the cause of such behavior. To study the effects on other types of data and to see how the unusual temperatures affected the weather of the region, *complete an analysis of one more site off the east coast of North America.*

Mean Sea Surface Data						
	Highest Temperatures			Lowest Temperatures		
Year						
Month						
Temp °C						

To develop a measure of how unusual, or normal, a data value may be, one needs some measure of both. To quantify data values as normal or unusual, people often compute two measures from their data:
• Mean—a weighted or unweighted average of data values
• Standard deviation—measures the scatter of data values with respect to the mean value
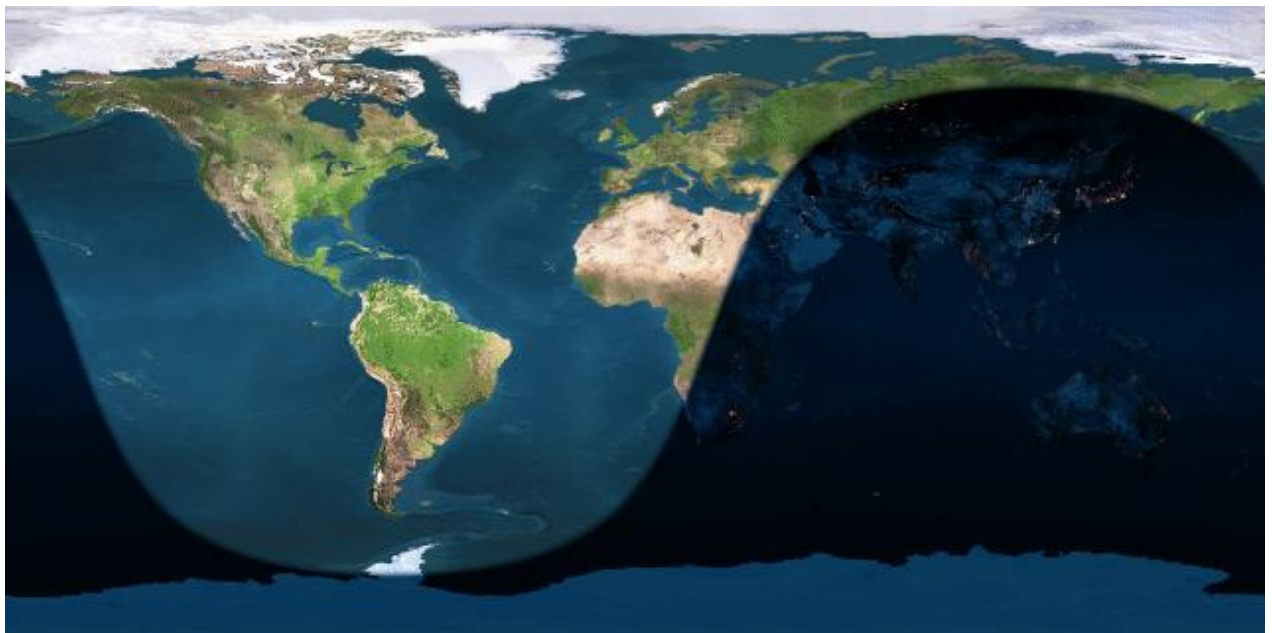
Earth Image from The Living Earth
http://www.fourmilab.ch/earthview/
2006 May 21 16:34 UTC

Temperatures Travel the Pathways Of The Sea

When you examined the sea surface temperature map earlier, you were asked to identify regions where cool water intruded into regions of normally warm water, and where warm water intruded in regions of normally cool water. One of the regions where cool water intrudes into a region of warm water is in the Eastern Pacific near the west coast of South America. The reason for this intrusion is the flow of surface currents. Shown below is an Ocean Surface Currents data computer model that uses OSCAR data showing ocean surface currents around October 15, 1992. The gray area on the right of the map shows part of the west coast of South America. The white area along the coast of South America has no data. The arrows show the direction of the currents and the current speed in meters per second.
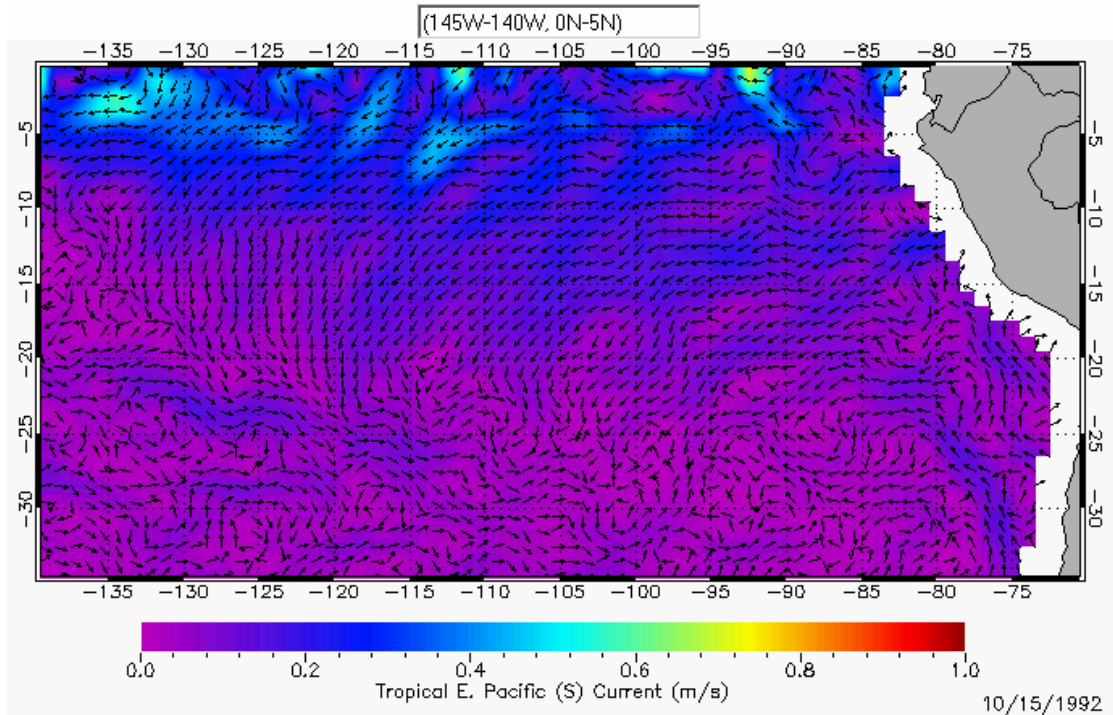
37. What speed do the following colors represent?

Magenta -
Darker blue -
Lighter blue -

38. In what direction do the surface currents just south of the Equator appear to travel?
.

39. Note in the southeast corner of the map a strong (blue) current flows along the coast of South America. What is the direction of this current?

The current moving up the western coast of South America is mostly westward flowing filaments of cold water. It is a surface current that includes Ekman transport. The westward-moving current along the Equator is called the Pacific South Equatorial current. These currents are very important for understanding the dynamics of El Niño.

The currents you've seen in the tropical Pacific provide an example of currents that circulate and mix warm and cool waters. This circulation helps moderate global temperatures.

The ocean influences the climate in a myriad of ways. Seemingly subtle changes in ocean currents, temperatures and salinity can impact winds and weather patterns throughout the world. Even the distribution and abundance of marine organisms can affect climate. Likewise, changes in air temperatures, winds, and precipitation affects the dynamics of the ocean. Climate cycles and anomalies such as El Niño and the North Atlantic Oscillation all involve the complex interplay between ocean and atmosphere. And now scientists are scrambling to learn how the warming of the atmosphere due to the increase of greenhouses gases will alter this dynamic.

Additional Investigations for Energy Balance in the Earth System

Search for weather and climate variations through use of the Sea Surface Environment Visualizer - http://www.oceanmotion.org/html/resources/ssedv.htm and the OSCAR Visualizer - http://www.oceanmotion.org/html/resources/oscar.htm

Research your theories about climate and weather by reading the articles in the Impact section of the Ocean Motion web site, listed below or by searching the World Wide Web.

El Niño
http://www.oceanmotion.org/html/impact/el-nino.htm

Global Warming and Atlantic Currents
http://www.oceanmotion.org/html/impact/globalwarming.htm

Global Warming Weakens Winds
http://www.oceanmotion.org/html/impact/weakwinds.htm

Satellites Record Weakening North Atlantic Current
http://www.oceanmotion.org/html/impact/climate-variability.htm

Matrix for Grading Lesson 5

4 Expert	Responses show accurate identification of graphs used to explain manipulation of sample data. Shows solid understanding of the model of the human body to explain energy balance in Earth system. Proficient interpolation of graphs to show diurnal heating and cooling cycle of the atmosphere. Proficient manipulation of computer model to read near real-time satellite data, and analysis of data is complete and accurate.
3 Proficient	Responses show accurate understanding of models and analogies used to explain scientific concepts and processes used in the lesson. Shows good understanding of the model of the human body to explain energy balance in Earth system. Mostly proficient interpolation of graphs to show diurnal heating and cooling cycle of the atmosphere. Mostly proficient manipulation of computer model to read near real-time satellite data and analysis of data are mostly complete and accurate.
2 Emergent	Responses show partial understanding of models and analogies used to explain scientific concepts and processes used in the lesson. Shows some understanding of the model of the human body to explain energy balance in Earth system. Mostly proficient interpolation of graphs to show diurnal heating and cooling cycle of the atmosphere. Somewhat proficient manipulation of computer model to read near real-time satellite data and analysis of data are partially complete and accurate.
1 Novice	Responses show very limited understanding of models and analogies used to explain scientific concepts and processes used in the lesson. Shows limited understanding of model of the human body to explain energy balance in Earth system. Mostly proficient interpolation of graphs to show diurnal heating and cooling cycle of the atmosphere. Limited or no ability to manipulate computer model to read near real-time satellite data and analysis of data are not complete.