introduction

The *National Science Education Standards* developed under the auspices of the National Research Council specifies "Science as Inquiry" as major content standard for all grade levels. The activities that students engage in during grades 9–12 and in undergraduate science courses should develop the students' understanding of and ability to do scientific inquiry. An understanding of the nature of scientific inquiry involves awareness of why scientists conduct investigations, the roles technology and mathematics play in scientific design and analysis, the criteria used to judge data and models, and the impact that communication has on the development of scientific ideas. Among the abilities identified as necessary to do scientific inquiry are

- identification of concepts and questions that guide scientific investigations;
- use of technology and mathematics to improve inquiries and communication skills
- formulation and revision of scientific explanations and models based on logic and evidence.

One of the recommendations of the National Science Foundation Report, *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology,* is that faculty "build into every course inquiry, processes of science...a knowledge of what [science, mathematics, engineering, and technology] practitioners do, and the excitement of cutting-edge research."

Both the National Council of Teachers of Mathematics in their publication, *Curriculum and Evaluation Standards for School Mathematics,* and the American Mathematical Association of Two Year Colleges in *Crossroads in Mathematics: Standards for Introductory College Mathematics Before Calculus* espouse the use of real-world examples and technology to teach and reinforce mathematical concepts.

To address the standards in both science and mathematics, the materials in this module were designed to use image processing technology to enhance a student's understanding of scientific inquiry using a well-publicized subject, the characteristics and dynamics of global land vegetation. The exercises employ "hands-on" data processing in the form of image generation and analysis to give students the opportunity to work with data as research scientists do. The electronic textbook provides the most current scientific thought with supporting data. Additional materials such as an introduction to basic image processing concepts, background on the ozone satellite and sensor, and format information for the data sets have been made available to address ancillary questions that may arise.

references

Crossroads in Mathematics: Standards for Introductory College Mathematics Before Calculus. American Mathematical Association of Two Year Colleges, 1995. http://www.richland.cc.il.us/imacc/standards/

Curriculum and Evaluation Standards for School Mathematics. National Council of Teachers of Mathematics. 1989. http://www.wnc.org/reform/journals/ENC2280/280dtoc1.htm

National Science Education Standards. National Research Council, National Academy Press, 1996. http://www.nap.edu/readingroom/books/nses/html/

Shaping the Future: New Expectations for Undergraduate Education in Science Mathematics, Engineering, and Technology. National Science Foundation, Directorate for Education and Human Resources, 1996 (NSF 96-139). http://www.ehr.nsf.gov/EHR/DUE/documents/review/96139/start.htm

exercises

Each exercise for the Oceanography Module was designed to illustrate concepts connected with issues in current global change research involving these atmosphere and ocean interactions. They are presented as guided inquiry activities. Working through an activity, students are asked to perform selected image processing steps using specified data sets. Questions associated with each operation direct attention to the concept being elicited or probe for a student's understanding of the tools being employed.

This instructor's guide provides the following for each exercise.

Learning objectives that specify the concepts and operations students are expected to investigate
Science process skills, those broadly transferable abilities used in scientific disciplines that students must employ to complete the exercise. A description can be found at http://www.science.cc.uwf.edu/narst/research/skill.htm
National Science Education Content Standards for grades 9–12 embodied in the exercise
Image processing skills or operations in *SEE Image* that students use to interpret the data sets
Mathematical tools that are required in the data processing or analysis
Resource materials where information to complete or enhance each exercise can be located
Answers to exercises with selected images.

We provided specific data files for your students to use with these exercises so we could give you, the instructor, an unambiguous answer key. Once your students are comfortable with the concepts and master the software, encourage them to explore the entire SST data set more fully. After all, they have almost 20 years of monthly mean SST

images right here on CD

Desktop | SEES CD | data |sst_entire

or on our Web site at

http://see.gsfc.nasa.gov/edu/SEES/

Have them complete the same exercises choosing other images or sequences of images.

for further study

In addition to the global, monthly mean SST data set provided on this CD, a high-resolution, regional data set is available for use with *SEE Image.* Monthly mean high resolution images are available for the western North Atlantic Ocean, the Gulf of Mexico, the eastern and western Pacific Oceans, and the Indian Ocean. For advanced exploration, have your students apply the *SEE Image* tools they have mastered on a particular region of the world's oceans. These data can be found at

http://www.ccpo.odu.edu/~lizsmith/SEES/Ocean_Circulation/SST/Data/regional/

Other sources of satellite-derived SST data abound. Although not formatted for use with *SEE Image,* the images found at these sites will be superior examples of SST and suitable for class discussion. Here are a few of the most user friendly archives:

1. Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center
   http://podaac.jpl.nasa.gov

2. National Oceanic and Atmospheric Administration (NOAA)
   http://www.noaa.gov

3. NOAA's CoastWatch Program
   http://psbsgi1.nesdis.noaa.gov:8080/NSORS/ML/nsors1.html

exercise 1
investigating the characteristics of the global monthly sea surface temperature data set for 1982–1998

learning objectives

When students complete Exercise 1 they should be able to

Open and interpret an annotated SST image.

Determine SST values in degrees Celsius for specific image pixels.

Determine the spatial resolution of an SST image.

Investigate advantages and disadvantages associated with daily and monthly-averaged SST data sets.

Determine the mathematical relationship between pixel value and temperature in degrees Celsius.

Calibrate an SST image in degrees Celsius.

science process skills

observing
inferring
communicating
measuring
interpreting data

national science education content standards

A: Develop the ability to do science inquiry
D: Understand energy in Earth systems
F: Understanding issues of environmental quality
G: Understand science as a human endeavor
Understand the nature of scientific knowledge

image processing skills

opening an image
applying a predetermined color table (LUT)
annotating an image with text
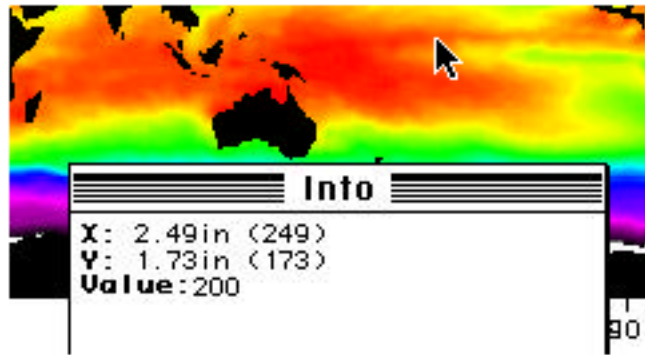calibrating an image

mathematical tools and skills

graphing
evaluating slope and intercept of a straight line
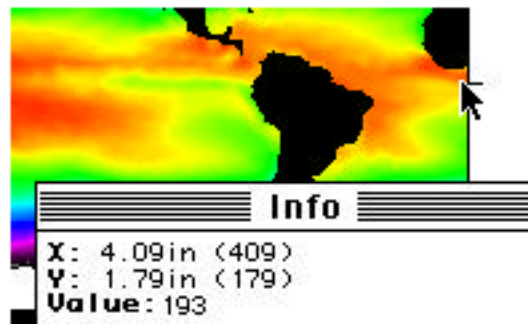determining mathematical relationship from a graph

answers to exercise 1

1. gm9701t.tif

2. January 1997

3. 200

4. a. 28° C

This figure shows the value in the Info Window for the geographic center of the image (where the arrow points).

   b. 27° C

The location of the arrow in this image shows this approximate location and the Info Window associated with it.

5. a. 360
   b. 180

6. a. 1
   b. 1

7. a. 1° latitude by 1° longitude
   b. 1° latitude by 1° longitude

8. a. black

    b. white

9. a. 70%

    b. 80%. Only 34,000 pixels of the 170,000 pixels of ocean are cloud free.

10. a. *Benefit:* In cloud free conditions, daily monitoring can reveal changes taking place over small space and time scales in remote regions where it is difficult to gather *in situ* data. The fine structure of the oceans (current boundaries, meanders and rings, thermal fronts) are visible in the daily images.

    Drawback: Clouds obscure large regions of the world's oceans on any one day. This makes long-term monitoring on a large scale very difficult, if the changes you want to observe are taking place rapidly or if you want to monitor the same location over several consecutive days. To fill the gaps, several images must be averaged or composited, which may smear or remove some small-scale features.

    b. *Benefit:* Clouds are much less of a problem if an image is created by taking the average of all the days in an entire month. This allows long-term, large-scale monitoring of even remote areas, as long as the features you are looking for do not evolve rapidly (you cannot tell what is happening on a daily basis, for instance, by using monthly-averaged images).

    Drawback: In regions where there are persistent clouds, a monthly average could be composed of just a few measurements, which would not be a robust statistic. As was mentioned above, short-term changes and fine-scale structures like eddies are lost.

11. Students may choose any file

12. a. 255

    b. land
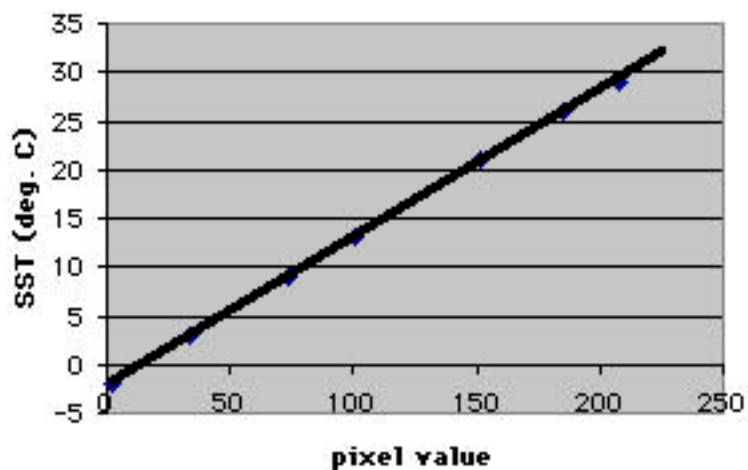
    c. 0

    d. ice and clouds

13.

	Pixel Value	SST (°C)
1	2	-2
2	34	3
3	74	9
4	101	13
5	152	21
6	185	26
7	208	29

(column headers: X = Pixel Value, Y = SST (°C))

14.
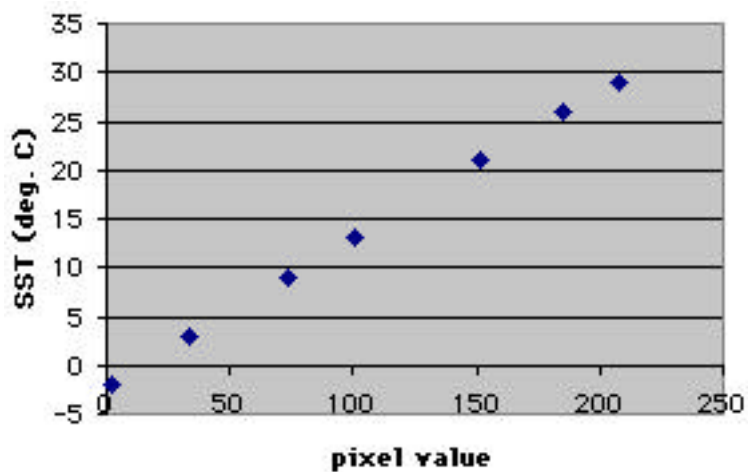
15. As pixel value increases, so does the value of SST.

16. a.

16. b.   positive

    c.   negative, but close to 0

17. a.   example 1: (21–9) / (152–74) = 12/78 = 0.15
        example 2: (29–21) / (208–152) = 8/56 = 0.14
        example 3: (13–3) / (101–34) = 10/67 = 0.15

        m = 0.15

    b.   between –2.0 and –2.5

    c.   SST = 0.15 (pixel value) –2.0

18. When your students compare their answers to this exercise, they all should have computed the same slope and y-intercept. Furthermore, their straight line graphs will all be identical, and identical to the plot on page 15 of the exercise, regardless of the specific pixel-SST pairs they chose. This is because there is a linear relationship (i.e., 1:1) between pixel value and SST which is constant throughout the data set.

19. The pixel value of 1 is approximately –2°C. The pixel value of 254 is approximately 36°C. The range of SSTs is from –2°C to 36°C.

20.   **COLDEST REGION**   **WARMEST REGION**

        Pixel Value= 1–10   **Pixel Value=** 210–220

        SST= –2 to 1°**C**   **SST=** 29 to 31°**C**

        Color= purple/magenta   **Color=** red

exercise 2
observations of the geographic, or spatial, variation of sst

learning objectives

When students complete Exercise 2 they should be able to

Using a graph of the distribution of solar radiation, predict regions of highest and lowest sea surface temperatures and confirm prediction with an SST image.

Use density slicing to investigate spatial sea surface temperature distributions.

Compare northern and southern hemisphere high latitude regions for geography and SST distributions.

Investigate latitudinal and longitudinal profiles of SST.

Relate ocean currents to energy distributions in ocean systems.

science process skills

observing
inferring
measuring
communicating
formulating hypotheses
interpreting data
formulating models

national science education content standards

A: Develop the ability to do science inquiry
D: Understand energy in Earth systems
F: Understand issues of environmental quality
G: Understand science as a human endeavor
Understand the nature of scientific knowledge

image processing skills

opening an image
applying a predetermined color table (LUT)
annotating an image with text
calibrating an image
applying density slicing
plotting an image profile

mathematical tools

interpreting a graph

answers to exercise 2

1. a. Tropics, equatorward of 30°N and 30°S.

   b. Near poles, poleward of 60°N and 60°S.

   c. Yes, more or less. The warmest SSTs are around the equator while the coldest SSTs are near the poles.

   d. Along the eastern and western sides of the North Atlantic and South Atlantic and the North Pacific and South Pacific Oceans. Along the eastern boundaries of the oceans in the northern hemisphere, upwelling is common, causing cooler SSTs to be apparent near the coast than at the same latitude in the middle of the gyre. Along the western boundaries, warm water currents like the Gulf Stream in the North Atlantic cause warmer water to be present near the coast than at the same latitude in the middle of the gyre.

2. September 1996

3. Warmest SSTs occur in the equatorial regions, also called the tropics, because this region of Earth receives the most incoming solar radiation annually.

4. a. The SST is uniform in the east-west direction, along lines of constant latitude, around the Antarctic continent.

   b. The range of SSTs in the range 0°C to 5°C are concentrated in the northwestern portions of the Atlantic and Pacific subpolar regions.

5. There is less land in the southern hemisphere compared to the northern hemisphere. In the southern hemisphere the ocean encircles the continent of Antarctica and the SSTs are very uniform in an east-west direction along lines of constant latitude. One reason for this uniform east-west distribution of SST is because there are no continental boundaries. This results in ocean currents flowing around Antarctica in a strict east-west sense, and moving (advecting) heat along lines of constant latitude, not across them.

   In the northern hemisphere the east-west distribution of SST is not as uniform. It breaks down along the boundaries between the oceans and the continents, especially along the western boundaries of the Atlantic and Pacific Oceans in both the northern and southern hemisphere. This is caused by two effects: first, the north-south movement (advection) of heat by the ocean currents along the eastern and western sides of ocean basins; second, the coldest SSTs are found in the northwestern portions of the Atlantic and Pacific Oceans because of the extreme cooling of the surface in winter in these regions by cold, dry continental air moving out over the ocean due to the prevailing winds in these regions.

6.
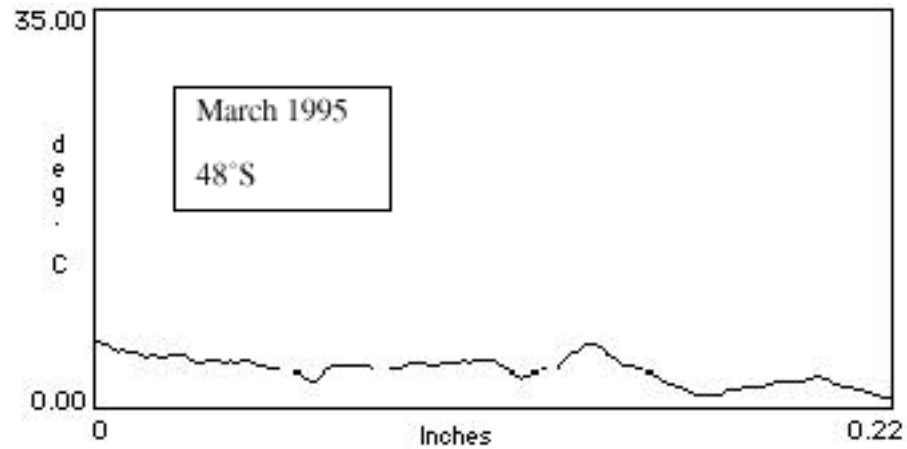
NOTE: The scale on the x-axis is labeled in inches. It is an arbitrary scale used by the SEE Image software. Obviously, this is not correct when referring to the image. The quantity that is significant is the relative distance along the line drawn on the image.
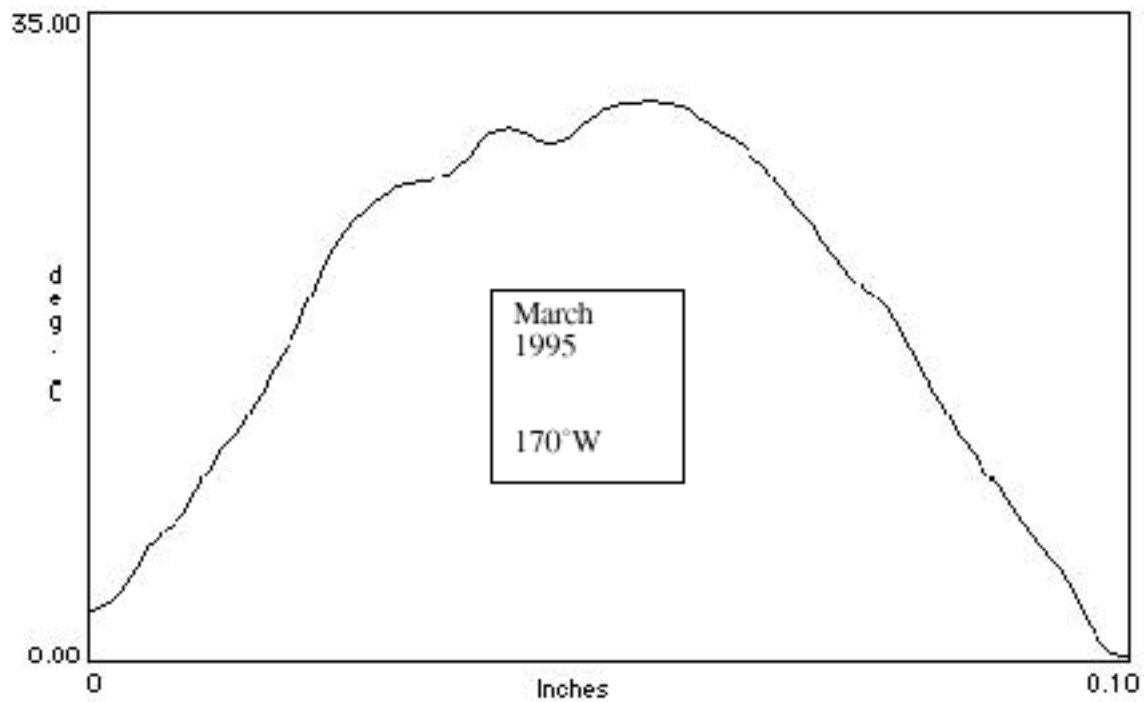
	Max SST	Min SST	Range
a.	10°C	30°C	7°C
b.	28°C	0°C	28°C

7. SST is quite uniform along lines of similar latitude from east to west, except for the western and eastern sides (or boundaries) of the ocean basins.

8. SST reaches a maximum around the tropics and a minimum around the poles. There is much more north-south variation (along lines of constant longitude) in SST than there is in the east-west direction (along lines of constant latitude).

9. SST is a function of solar radiation received from the Sun. The amount of incoming solar radiation arriving at Earth's surface is a strong function of latitude because of Earth's tilt on its axis relative to the Sun. More solar radiation reaches the equatorial regions of Earth over a year than reaches the polar regions of Earth.

10. a. & b. For both, choose areas along the eastern and western boundaries of the Pacific, Atlantic, or Indian Oceans.

11. a.   This depends on the student's choice in question 10a.

    b.   This depends on the student's choice in question 10b.

12. In order for Earth to be habitable, excess heat must be continually moved from the tropics to the poles. This is achieved via the global circulation of the atmosphere and the oceans. Considering just the ocean circulation, on the western sides of ocean basins, very strong currents move warm water toward the poles. The balance is complete because on the eastern sides of basins currents move cold water toward the equator.

exercise 3
observation of the seasonal variation of sea surface temperature

learning objectives
When students complete Exercise 3 they should be able to

Investigate variation in SSTs during a year from global, monthly-averaged SST images.

Compare the image viewing techniques of navigating a stack, montage, and stack animation to determine SST seasonal variation in the northern and southern hemispheres (with special note of land boundaries).

Subset SST images to generate SST montages of the southern and norther hemispheres to explore SST variations.

Use the standard deviation of an image stack to identify regions of greatest and least seasonal SST change.

Determine mean SST values for a selected region on an image stack; graph the mean vs. month of the selected region to observe seasonal changes; determine standard deviations for the selected region, plot, and interpret.

Explore changes or anomalies by determining arithmetic differences between monthly average images and interpret the differences.

science process skills
observing
inferring
measuring
communicating
interpreting data

national science education content standards
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Understand the nature of scientific knowledge

image processing skills
opening multiple images
applying a predetermined color table (LUT)
generating a montage
calibrating a stack of images
applying density slicing
animating an image stack
subsetting an image
applying image math

mathematical tools
evaluating standard deviation
generating a graph
interpreting a graph
generating and interpreting difference values

answers to exercise 3

1. In January through March, the area of warmest SSTs in the southern hemisphere increases. In May through September, the area of warmest SSTs shifts northward globally. In October through December, the area of warmest SSTs shifts southward and decreases.

2. In January through April, the area of coldest SSTs in the northern hemisphere increases and moves southward. In May through September, the area of coldest SSTs in the northern hemisphere decreases while in the souther hemisphere the coldest SSTs move equatorward slightly. In October through December, the area of coldest SSTs in the northern hemisphere increases and moves equatorward, while in the southern hemisphere the coldest SSTs move poleward slightly.

3. a. The isotherms shift to the north slightly during the southern hemisphere winter and shift south again during its summer.

   b. From month to month, however, there is little variation in SST along lines of constant latitude in the southern oceans. There is more SST variation in the northern hemisphere, especially along the western boundaries of the North Atlantic and North Pacific Oceans, where warm ocean currents transport heat northward, thus shifting warm isotherms northward and disrupting the latitudinal distribution of SST observed in the southern oceans.

4. There is more land in the northern hemisphere than in the southern hemisphere. This is significant because land heats and cools more readily than water due to its lower specific heat and its inability to store heat to depth, like the ocean. Thus, heating and cooling, especially at mid latitudes, produces larger temperature changes in the northern hemisphere than in the southern hemisphere.

   The coldest SSTs are found in the northwestern portions of the Atlantic and Pacific Oceans, where cold, dry, continental winds blow over the oceans and cool the surface waters. Second, there are stronger ocean currents along the western boundaries of the North Atlantic and North Pacific than in the South Atlantic and South Pacific.

   Imagine if Earth were totally water covered, or if all the material on Earth had the same specific heat, heat-storage capacity, and reflective index...the climatic zones, in this case, would be nicely defined and very uniform. There would be no difficulty in tracing isotherms of SST, for instance, around the world through both ocean and land environments along a constant latitude.

5. You can readily see the isotherms shifting poleward in the winter and equatorward in the summer. The technique of animation makes it much easier to see the seasonal variation in SST.

6. In the summer, the warmest SSTs shift northward and hug the western boundaries of both the North Atlantic and the North Pacific. Even in these low resolution images, the warm Gulf Stream current is visible in the northwest Atlantic Ocean, as is the Kuroshio Current in the northwest Pacific Ocean. Likewise, in the winters, the western boundary regions of the oceans in the northern hemisphere don't get as cold as the eastern boundaries.

7. a. July through September.

    b. Equatorward about 45°N, and the range of SSTs in this region is approximately 29°C–31°C.

8. a. January through March.

    b. Poleward of 45°N in the northwest portions of the Atlantic and Pacific Oceans, and the range of SSTs in this region is approximately 1°C–3°C.

9. a. January through March.

    b. Equatorward of about 40°S, and the range is approximately 28°C–30°C. The warmest SSTs don't extend as far poleward in the southern hemisphere summer as they do in the northern hemisphere during its summer.

10. a. September is when the coldest SSTs seem to extend the farthest equatorward.

    b. Near the sea ice around the continent of Antarctica and the range is approximately 0°C–1°C.

11. a. Yes, regarding the warmest SSTs with the northern hemisphere only slightly warmer (northern, 29°C–31°C; southern, 28°C–30°C).

    b. No.

    c. Because there is more water than land in the southern hemisphere, and since water has a high heat capacity, it takes more energy to heat up and cool off the oceans in the southern hemisphere as compared with the northern hemisphere oceans. One reason we don't observe this as a strong trend in the data is because of the coarse spatial resolution of this particular data set.

        As for the coldest temperatures, the range in the southern hemisphere is only about a degree, while in the northern hemisphere it's a few degrees. This is what we expect based on the explanation given above.

12. a. Standard deviation is a statistical measure of variability from the mean and in the case of this image we created it is a measure of temporal variability for each pixel, from the mean for that pixel computed over the 12 months.

    b. The image of standard deviation shows regions of high variability in SST over a year, and regions of low variability of SST over a year.

13. a. Areas of red and white in the image of standard deviation correspond to regions with relatively low variability from month to month as compared with the mean SST. The standard deviations in these regions is small (about 1°C).

   b. Areas of green and blue correspond to regions of relatively high variability from month to month, as compared with the mean. The standard deviations in these regions is high (around 5°C–6°C).

14. a. 30°N–45°N and 30°S–45°S

   b. tropics, equatorward of about 22°N or S.

15. a. & b.
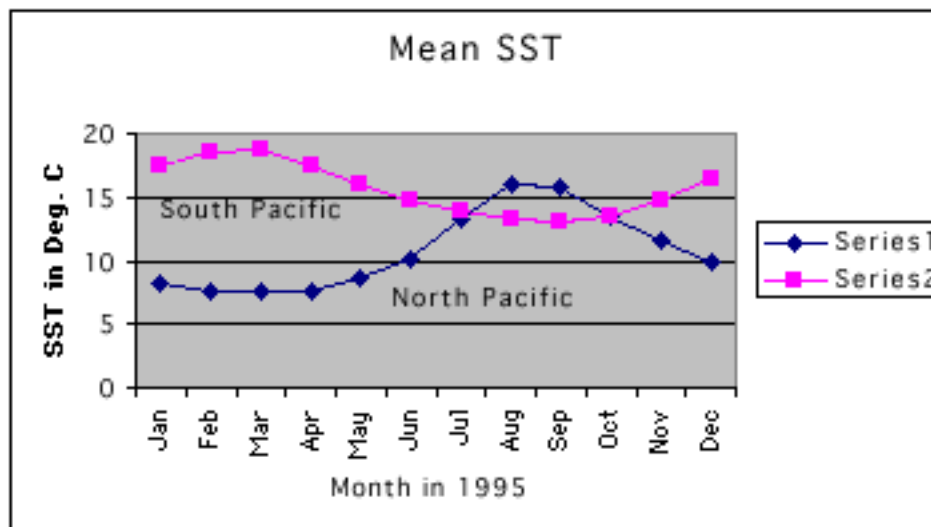
c.
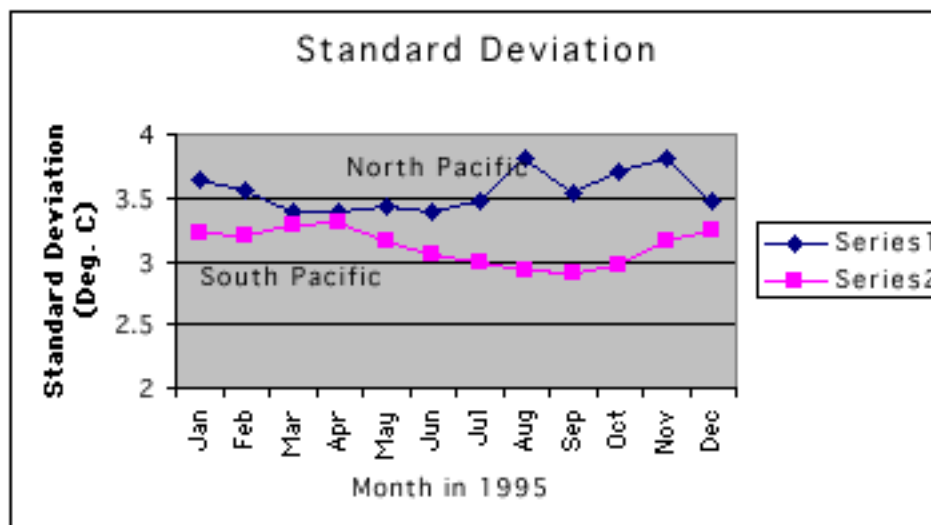
d. The plots of mean SST in the North and South Pacific are the inverse of one another. That is, in the months January through June, when SSTs are warm in the South Pacific, they are cool in the North Pacific. January through June is the winter-spring season in the northern hemisphere, so we expect temperatures to be cool but warming. Because of the tilt of Earth on its axis relative to the Sun, it is the summer-fall season in the southern hemisphere at this same time, so we expect and observe that SSTs are warm and then starting to cool. From around July through December, it is the summer-fall in the northern hemisphere (Earth has moved around the Sun such that the northern hemisphere is tilted toward the Sun during this time) so SSTs in the North Pacific are at a maximum and begin to cool off in September. However, in the southern hemisphere during these months it is winter-spring and we observe from the plot that SSTs are their coldest in September but are beginning to warm up.

In general, standard deviation of SST is higher in the North Pacific than in the South Pacific. This is because of the predominance of land in the northern hemisphere, as compared with the southern hemisphere, and the corresponding greater range of SST over the course of the year. Interestingly, during the southern hemisphere winter-spring (July–November), the variability of SST is at a minimum. This is a result of the high heat storage capacity of water. Even though winter air temperatures in the southern hemisphere are cool, and the region is receiving little direct solar radiation, SST doesn't change (i.e., cool) very readily. During this time (July–November), which is the northern hemisphere's summer-fall, SST variability reaches its maximum. In general, standard deviations are higher in the northern hemisphere relative to the southern hemisphere because of the presence of strong western boundary currents like the Gulf Stream, and because of cold, dry continental winds that blow from land to ocean and cause great reductions in the surface temperatures.

Low standard deviations in the winter months (this is true for both hemispheres' winters) mean that SST in the rectangular region we selected is most uniform in winter. This is because the ocean surface will be cooled to a certain minimum temperature, determined from the subsurface main thermocline. So, the ocean surface gets cooled to some minimum in winter and this surface temperature is more uniform in the rectangular region we selected because the temperature is determined from subsurface conditions, which tend to be more uniform than surface conditions. Conversely, the standard deviation is higher in summer because the surface conditions are more variable in summer. The existence of thermal fronts will result in more variable surface conditions.

16.
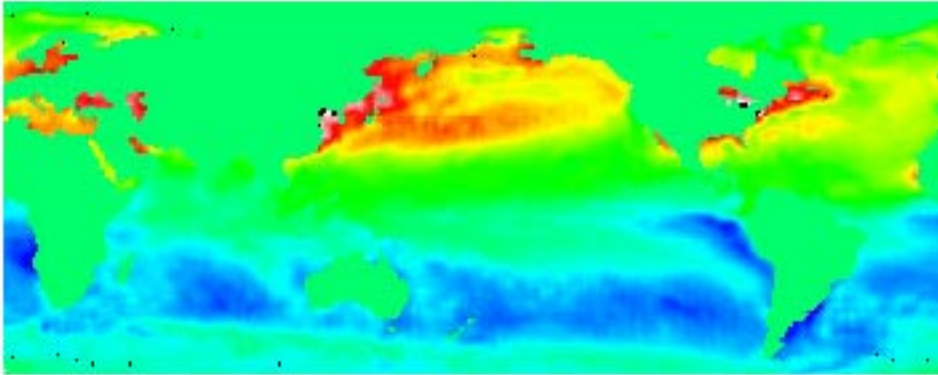
   a. reds and yellows

   b. shades of blue

17. a. When SST differences are positive, which occurs in the northern hemisphere, it means that SST values were greater in the northern hemisphere in September than in March (remember, September minus March). We expect this because September is when the oceans in the northern hemisphere are their warmest, at the end of a long, hot summer. In March, SST in the norther hemisphere is at its minimum, the result of a cold winter.

   b. When SST differences are negative, which occurs in the southern hemisphere, it means that SST values were larger in the southern hemisphere in March than in September. We also expect this result because September in the southern hemisphere is when the oceans are at their minimum, since it is the end of the southern hemisphere winter. However, in March, southern hemisphere SSTs should be still quite warm because that is the end of the summer season in that hemisphere.

18. a. northern hemisphere

   b. see 17a.

19. a. southern hemisphere

   b. see 17b.

20. a. The largest differences, which are positive, are along the western boundaries of the North Atlantic and North Pacific Oceans, where seasonal heating and cooling is very large, and ocean currents play a large role.

   b. The smallest differences, which are around 0°C (both positive and negative) are found around the tropics. The seasonal warming and cooling of Earth in this region is more uniform—it is warm most of the time during all seasons.

exercise 4

observing the year-to-year, or interannual, variation of sea surface temperature

learning objectives

When students complete Exercise 4 they should be able to

Investigate the variations in regions of high SST using a series of December global, monthly averaged images from 1982–1998

Evaluate using a stack, montage, or stack animation to study interannual SST variations

Identify oceans with greatest December SST variations and anomalous years

Measure areas, mean densities, and standard deviations for regions with highest SST in the December SST time series; compare data over time

Generate a standard deviation image from the December SST time series; identify regions with greatest interannual variability

Subset the December SST time series selecting the eastern equatorial Pacific Ocean and generate mean densities and standard deviations for this region on each image; plot the resulting data vs. year; understand the trends and reasons for the variability

Understand and interpret SST climatology images in a set of 12 months

Generate and plot a time series of mean SST and standard deviation values for years between 1982 and 1998 for the eastern equatorial Pacific Ocean; generate a climatology SST vs time plot for the same region; compare plots of various years and the climatology to identify El Niño and non-El Niño years; evaluate the duration and strength of El Niño events in SST

Use image math to generate anomaly fields based on climatology SST data for El Niño years and interpret the resulting images.

science process skills

observing
inferring
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interpreting data

national science education content standards

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Understand the nature of scientific knowledge

image processing skills

opening and stacking multiple images
applying a predetermined color table (LUT)
calibrating an image stack
generating a montage
applying density slicing
generating a standard deviation image
measuring area using density slicing

mathematical tools

interpreting areas, means, and standard deviations
generating a graph
interpreting a graph

answers to exercise 4

1. a. 1982 and 1997

   b. 1984 and 1988

2. In 1982 and 1997 the eastern equatorial Pacific Ocean was uniformly warm all along the equator. This absence of upwelling along the equator is a typical signature of El Niño. In 1984 and 1988 there is a "cold tongue" of water along the equator in the eastern equatorial Pacific, which is typical of non-El Niño years.

3. Students' answers will vary.

4. Students' answers will vary.

5. Students' answers will vary.

6 Largest variability occurs in the tropics.

7. a. Anomalous years are those where there is little or no upwelling along the equator in the eastern Pacific Ocean.

   b. Usually there is moderate to strong upwelling along the equator in the eastern Pacific. This is because of divergent flow along the equator caused by the prevailing currents in the region and the effect of Earth's rotation. Divergence along the equator allows cold, deep water to upwell to the surface and the resulting SSTs are cool. During an El Niño this pattern of divergence and upwelling ceases because of a slackening of the prevailing winds along the equator and the waters remain much warmer. El Niño events are unusual, or anomalous, because they occur only every several years and ar not predictable.

8. Most pronounced in the tropics and least pronounced in the midlatitudes.

9. a. In 1982 the warmest SSTs covered approximately 109,878,680 sq. km.

   b. In 1997 the warmest SSTs covered approximately 124,429,776 sq. km.

10. a. In 1984 the warmest SSTs covered only 95,808,096 sq. km.

   b. In 1988 the warmest SSTs covered only 96,313,256 sq. km.

11. In 1982 and 1997 the eastern equatorial Pacific Ocean was uniformly warm all along the equator. This absence of upwelling along the equator is a typical signature of El Niño. In 1984 and 1988 there is a "cold tongue" of water along the equator in the eastern equatorial Pacific, which is typical of non-El Niño years.
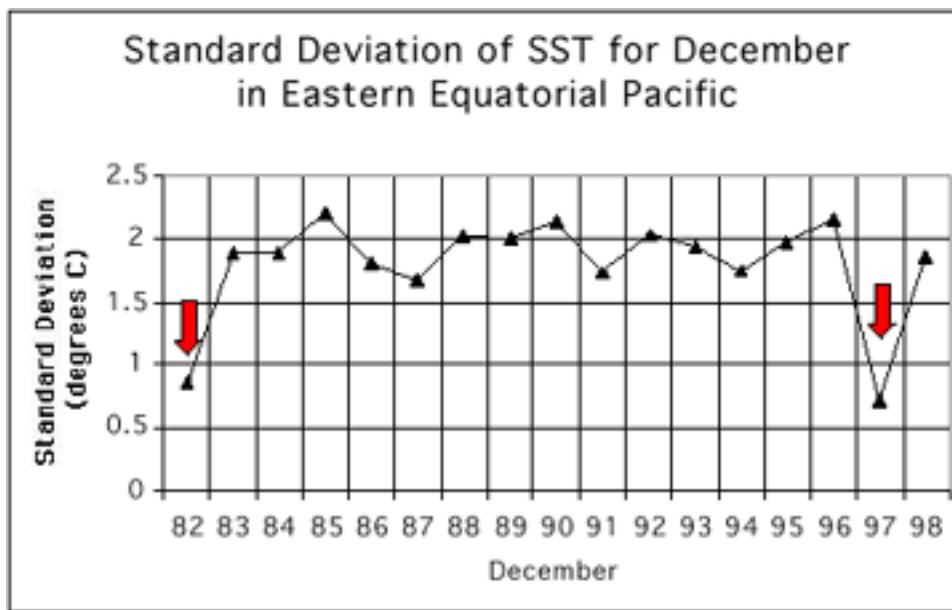
    Reread your answer to question 2 in this exercise. Would you make any changes to your answer now that you have the quantitative data?

12. Eastern equatorial Pacific Ocean.

13. Confirms qualitative results.

14. a.

Mean December SST in Eastern Equatorial Pacific Ocean

Standard Deviation of SST for December in Eastern Equatorial Pacific
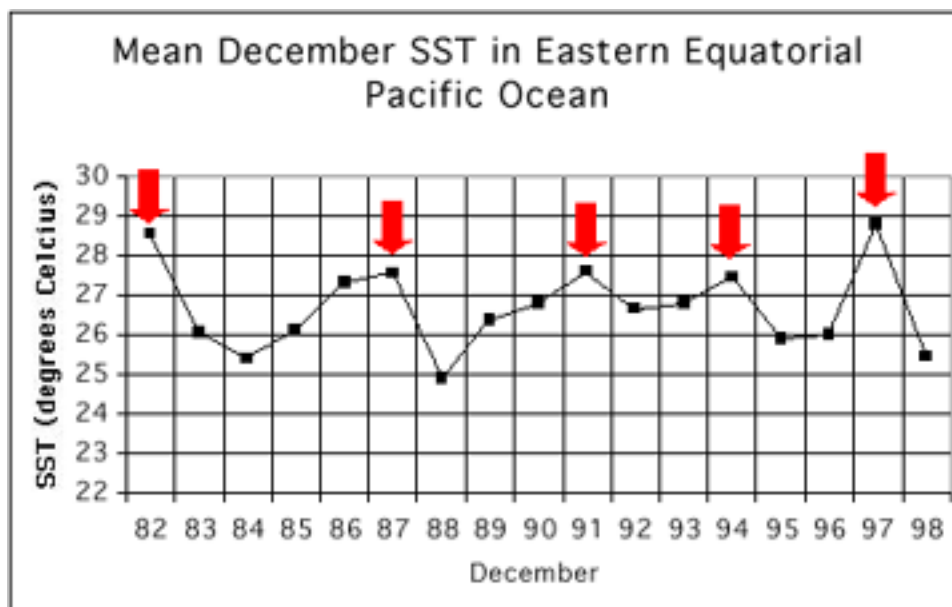
14. b. Mean—The bold arrows indicate years when the SST in the eastern equatorial Pacific Ocean was anomalously or unusually warm. In 1982 we know there was a very intense El Niño, and it was the first El Niño of the century oceanographers could observe thanks to technology advancements. 1987, 1991, and 1994 were all years of weaker, but distinguishable El Niños. In 1997 there was a very intense El Niño that was captured not only by in situ instruments but also by a suite of satellites.

Standard Deviation—The plot of standard deviation as a function of time shows how the SST in the region we selected varies from the mean, for each December in the 17-year series. The most notable features of this plot are the two very low standard deviations in 1982 and 1997. These years correspond to intense El Niños, during which time the SST in the region is uniformly warm, hence there is not much variation in SST from the mean for those years. Other years show a more expected pattern of variation from the mean SST because of the upwelling that usually occurs in this region.

15. a.

Monthly SST in Eastern Equatorial Pacific Ocean (1982-1998)
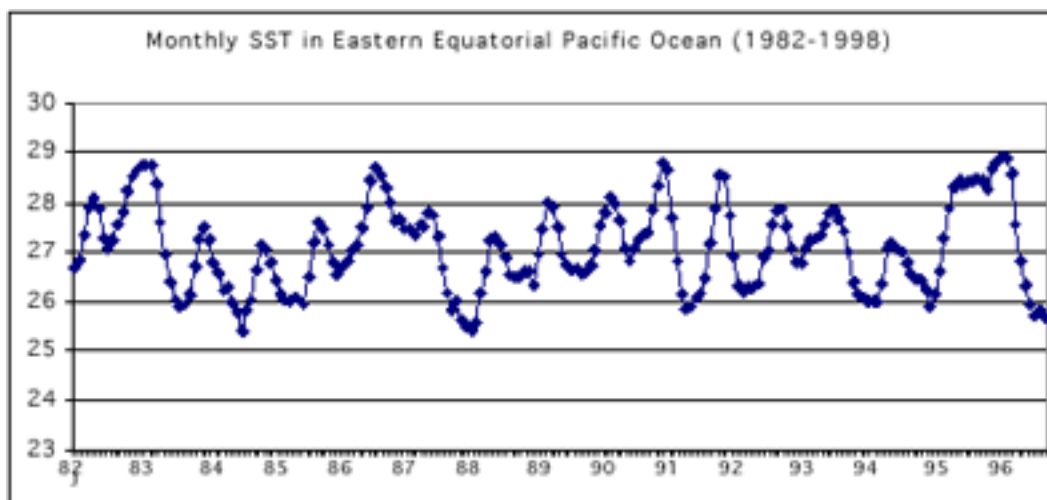
15. b. An example of the kind of plot each team should create is shown below. The curve with triangles shows a time series in the selected region of the eastern equatorial Pacific Ocean for each month in 1982, which was an El Niño year. The SSTs in the equatorial Pacific during an El Niño are warmer than during normal, non-El Niño years. The curve with diamonds shows a time series in the same selected region for the climatological average of SST over many years. The climatological average represents "normal" conditions. Creating plots like this for each year makes it easy to see which years are anomalously warm or cool or close to normal conditions.
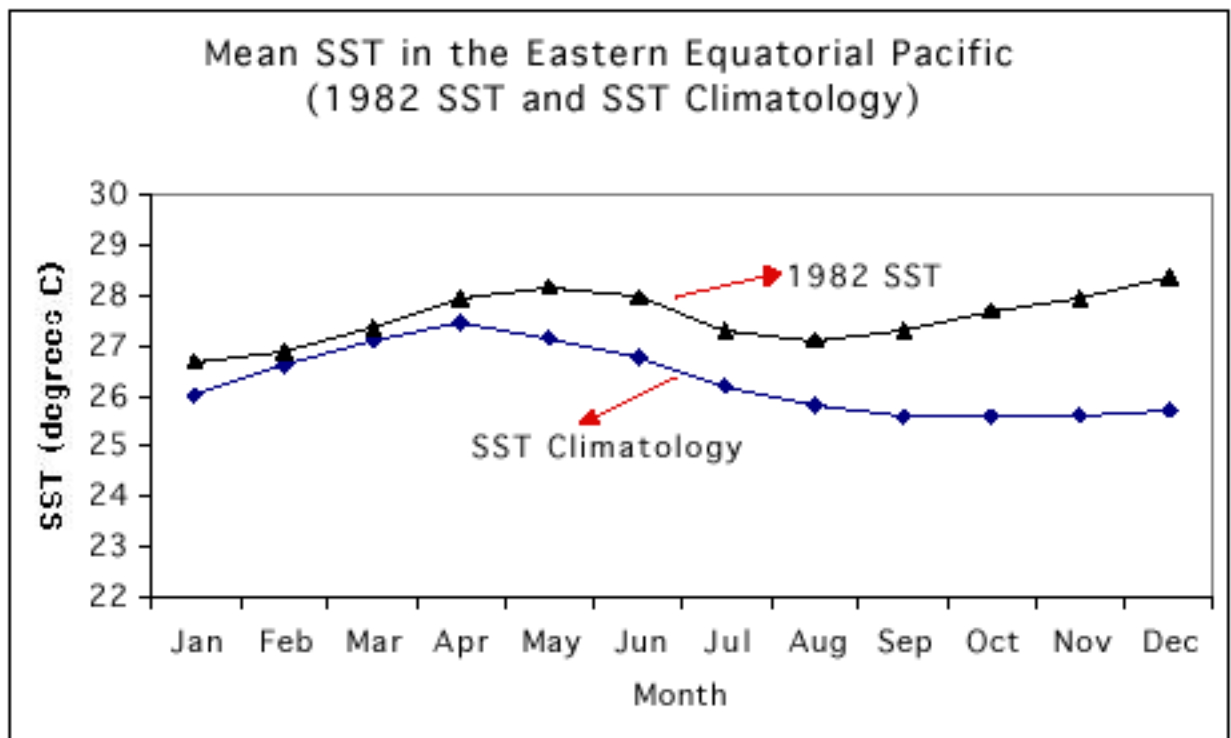
16. a. 1982, 1987, 1991, 1994, and 1997 were all El Niño years.

    b. 1983, 1986, 1992, 1993, 1996, and 1998.

17. The strongest El Niños occurred in 1982 and 1997.

18. a.–c. The plots your students create will be much easier to read since they will be bigger. We suggest each research team create their plots using the same Y-axis scale so the plots can be taped on the wall, side by side, to build one long time-series from which these questions can be answered.