CALCULATING THERMAL STRESS AND PREDICTING CORAL BLEACHING: NOAA CORAL REEF WATCH METHODOLOGY

Aim of Lesson

To learn how to convert satellite sea surface temperature data into measurements of thermal stress, then use these stress metrics to predict coral bleaching.

Objectives

1. To become familiar with the HDF data formats used by the NOAA Coral Reef Watch program.

2. To learn about climatologies and how they are calculated.

3. To thoroughly understand, step-by-step, how the Coral Reef Watch thermal stress metrics are calculated.

4. To interpret these satellite data metrics to predict coral bleaching.

Overview of Lesson

Mass coral bleaching is primarily caused by unusually high water temperatures that stress corals. In these conditions coral polyps expel the greenish-brown symbiotic algae that live in their tissues, showing the white skeleton underneath. If the bleaching is severe or prolonged, individual polyps or whole colonies will die. As ocean temperatures continue to rise due to global climate change, coral bleaching events are expected to increase in frequency and severity. Bleaching is caused by prolonged exposure to warm water, and the temperature of the ocean is easily measured from satellites. The US National Oceanic and Atmospheric Administration (NOAA) has developed a technique to measure the temperature stress that can lead to coral bleaching. Satellite data give us a global, near-real-time perspective on where bleaching is happening. In this lesson, you will learn how to use NOAA data and methodology to predict bleaching.

This lesson begins by describing the sea surface temperature (SST) data files that NOAA produces, and leads you through the steps to calculate a long-term average temperature. This average temperature, or climatology, is then subtracted from a temperature image to produce an SST anomaly image — highlighting regions that are warmer or cooler than average. You will then learn about a specialized anomaly, called a HotSpot, that shows ocean areas that are above the average temperature expected during the warmest month; these are the areas that are experiencing the thermal stress that can lead to coral bleaching. Finally, you will look for regions that have been under HotSpot stress for a prolonged period, calculating a metric called the Degree Heating Week. It is this final data product that is the best predictor of coral bleaching.

To demonstrate how these satellite data are used in the real world, the lesson ends with an activity based on a bleaching event in the Caribbean Sea in 2005. You will interpret satellite metrics to predict coral bleaching extent and severity, then compare your predictions with *in situ* bleaching data.

Background Information

Chapter 9 in *Coral Reefs and Climate Change: Science and Management* has an in-depth discussion the NOAA Coral Reef Watch products and methodology, and you are recommended to consult this book or similar texts for further details.

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. Most of the lesson is confined to displaying and stacking images, applying color palettes, and running formulas. Tutorials 2, 6, and 10 in the *Introduction to using the Bilko 3 image processing software* are particularly relevant and provide a good grounding for this lesson. It may also be useful to have studied Mini-lesson 3: *Advanced use of formulas*, although this is not a necessary prerequisite.

Image data

The images used in this module are global sea surface temperature data. The data were acquired by the Advanced Very High Resolution Radiometer (AVHRR) sensor, carried on NOAA's polar orbiting environmental satellites (POES). AVHRR is a broad-band, four or five channel scanner, sensing in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum. The POES satellite system offers the advantage of daily global coverage, since each satellite makes near-polar orbits roughly 14 times daily.

The radiance observations have been converted into temperature in degrees Celsius, using a multi-channel algorithm. Briefly, this method uses the relative radiances in the infrared and near-infrared to correct for atmospheric attenuation and calculate the temperature of the ocean surface. The satellite SST algorithms are calibrated and routinely validated against *in situ* buoy data to ensure their accuracy. Cloudy areas are detected by their cold temperature, and are masked out.

The Coral Reef Watch (CRW) operational SST product uses only nighttime satellite SST observations. Daytime data are excluded to eliminate diel variation caused by solar heating at the sea surface (primarily at the "skin" interface, 10-20 μm) during the day and to avoid contamination from solar glare. Compared with daytime SST and day-night blended SST, nighttime SST provides more conservative and stable estimate of thermal stress conducive to coral bleaching.

The spatial resolution of the dataset is 0.5 degree, meaning that the pixels are about 50 km x 50 km near the equator. The product is updated twice-weekly on Monday morning (using observations from the previous Thursday through Sunday) and Thursday morning (observations from the previous Monday through Wednesday), U.S. Eastern Time.

The files we will use for this lesson are stored as Hierarchical Data Format (HDF) files. This file type consists of binary data, with a header that describes the data contained in the file. Data and images are available for free on the web at http://coralreefwatch.noaa.gov/satellite.

The full dataset covers 1985 to the present, but the data used for this lesson were acquired in 2005. Many of the examples focus on September 17, 2005, during a bleaching event in the Caribbean basin.

Lesson Outline

Open and display Sea Surface Temperature HDF data files

The first part of this lesson will introduce you to the data files that NOAA Coral Reef Watch produces for its SST products. You will open an HDF file, display a global ocean temperature image, and apply the NOAA color palette to the image. *Note* that the values are stored in a scaled data format, so you will have to apply a formula to convert the integer data into temperature values.

Activity: Launch *Bilko*. In the **File**, **Open** dialog box deselect **Extract** and **Minimize** (if they are checked). Enter the *sst_stack_hdf* folder, then select *sst.night.field.50km.n18.20050917.hdf* from the list of image files with the mouse pointer and click on [Open]. This will bring up a window that shows the attributes of the HDF scientific data file. In the left-hand panel, click on the ⊞ button next to the two folders to expand the view.
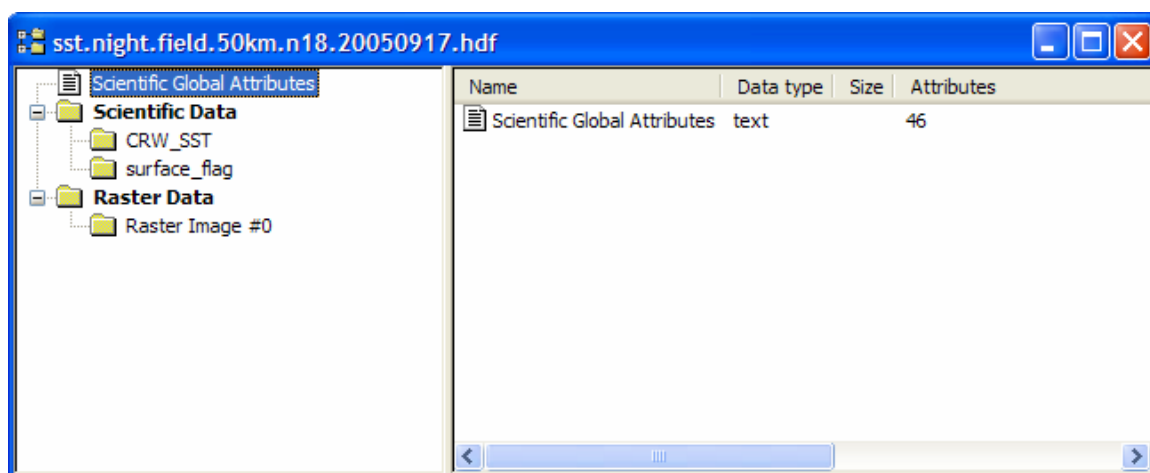
The left-hand panel shows the types of data that are available in this file. **CRW_SST** is the sea surface temperature data, **surface_flag** shows land (set to 64)/ice (set to 255) masks, and **Raster Image #0** shows an image of the SST data. Note the file naming convention used for these Coral Reef Watch HDF files: "50km" is the spatial resolution, "n18" means that the NOAA-18 satellite acquired the data, and "20050917" is the date (17 September 2005) for the end of the half-week data file.

Activity: Click on "Raster Image #0" in the left-hand panel to select that image, and then double-click on "Raster Image #0" in the right-hand panel to open the browse image to see what the data will look like when properly displayed. Minimize the browse image by clicking [-] at the top-right of the image window.

Now click on the first item in the left-hand panel, "Scientific Global Attributes", and double-click it in the right-hand panel to view the text. This gives detailed information about the file: when it was acquired, who produced it, the latitude and longitude covered, etc. Examine the attributes, especially noting that the date from the file name matches the date in the stop_date attribute. Close the window when you are done.
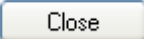
Under **Scientific Data** in the left-hand panel, click on CRW_SST. When it appears in the right-hand panel, right click on CRW_SST and choose **Open Properties** to see the attributes of the SST data. Carefully read the information.

Question 1: What value should the data be multiplied by to convert to degrees Celsius? What is the name of the attribute that holds that scaling constant?

Activity: Close the SST attributes window. Double-click on "CRW_SST" in the right-hand panel. This will open a **Redisplay Image** dialog box; accept the defaults by clicking [Apply]. You will see a global SST image in shades of grey. Click in any ocean basin to display a data value in the bottom-right corner of the *Bilko* window. Note that all of the values are integers. `047°30'00.00"W  24°30'00.00"N  (02820) 216`

You will now convert these integer values into temperatures by multiplying by a scaling constant. Use **File, Open** to bring up the **Open** dialog box. Select FORMULAS (*.frm) from the **Files of type:** drop-down menu and open the formula *SST_convert.frm* which is stored in the main lesson folder. This formula looks up the **scale_factor** attribute for the image, and then multiplies the image by that factor. Copy the formula by clicking on the Copy button 📋 and then click on the image and apply the formula by clicking on the Paste button 📋. The values in the image will now be floating-point numbers that represent the temperature in degrees Celsius. `047°30'00.00"W  24°30'00.00"N  (28.2)    216`

The image is still in grayscale, so the next step is to apply the NOAA color palette. Use **File, Open** to bring up the **Open** dialog box. Select PALETTES (*.pal) from the **Files of type:** drop-down menu and open the palette *CRW_SST.pal*. This is the rainbow color scale that NOAA Coral Reef Watch uses for its sea surface temperature images. Copy the palette by clicking on the Copy button 📋 and then click on the image and apply the palette by clicking on the Paste button 📋.

To make the image look exactly like the ones from NOAA, the final step is to rescale the image. Use **Image**, **Redisplay** to bring up the dialog box. Set Min: -2 and Max: 34. Leave everything else the same, and click [Apply] to rescale the image then [Close]. Restore the Raster Image #0 browse image you opened in the first step by clicking 🗗 on the minimized image. Compare the colors in two images to satisfy yourself that your SST image looks like the one from NOAA.

Question 2:   What was the temperature north of the US Virgin Islands (at 63°W, 20°N) on September 17, 2005? *Hint*: use **Edit**, **Go To…** to bring up the **Go To** dialog box to position the cursor.

Once you have completed this part of the lesson, close all files without saving their contents. [*Hint:* use **Window, Close All**]

Calculating an SST climatology

Coral bleaching occurs in areas with unusually high water temperatures that persist for a long time. So the first step in looking for coral bleaching conditions is to define what a "normal" temperature would be, so you can start to look for areas where the temperature is unusually warm. We will do this by calculating monthly mean temperatures for 2005.

Start by stacking the SST data from individual HDF files.

Activity: Use **File, Open** to bring up the **Open** dialog box. Select IMAGES from the **Files of type:** drop-down menu, and enter the **sst_stack_hdf** folder. Open the files for January, 2005 (hint: to select all nine files, click on *sst.night.field.50km.n16.20050101.hdf* then hold down the *<Shift>* key and click on *sst.night.field.50km.n16.20050129.hdf*; or press *<Ctrl>*+A to select all files). The following series of steps should be done for each of the nine files in the *Bilko* window; it doesn't matter which file you do first.

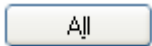   •   In the left-hand pane, click on ⊞ 📁 **Scientific Data**.

- In the right-hand pane, double-click on 📁CRW_SST to open the SST image.

- When the **Redisplay Image** dialog opens, just click [Apply].

- Minimize the SST image by clicking [-] in the top-right of that window.

- Close the HDF file by clicking [✖] in the top-right of the HDF file window.

You will end up with nine black-and-white SST images, all minimized at the bottom of the *Bilko* window. To be able to manipulate all of the images together as one (to calculate an average, for instance), you will need to connect the images. Use **Image, Connect…** to bring up the **Connect** dialog box. Click and drag to select all nine images, and then click the **Stacked** checkbox.
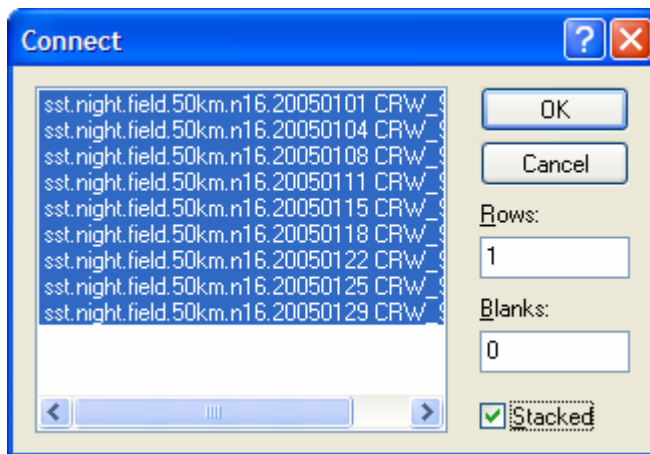
Click **OK** to connect the images into a stacked set. A new window will appear for the stacked images, and a **Selector** dialog will also appear. You can switch from one image to another by choosing a different HDF file in the **Selector** drop-down menu, or by clicking on the loop 🎞 button to see each image in turn.

A full year of SST data is 105 files: 52 weeks of data, with two updates per week. As you see, opening each image from an HDF file takes many clicks! So to save time, you will now switch to using a set of 105 SST images that have already been opened and stacked.

Activity: Close all of the open files without saving by using **Window**, **Close All**. Use **File, Open** to bring up the **Open** dialog box. Select SETS (*.set) from the **Files of type:** drop-down menu, enter the *sst_stack_2005* folder, and open the set *sst_stack_2005.set*. When the **Redisplay Image** dialog opens, just click [All] to apply the default settings to all 105 images. *Bilko* may take a few moments to finish redisplaying.

Now you will convert all of these images from integers to floating-point temperature values. The scale_factor attribute is stored with each image; drag down the top bar of the image to see the attributes and their values. Use **File, Open** to open the formula *SST_convert_stack_105.frm*. This formula will loop through 105 images and multiply each one by the scale_factor. With the formula window active, click the copy button 📋 in the toolbar at the top of the window; then switch to the image stack and click the paste button 📋 to apply. A **Status** box will appear as the formula is applied to each image in the stack.

Now the final step is to apply a formula that will calculate monthly SST means from the 2005 data. Use **File, Open** to open the formula called ***monthly_mean_sst.frm***. This formula will loop through 12 months to calculate averages. Taking January as an example, it will look in the first position of the "date" array and look up a text string "200501" that corresponds to January, 2005. The formula then loops through all 105 images and looks for ones with "200501" in the file name. Only images that have that string in their file name will be included in the January average.

Copy the formula, and then paste it onto the stack of SST images to apply the formula. A **Status** window will appear, and it may take a short time until the calculations are complete. The result will be a stack of 12 images, one for each month of the year 2005. The first image will be the January average, the second is the February average, etc.

Question 3: In 2005, which month had the warmest average temperature in the southern Great Barrier Reef, Australia? What was the average temperature in that month? Use 152°E, 23°S as a representative pixel. *Hint*: if you place the cursor on the pixel using **Edit**, **Go To…** then loop through the images using the Loop button ▦ in the toolbar, each month's temperature value will be shown in the Status Bar at the bottom-right of the *Bilko* window. You can also use the *<Tab>* key to advance one image, and *<Shift>+<Tab>* to go back one image.

Optional: An advanced option is to display a time series graph for this pixel. With the cursor still placed at 152°E, 23°S in the stacked images, choose **File**, **New**. In the **New** dialog box, choose TRANSECT Document and make sure the **Apply stretches to new documents** checkbox is not checked. Click [OK]. This will display a graph of the monthly means at the selected pixel, which is essentially a "transect" through time. Note that the numbers on the x-axis correspond to the month minus one. So the "zero" mean is for the first month, the "one" mean is for the second month, etc. You can click on the graph or use the arrow keys to place the cursor. The maximum value is also displayed at the top-center of the graph. Once you have your answer, you can try one more interesting *Bilko* feature. Leaving the transect open in the background, make the stacked images the active window. Click on the ⊞ icon in the top toolbar to enable point selection with the cursor. Now click on the image to place the cursor somewhere else in the image; note that the transect window changes automatically, to show the time series graph for the new pixel. You can even click and drag around on the stacked images, and the transect window will continually change.
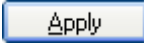
Once you have completed this part of the lesson, close all files without saving. *Hint*: use **Window**, **Close All** to avoid *Bilko* asking if you want to save the changes to each of the 105 SST images!

Create and display an SST anomaly image

The monthly climatology you just created only used data from 2005, as an example of how a climatology is calculated. One year of data isn't really enough, of course. If you happen to choose an unusual year, an El Niño year for example, your "average" condition would be seriously wrong. It is much safer to use many years of data. For the rest of this lesson, you will switch to using the NOAA Coral Reef Watch operational climatology which uses seven years of data. These monthly means include data from 1985-1993, with observations from the years 1991 and 1992 omitted due to aerosol contamination from the eruption of the Mt. Pinatubo volcano in the Philippines in June 1991 (http://vulcan.wr.usgs.gov/Outreach/AboutVolcanoes/do_volcanoes_affect_weather.html).

We can calculate an SST anomaly by subtracting the average (climatology) temperature from today's temperature observations. This is the same as a weather report that tells us that today's temperature is 5 degrees above average. That would translate into a temperature anomaly of +5 degrees. Positive anomaly values mean that the temperature is warmer than average; negative anomalies mean the temperature is cooler than average. In this exercise, you will calculate a global sea surface
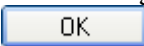
temperature anomaly image for September 17, 2005, to see where the unusual temperatures were on that day.

Activity: Use **File**, **Open** to bring up the **Open** dialog box. Select IMAGES from the **Files of type:** drop-down menu, enter the *sst_stack_hdf* folder, and open *sst.night.field.50km.n18.20050917.hdf*, which is an HDF file with global SST data from September 17, 2005. In the left-hand pane, click on ⊞ 📁 **Scientific Data**. In the right-hand pane, double-click on 📁 CRW_SST to open the SST image. When the **Redisplay Image** dialog opens, just click Apply. Convert the integer data to floating-point temperatures using the *SST_convert.frm* formula.

Use **Image**, **Redisplay** to change the temperature range to -2.0 to 34.0. Use **File, Open** to bring up the **Open** dialog box. Select PALETTES (*.pal) from the **Files of type:** drop-down menu and open the palette *CRW_SST.pal*. Copy the palette by clicking on the Copy button 📋, and then click on the image and apply the palette by clicking the Paste button 📋.

Now open and display the climatology file for September. Use **File, Open** to bring up the **Open** dialog box. Select IMAGES from the **Files of type:** drop-down menu, enter the **climatology_stack** folder, and open *september.interp CRW_SST.dat*. The Redisplay Image dialog box will appear; change the temperature range to -2.0 to 34.0. Apply the palette *CRW_SST.pal* to the SST climatology image.

A visual comparison of the two images should convince you that there are many similarities between the SST on September 17, 2005 and the September average. The broad-scale patterns look very similar, and it is difficult for our eyes to pick out the areas of difference. For coral bleaching, though, we need to quickly pinpoint areas where the temperatures are unusually warm. We will do this by calculating the SST anomaly.

Activity: Connect the two images. Use **Image**, **Connect** to open the **Connect** dialog box. Highlight the two images in the left-hand window, click on the **Stacked** checkbox, and then click OK. Make sure that the climatology image is on the top of the stack as the first image (check the drop-down menu in the **Selector** dialog box to see if it is listed as @1. If it is not, select the climatology image then press *<1>* on your keyboard to move the image to the #1 position in the stack. Open the formula document called *sst_anomaly_calculate.frm* in the main lesson folder and read over the very simple formula that subtracts the two images. Use copy 📋 and paste 📋 to apply the formula to the stacked images. This will create a new image that shows the the global SST anomaly.

Using **Image**, **Redisplay** change the temperature range to -5.0 to 5.0. Then open and apply the palette called *CRW_SST_ANOMALY.pal*. Areas that were warmer than average will be highlighted in orange to red colors, and areas that were cooler than average are shown in blue to purple colors. Compare this anomaly image from September 17th to the SST image for that same date. Note that many of the warmest areas were unusually warm, but not all. Some cool areas in the tropics are perfectly normal: the cool SSTs along the east coast of Africa are very close to the average temperature for that time of year, as you see in by the absence of large anomaly values.

Question 4:   What were the anomalies like in the Gulf of Mexico and Caribbean basins on September 17, 2005? Where was the temperature furthest above average, and what were the maximum anomalies? Where was the temperature furthest below average, and what were the minimum anomalies? See image below to define the region. *Hint*: making the

image window bigger and using **View**, **Zoom** (or pressing *<Ctrl>* and using mouse wheel) to magnify the image by 500% will help you see details.

Once you have completed this part of the lesson, close all files without saving their contents.

Create a "Maximum Monthly Mean" climatology

You will remember from the introduction that corals are very sensitive to warm sea temperatures. So to look for areas at risk of bleaching, we could start by looking for places that are warmer than normal – places with a positive SST anomaly. But it turns out that we can be even more specific than that. Scientists have shown that corals start to become stressed when the SST is 1°C warmer than the highest monthly mean temperature (Glynn and D'Croz, 1990). Let's look at a time-series graph of satellite data at one pixel to see what this "maximum monthly mean" (MMM) concept means.
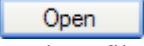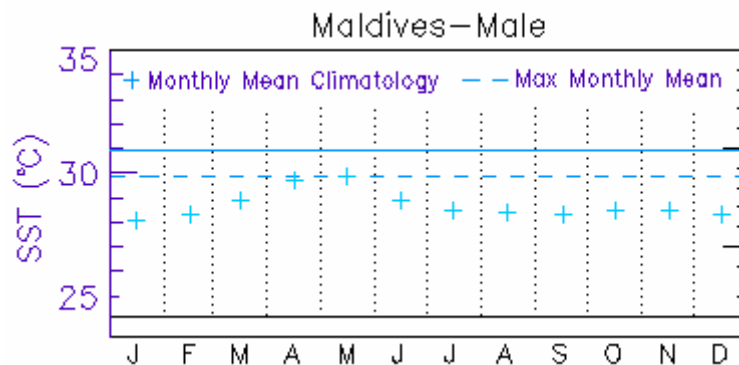

The light-blue crosses represent the mean temperature for each month. Remember that this mean is based on 7 years data between 1985-1993, with 1991 and 1992 omitted because of Mt. Pinatubo's eruption. Now we need to look for the warmest month in the seasonal cycle; for the Maldives, the mean temperature reaches a maximum of 29.9°C in May. So for this coral reef site, the maximum monthly mean (MMM) is 29.9°C (shown as a light-blue horizontal dashed line). One degree above the maximum monthly mean is called the "bleaching threshold" temperature. The bleaching threshold is shown on the time-series graph above as a solid light blue horizontal line. When the sea surface temperature is warmer than the bleaching threshold temperature, the corals will experience thermal stress. If this thermal stress persists over time, it will cause mass coral bleaching.

In this part of the lesson, you will calculate a map of the MMM climatology for all pixels around the world.

Activity: Use **File**, **Open** to enter the ***climatology_stack*** folder and open ***monthly_climatology.set***, the stacked set of Coral Reef Watch monthly climatologies. When the **Redisplay Image** dialog box comes up, click [All] to accept the default for all 12 images in the set.

Open the formula document called ***maximum_monthly_mean.frm***. This very simple formula simply loops through the stacked images and retains the maximum value for each pixel. Copy this formula, and then paste it on the stacked climatology images to execute. The result is a new image that contains the warmest monthly mean temperature for each pixel. This is the global Maximum Monthly Mean climatology. Use **Image**, **Redisplay** to set the minimum to -2 and the maximum to 34. Use **File**, **Open** to apply the color palette called ***CRW_SST.pal***. [*Hint*: if you don't want to open the palette file into the *Bilko* window, click the **Apply** checkbox in the **Open** dialog box then click [Open]. This will just apply the palette to the active image, instead of opening the palette file.]

Question 5: Which region in the world has the warmest MMM climatology? What is the average temperature there during the warmest month? What might that mean for the coral reefs in that region?

Activity: Use **File**, **Save As…** to save the image as a *Bilko* file called ***mmm_climatology.dat***. Close all of the files except ***mmm_climatology.dat***. [*Hint:* with ***mmm_climatology.dat*** selected as the active image, select **Window, Close All Except**.] We will use this image to create HotSpots in the next section.

Create and display a HotSpot image

CRW's Coral Bleaching HotSpot is a measure of the thermal stress that can lead to coral bleaching. It is an anomaly product, but not a typical SST anomaly which is based on the average conditions for that month. The HotSpot anomaly is based on the maximum monthly mean (MMM) climatology. The technique was developed based on the earlier work by Goreau and Hayes (1994) and Glynn and D'Croz (1990), showing that temperatures more than 1°C above the usual summertime maximum are sufficient to cause stress on corals. Based on these studies, the MMM SST climatology was derived as a threshold for satellite monitoring of coral bleaching stress.

The value of each pixel in a HotSpot image is the difference between the measured nighttime satellite SST and the MMM SST climatology in °C:

$$HotSpot = SST - MMM\_SST\_climatology$$

However, only positive values are derived, since the HotSpot is designed to show the occurrence and distribution of thermal stress conducive to coral bleaching. The HotSpot color palette highlights (in yellow to red color) anomalies that are at least 1.0°C, above the bleaching threshold temperature.

Activity: Use **File**, **Open** to bring up the **Open** dialog box. Select IMAGES from the **Files of type:** drop-down menu, enter the ***sst_stack_hdf*** folder, and open ***sst.night.field.50km.n18.20050917.hdf***, which is an HDF file with global SST data from September 17, 2005. In the left-hand pane, click on ⊞ 🗀 **Scientific Data**. In the right-hand pane, double-click on 🗀 CRW_SST to open the SST image. When the **Redisplay Image** dialog opens, just click [Apply] to accept the default display options. Convert the integer data to floating-point temperatures using the ***SST_convert.frm*** formula.

Underline If your maximum monthly mean climatology file is not already open from the previous section, follow these steps to open and display the image. Use **File, Open** to bring up the **Open** dialog box. Select IMAGES from the **Files of type:** drop-down menu and open ***mmm_climatology.dat***. In the **Redisplay Image** dialog box change the temperature range to -2.0 to 34.0. Apply the palette ***CRW_SST.pal*** to the SST climatology image.

Connect the two images. Use **Image, Connect** to open the **Connect** dialog box. Highlight the two images, click on the Stacked checkbox, and then click [OK]. Make sure that *mmm_climatology.dat* is on the top of the stack as the first image. [*Hint:* check the title bar or drop-down menu in the **Selector** dialog box to see if it is listed as image 1 in the set or @1. If it is not, select the climatology image then press *<1>* on your keyboard to move the image to the #1 position in the stack.] Open the formula document called *hotspot_calculate.frm* and read over the formula. The formula subtracts the two images, but sets any negative numbers to zero. The result will be to show anomalies only in areas that are warmer than the maximum monthly mean climatology. Use the copy 🔳 and paste 🔳 buttons to apply the formula to the stacked images. This will create a new global HotSpots image.

The initial result will look very boring, with no detail visible (as below). Now you will modify how the image is displayed, so that it will look like the NOAA Coral Reef Watch operational images.
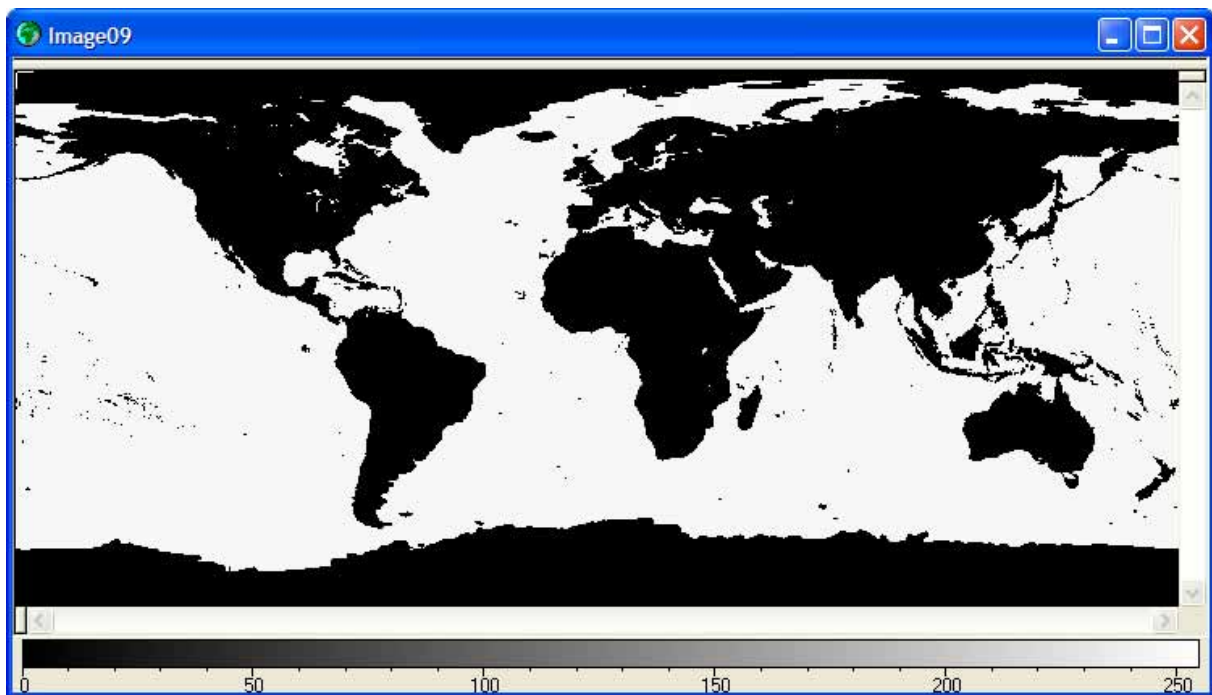
Activity: Using **Image**, **Redisplay** change the Stretch Settings **Min:** to -0.01 and **Max:** to 5.0. Also enter -999 in the **Null Value(s):** then click the checkbox next to it; this means that a value of -999 in the data will be considered as "null" in the displayed image. Click **Apply** then **Close**.

Finally, open and apply the palette called *CRW_HotSpot.pal*.

Areas in white are cooler than the mean temperature for the warmest month, the MMM climatology. Areas shown in lavender/purple colors have a HotSpot value between 0 and 1; in other words, these regions were above the MMM, but still below the bleaching threshold temperature. Any regions shown in orange to red are more than 1°C above the MMM. That means that the HotSpot is ≥ 1°C, the sea
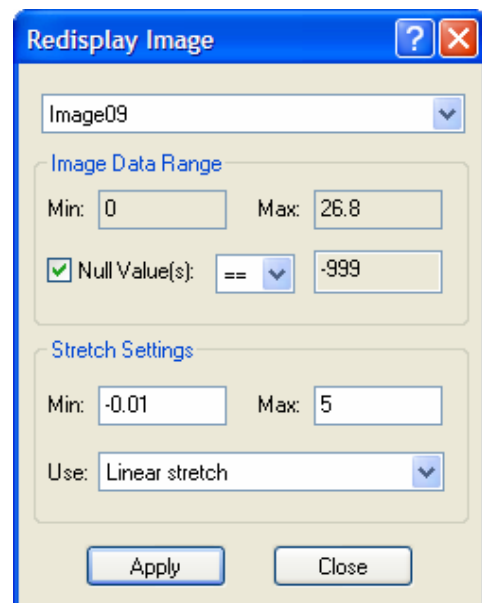
surface temperature is above the bleaching threshold, and any corals in that region will be experiencing thermal stress.

Question 6:   The map below shows the distribution of coral reefs around the world (map modified from the UNEP World Conservation Monitoring Centre). Compare this image to your HotSpot map for September 17, 2005. Where do you see coral reefs experiencing HotSpots? What coral reef areas were above the bleaching threshold on that date? *Hint*: making the image window bigger and using **View**, **Zoom** to magnify the image to 500% will allow you to see more detail.

Once you have completed this part of the lesson, close all files without saving their contents.

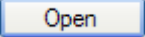## Calculate and display Degree Heating Weeks

Earlier in this tutorial, you learned that corals are sensitive to temperatures warmer than the bleaching threshold, 1°C above the maximum monthly mean temperature. A HotSpot chart gives a snapshot of where corals are stressed at one moment in time. But also remember that the heat stress will build up if the temperature around the corals stays above the bleaching threshold over time. So we need some way to not only measure how far the temperature is above the threshold, but also how long it has stayed above. This is what the Degree Heating Weeks (DHW) product is designed to portray.

DHWs show how much thermal stress has accumulated in an area over the past 12 weeks (3 months). In other words, we add up the HotSpot values whenever the temperature exceeds the bleaching threshold. It is a running sum: as we advance one half-week in time (a timestep), a half-week timestep "falls off" the back end of the 12-week window.

The units for DHW are "degree C-weeks", combining the intensity and duration of thermal stress into one single number. Based on research at Coral Reef Watch, when the thermal stress reaches four degree C-weeks, you can expect to see significant coral bleaching, especially in more sensitive species. When thermal stress is eight degree C-weeks or higher, you would likely see widespread bleaching and mortality from the thermal stress.

In this section of the tutorial, you will use a stacked set of 24 HotSpot images, covering the 12-week period leading up to September 17, 2005, to produce a DHW image for that date.

Activity: Use **File, Open** to bring up the **Open** dialog box. Select SETS (*.set) from the **Files of type:** drop-down menu, enter the folder called ***hotspot_stack,*** and open the set ***hotspot_stack_2005.set***. When the **Redisplay Image** dialog opens, just click [All] to apply the default settings to all 24 images. Note that these images are still in integer form, and must be converted to temperature. Use **File**, **Open** to open the formula called ***SST_convert_stack_24.frm***, which will multiply each image in the stacked set by the scale factor. Use copy and paste or hold down the *<Ctrl>* key and use drag-and-drop to apply the formula to the stack.

To make these images display like the Coral Reef Watch images, right-click on the stack and select Redisplay to bring up the **Redisplay Image** dialog box. Change the Stretch Settings range to -0.01 to 5.0. Click **Apply** then **Close**. Now use **File**, **Open** again to bring up the **Open** dialog. Select Palettes (*.pal) from the **Files of type:** drop-down menu and select the *CRW_HotSpot.pal* palette. *Note*: make sure the **Apply** checkbox at the bottom of the window is checked; this option will apply the palette to every image in the stacked set. Click [Open] to apply the palette.

Loop through the three months of images using the Loop button ▐█ in the toolbar (you can also start and stop the animation by pressing the *<Spacebar>* on your keyboard). Look for areas where the HotSpots persist over time, especially where the HotSpots stay above 1°C, shown in orange to red colors. Remember where these areas are, because this is where DHWs will be high—as you will see in the next step.

Activity: Open the formula document called *dhw_calculate.frm*. This formula will loop through the HotSpot images, adding up any values that are greater than or equal to 1°C. Because the HotSpots are updated twice a week, the result is then divided in half so that the units of the result will be °C-weeks. Copy the formula and paste it to the stacked set of HotSpot images.

The result will be a Degree Heating Weeks image for September 17, 2005. Again, the image will initially just look dark and boring. To display it like the NOAA Coral Reef Watch images, you will first redisplay the image. Set the Stretch settings minimum to -0.05 and the maximum to 16. Then apply the *CRW_DHW.pal* color palette.

Question 7: What coral reefs around the world were experiencing significant Degree Heating Weeks (4 or more – green to reddish hues) on this date? Where were the DHWs the highest, in a coral reef area?
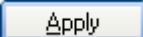
Once you have completed this part of the lesson, close all files without saving their contents.

Prediction of coral bleaching from DHWs

Degree Heating Weeks (DHWs) show us where temperatures have been higher than the average for the warmest month, but how does that relate to coral bleaching? Based on research at Coral Reef Watch, when the thermal stress reaches four degree C-weeks, you can expect to see significant coral bleaching, especially in more sensitive species. When thermal stress is eight degree C-weeks or higher, you would likely see widespread bleaching and mortality from the thermal stress. In the DHW images, these thresholds correspond roughly to green colors (DHW above 4), ranging upward into the yellow to red (DHW above 8).

In this section of the tutorial, you will examine the images in an HDF file, focusing on the Caribbean and Gulf of Mexico regions. You will be looking at the conditions around a particular coral reef area, in the U.S. Virgin Islands (65°W, 18°N). Based on the thermal stress products we have learned about in this module, you will answer some questions about the conditions on September 17th, 2005, and predict whether that area experienced coral bleaching.

Activity: Open the image file named *sst.coralreef.fields.50km.n18.20050917.hdf*. In the left-hand pane, click on ⊞ 📁 Scientific Data. In the right-hand pane, you will see that this one file contains all of the NOAA Coral Reef Watch data for September 17th, 2005: SST, SST anomaly, HotSpots, and DHWs. We will examine each of these in turn. Remember that **surface_flag** shows land/ice masks, but we won't use those masks in this exercise.
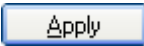
In the right-hand pane, double-click on 📁CRW_SST. Click [Apply] to accept the default display options. This image shows the sea surface temperature, but remember

that the values are stored as integers so our first step is to convert to floating-point temperatures. Open the formula called **SST_convert.frm**, and use the copy 📋 and paste 📋 buttons to apply the formula to the SST image. Redisplay the image so that the Stretch Settings maximum is 34.0 and the minimum is -2.0. Finally, apply the color palette called **CRW_SST.pal**.
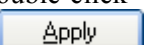
Question 8.a   What was the sea surface temperature in your US Virgin Islands pixel on September 17th, 2005? *Hint*: use **Edit**, **Go To…** to go directly to the pixel at 65°W, 18°N (select Point selection and type in either -65 and 18 as the X: and Y: or 65W and 18N). You can also **View**, **Zoom** to 500% to get a closer view of the area.

Activity: Close the SST window without saving changes. Double-click on 📁 CRW_SSTANOMALY and accept the default display options. Convert to temperature using the **SST_convert.frm** formula, redisplay with Stretch Settings set to minimum -5 and maximum 5, and apply the **CRW_SST_ANOMALY.pal** color palette.

Question 8.b   Was the temperature above or below average in the USVI pixel on that day? What was the anomaly?

Activity: Close the SST anomaly window without saving changes. Double-click on 📁 CRW_HOTSPOT. Un-check the **Null Value(s):** checkbox and then click [Apply] to accept the default display options. Convert to temperature using the **SST_convert.frm** formula. Redisplay with Stretch Settings set to minimum -0.01 and maximum 5, and a null value of -77.77. Finally, apply the **CRW_HotSpot.pal** color palette.

Question 8.c   Was the temperature above the maximum monthly mean in the USVI pixel on that day? If so, what was the HotSpot value? Was the temperature above the bleaching threshold?

Activity: Close the HotSpot image window without saving changes. Double-click on 📁 CRW_DHW. Un-check the **Null Value(s):** checkbox and then click [Apply] to accept the default display options. Convert to temperature using the **SST_convert.frm** formula. Redisplay with Stretch Settings set to minimum -0.05 and maximum 16, and a null value of -77.77. Finally, apply the **CRW_DHW.pal** color palette.

Question 8.d   What was the DHW value in the USVI pixel on September 17th, 2005?

Unfortunately for the corals in the US Virgin Islands, the thermal stress didn't end in mid-September. The warm temperatures persisted, and DHWs continued to accumulate until the middle of October across much of the eastern Caribbean. As a final exercise, we will look at a composite image that shows the maximum DHW values experienced in this region during 2005.

Activity: Use **Window**, **Close All** to close everything without saving changes. Open the bitmap image named **2005_Maximum_DHW.bmp**. *Note* that this is not a data file where you can look at actual values in a lat/lon grid. It's just a normal image of DHWs, with a color bar and some reef location names already added.

Question 9   What was the maximum DHW value at each of the four reef locations highlighted on the map (Bermuda, Lee Stocking Island, Puerto Rico, and the US Virgin Islands)? How much coral bleaching do you think occurred at each of these four coral reefs during 2005? Remember the DHW threshold values discussed at the beginning of this section.

Comparison of predictions to *in situ* bleaching data

This coral bleaching event in 2005 prompted an unprecedented field monitoring effort to document the extent and severity of bleaching. Universities, research institutes, NGOs, and private individuals

conducted over 1500 on-site surveys throughout the region. In the figure below, each dot represents the average percentage of the coral colonies bleached at that location.
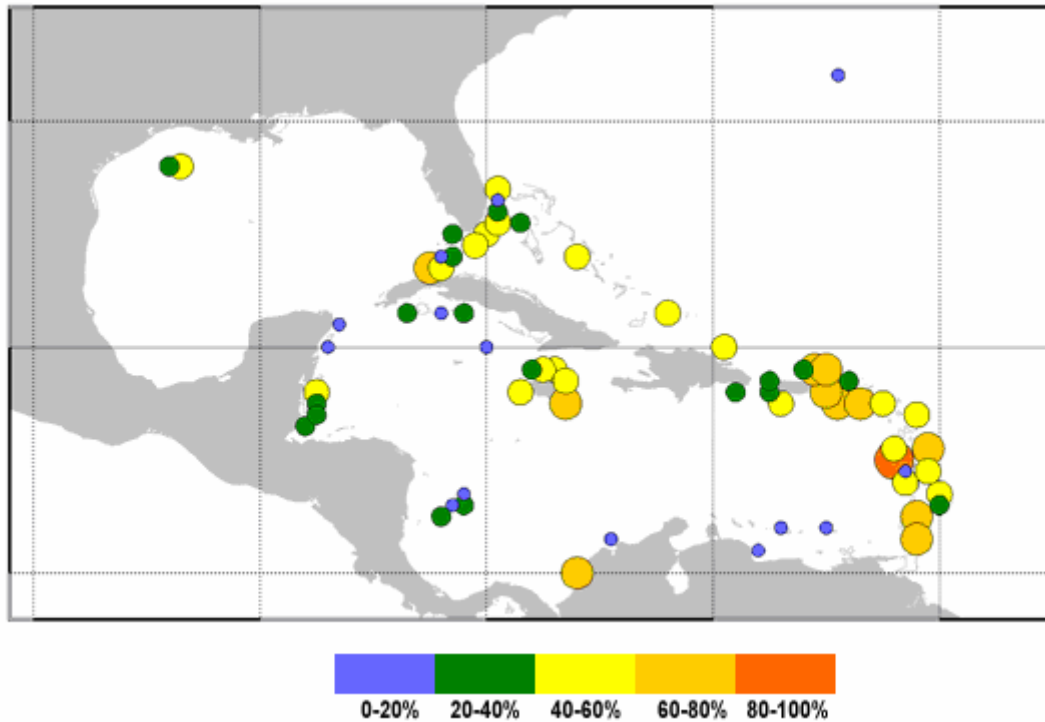
The graph below focuses on the four locations you looked at in question 9. Recall that the DHWs were highest in the US Virgin Islands, then lower in Puerto Rico and Lee Stocking Island, and lowest in Bermuda.
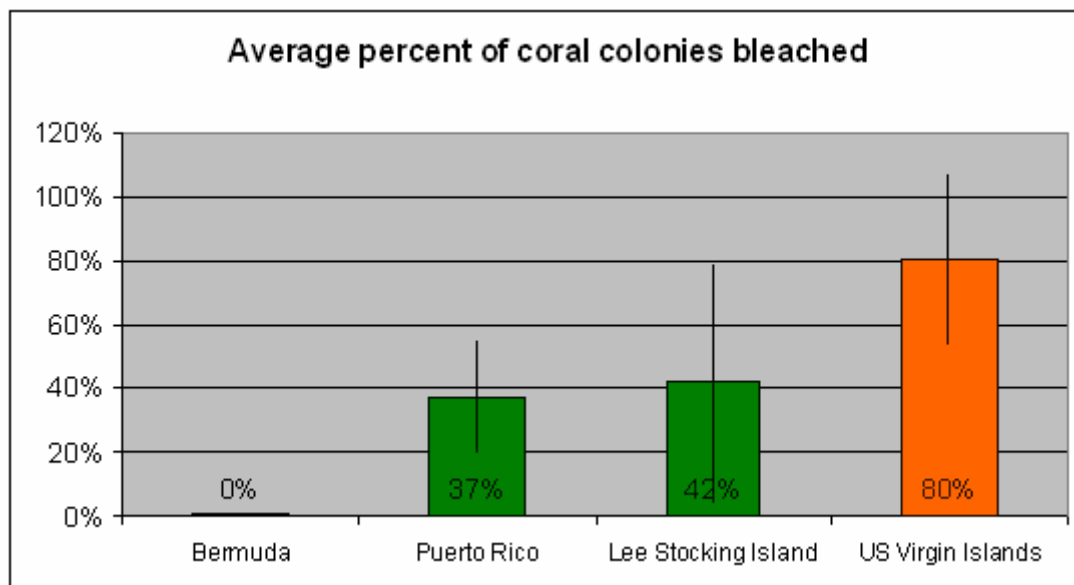
As expected, the bleaching was worst in the US Virgin Islands, where about 80% of the coral colonies were bleached. Puerto Rico had 37% of colonies bleached; Lee Stocking Island had 42%. Note that there is a lot of variability in the data (shown by the error bars); Puerto Rico and the Lee Stocking Island were statistically identical. In Bermuda the bleaching was very light: less than 1% of coral colonies bleached.

References

Glynn, P. W. and L. D'Croz, 1990. Experimental evidence for high temperature stress as the cause of El Niño coincident coral mortality. *Coral Reefs*, **8**: 181-191.

Goreau, T. J. and R. L. Hayes, 1994. Coral bleaching and ocean ''hot spots.'' *Ambio* 23:176–180.

Strong, A. E., F. Arzayus, W. Skirving and S. F. Heron, 2006. Identifying Coral Bleaching Remotely via Coral Reef Watch - Improved Integration and Implications for Changing Climate. *In* J.T. Phinney*, et al.* [Eds.], *Coral Reefs and Climate Change: Science and Management*. Coastal and Estuarine Studies, Vol. 61, American Geophysical Union, Washington, DC. 163-180 pp.

Acknowledgements

Answers to Questions

1. The data in CRW_SST has to be multiplied by 0.01 to convert to degrees Celsius. That value is held in an attribute called **scale_factor**. The data in all of the NOAA Coral Reef Watch HDF files is stored as integers. This is because integers take up less space than floating point numbers, making the file sizes smaller. When you work with these data files, it is *very important* to multiply everything by the **scale_factor**. If not, you will get values that are 100 times too big!

2. The temperature was 29.6°C.

3. December (month #12) was the warmest. The December average during 2005 was 27.3667°C.

4. The temperature was above average for most of the region on September 17, 2005. The highest positive anomalies were around the Bahamas, where SST was around 1.8 to 2.1°C above average. An area to the east of the Lesser Antilles had anomalies that were almost as high, around 1.8°C.
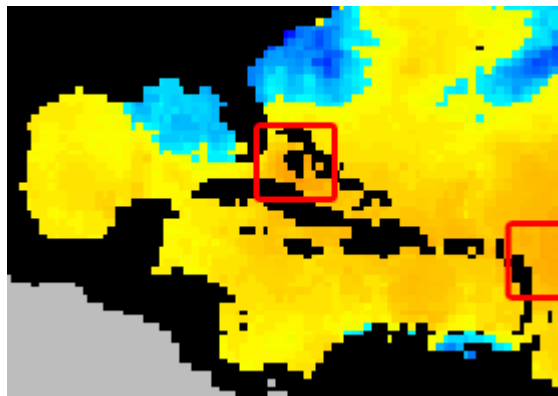

A few places had negative anomalies, e.g. the coastal areas to the north of Florida and a narrow area off the northern coast of Venezuela. The coldest anomalies, though, were in open ocean water to the east of Bermuda, where many pixels were around 2°C below the average temperature. In fact, this area had just been hit by Hurricanes Maria and Nate, which both passed east of Bermuda in early to mid-September. Tropical cyclones extract heat from the surface water and also upwell cooler water from deep mixing. These "wake cooling" tracks are often clearly visible in SST Anomaly images.
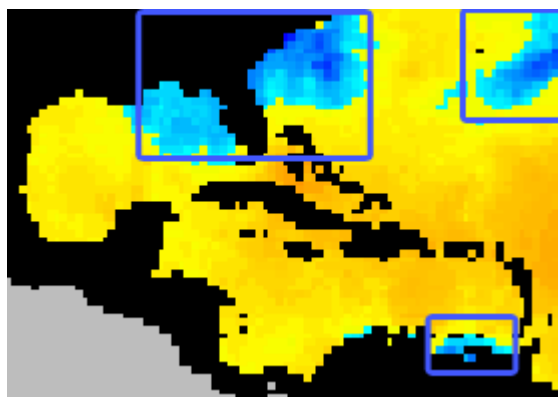
5. The Persian/Arabian Gulf region has the highest MMM climatology, up to about 32.5°C. That means that the corals that grow in this region are adapted to very warm conditions, and will survive temperatures that would cause severe bleaching in corals that grow in cooler waters. Note that this doesn't mean that corals there are safe from coral bleaching. Just like in any other area, if the water temperature in the Gulf rises above the bleaching threshold (one degree above the MMM, i.e. >33.5°C) these corals will experience thermal stress and will start to bleach. If you use the cursor to select a rectangle (see image to right) around the Persian/Arabian Gulf (check that Apply stretches to charts, clipboard etc. is NOT checked in the **Stretch, Options** dialog box) and select **File, New** and HISTOGRAM Document, you will see a histogram of the MMM temperatures. These range from 31.5-32.5°C with the mean temperature during the warmest month being 32.0531°C according to the histogram.

6. Nowhere in the Southern Hemisphere was under HotSpots; September is the spring there, so we wouldn't expect any areas to be above the MMM. There were a few coral reef regions that had HotSpots: central Hawaiian Islands, southern Gulf of California, eastern Caribbean Sea, west coast of Africa, southern Red Sea and part of Arabian/Persian Gulf, Philippines, and Marshall Islands. The only area with widespread temperatures above the bleaching threshold, shown in orange to red, was the eastern Caribbean Sea. The SST was also above the bleaching threshold off the west coast of Africa; however, coral reefs are not very well-developed in that region.
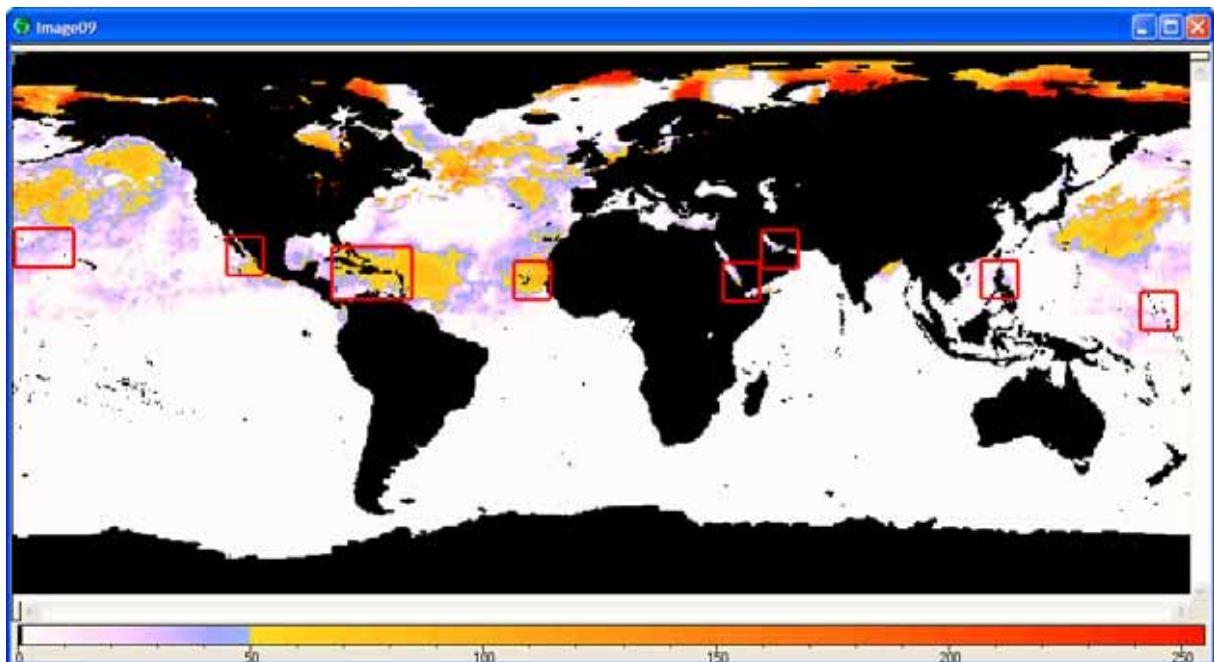
7. The coral reefs that had DHWs are similar to the regions that had HotSpots on September 17th: low values in the central Hawaiian Islands, southern Gulf of California, eastern Caribbean Sea, west coast of Africa, southern Red Sea and Arabian/Persian Gulf, north-west Philippines, and small amounts in the Marshall Islands. This is not surprising, of course, since DHWs are just the HotSpots added up over time. DHWs were highest in the eastern Caribbean Sea, though many of the coastal areas in the Gulf of Mexico and Caribbean region showed accumulations of thermal stress. We will examine this area more closely in the next section of the module.
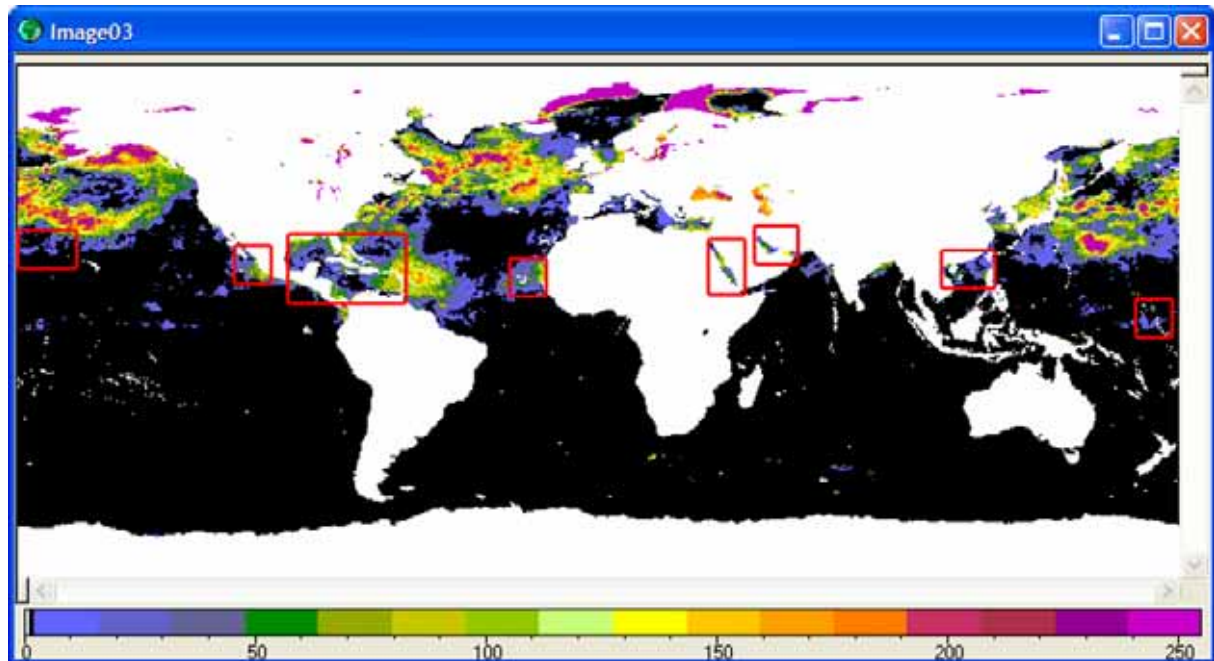
8. (a) 29.8°C. (b) above average, with an anomaly of +1.3°C. (c) Yes, the temperature was above the MMM, with a HotSpot value of 1.3°C; the HotSpot is greater than one, so the temperature was above the bleaching threshold. (d) 3.85 °C–weeks.

9. Bermuda: 3 °C–weeks, no major bleaching expected.

   Lee Stocking Island: 6 °C–weeks, significant bleaching expected.

   Puerto Rico: 8 °C–weeks, severe bleaching expected with some risk of mortality.

   US Virgin Islands: 11 °C–weeks, very severe bleaching and mortality expected.