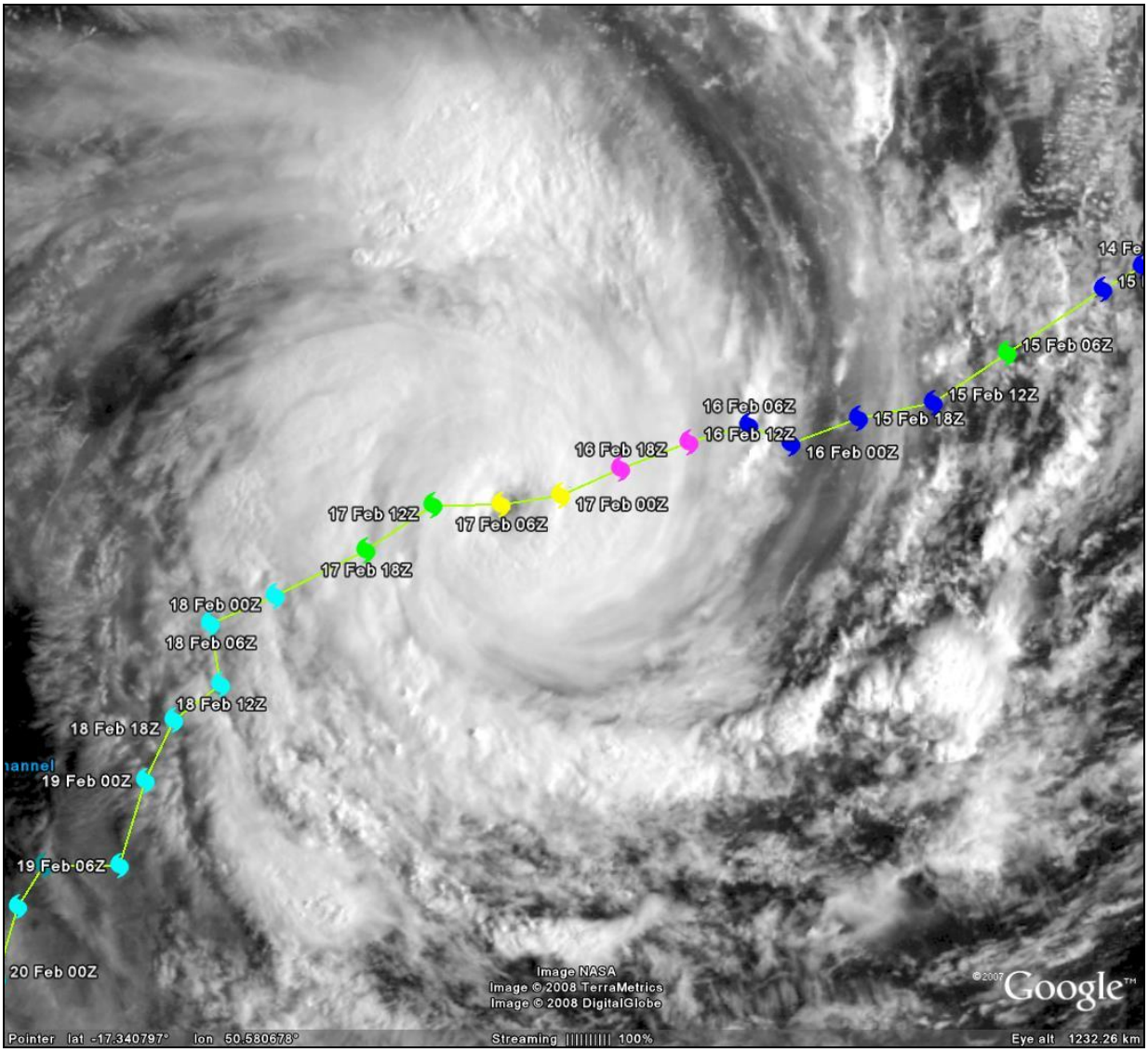
Using the Features of the Tropical Cyclones on Earth (TC-Earth) Application



Tropical cyclone Ivan approaching landfall on the eastern coast of Madagascar, February 2008

Joe Turk
Marine Meteorology Division
Naval Research Laboratory (NRL)
Monterey, CA
joe.turk@nrlmry.navy.mil

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1. Description

Virtual globes provide an effective framework for efficiently demonstrating meteorological and oceanographic concepts such as weather and climate to not only specialized weather forecasters, but to students and the public audience. With their emphasis upon geolocated data, virtual globes such as Google Earth represent the next evolution beyond the traditional browser; for this reason they are often referred to as "geobrowsers".

Within the past 10 years, a wide variety of publically available environmental satellite-based data has become available to users and gained popular exposure. For example, the NASA Earth Observing System (EOS) satellites (Terra, Aqua and Aura) are routinely used worldwide to depict phenomena such as fires, sand storms, volcanic activity, weather events such as flash floods, and other ocean and climate-related events. The Naval Research Laboratory (NRL) has maintained a popular web-based tropical cyclone (TC) website (NRL TC-Web) with a diverse selection of environmental satellite imagery covering worldwide tropical cyclones, including as an extensive image archive going back to 1997. To facilitate the display, animation and layering of satellite with other observational datasets in a user-selective fashion, the NRL TC-Web satellite data processing stream was adapted for use within the Google Earth framework. The resulting NRL Tropical Cyclones on Earth (TC-Earth) application is designed to exploit the capabilities of virtual globe technology to facilitate the display, animation and layering of multiple environmental satellite imaging and sounding sensors for effective visualization of tropical cyclone evolution. As with the NRL TC-Web, the TC-Earth application is a dynamic, realtime application, driven by the locations of active and historical tropical cyclones. TC-Earth has a simple interface that is designed around a series of placemarks that follow the storm track history. The position coordinates along the storm track are used to map-register imagery and subset other types of information, allowing the user a wide range of freedom to choose data types, overlay combinations, and animations with a minimum of number of clicks.

Google Earth allows one to define how, where, and when these data are displayed or animated. Since environmental satellite data are available with a variety of horizontal spatial resolutions, the imagery is "tiled" at a very small size. This allows low-bandwidth users to efficiently view and animate a sequence of imagery while zoomed at a high altitude, whereas high-bandwidth users can take full advantage of the native, fine-scale imagery resolution when zooming in to lower altitudes, which automatically triggers downloads of higher resolution image tiles. Dynamically updated network links automatically refresh the most recent satellite data. Geographical regions can be used such that datasets are downloaded (and can appear and/or disappear) only when the user navigates their viewing location to the region of interest. Since there may be multiple tropical cyclones active at any given time, the user can easily navigate between them. Updating a current image animation is efficient, since only the new images in the sequence need to be downloaded.

2. Requirements

You should already have Google Earth 4.3 (released 16 April 2008) installed and your operating system set up to recognize kml file types. If you don't have Google Earth installed, it is

available for download for Windows, Mac OS X and Linux operating systems. The performance of this application is largely dependent upon the network speed, the type of processor and graphics card. It is recommended that you increase the disk cache size to as large as you can (2 GB is the maximum). Under Earth's "Tools" -> "Options", select the "Cache" tab, and increase this from the default provided. A basic knowledge of how to navigate within Google Earth is assumed.

3. Background

To use TC-Earth one should understand a few basic concepts about tropical cyclones, satellite orbits and what the sensors onboard these satellites "see" from space. For users unfamiliar with these concepts, this section provides you with sufficient background knowledge to navigate within TC-Earth.

a) Tropical Cyclones

Tropical cyclones form and evolve over warm ocean waters, occurring within predominant ocean basins depending upon the time of year. The Atlantic (ATL) season runs from June-November of each year, the Eastern Pacific (EPAC) and Central Pacific (CPAC) between May-November, and tropical cyclones in these two basins are referred to as hurricanes. Tropical cyclones are most common in the Western Pacific (WPAC) basin (tropical activity year-round, minimum in February), and in the Indian Ocean (IO) and Arabian Peninsula region (activity which peaks in April and again in November). Tropical cyclones occurring in the Indian Ocean are referred to as typhoons. In the southern hemisphere (SHEM), common tropical cyclone genesis regions are northwest and east of Australia, and often in the southern Indian Ocean, where they frequently move west towards southern Africa. As a tropical cyclone first "spins up" in an area of low pressure, the clouds appear disorganized and the system is referred to as a tropical depression until the maximum winds exceed 33 knots. At this intensity, the system is referred to as tropical storm and assigned a unique, sequential number. Beyond 63 knots, official names are assigned and the storm is officially categorized as a tropical cyclone. In this application, we use the term "storm" loosely to refer to a tropical depression, storm, or cyclone. In this application, the storms are identified by three identifiers: the storm basin (ATL, CPAC, WPAC, EPAC, IO, or SHEM), the storm number, and the storm name.

b) Satellite Orbits and Data Latency

Environmental monitoring satellites are nearly always launched into one of two types of orbit patterns, geostationary (GEO) orbits or low-Earth orbits (LEO). A satellite in a geostationary orbit is positioned at a fixed longitude directly above the equator, with an altitude of 35786-km above ground. From this perspective, the satellite orbital period matches that of the Earth. In other words, to an observer on the satellite the Earth appears stationary, and vice-versa. Imaging sensors onboard GEO satellites are able to scan the entire "disk" of the Earth as seem from space typically every 30 minutes, as shown in the left panel of Figure 1. Telemetry data from sensors onboard GEO satellites is transmitted in realtime to dedicated ground stations, with navigated and calibrated data available for processing within minutes. Since any given tropical cyclone

and its surroundings can be viewed from sensors onboard at least one of the network of (as of early 2008) five operationally maintained geostationary satellites, the overall data latency for geostationary satellite data is very small.

Satellites placed into LEO are launched into space by smaller boosters and placed at altitudes under 1000-km above ground. Usually, they are placed into an orbit which passes over the polar regions, completing one revolution every 90 minutes. While the satellite is moving around the Earth, the Earth underneath the satellite is rotating about its axis, so over the course of one day much of the Earth is covered one time or another. Since they are closer to the Earth, sensors onboard low-Earth orbiting satellites cover a limited area under the satellite as it flies around the Earth. The right panel of Figure 1 shows the amount of coverage that a typical scanning sensor onboard a LEO satellite flying in an 800-km orbit can gather during one entire day.

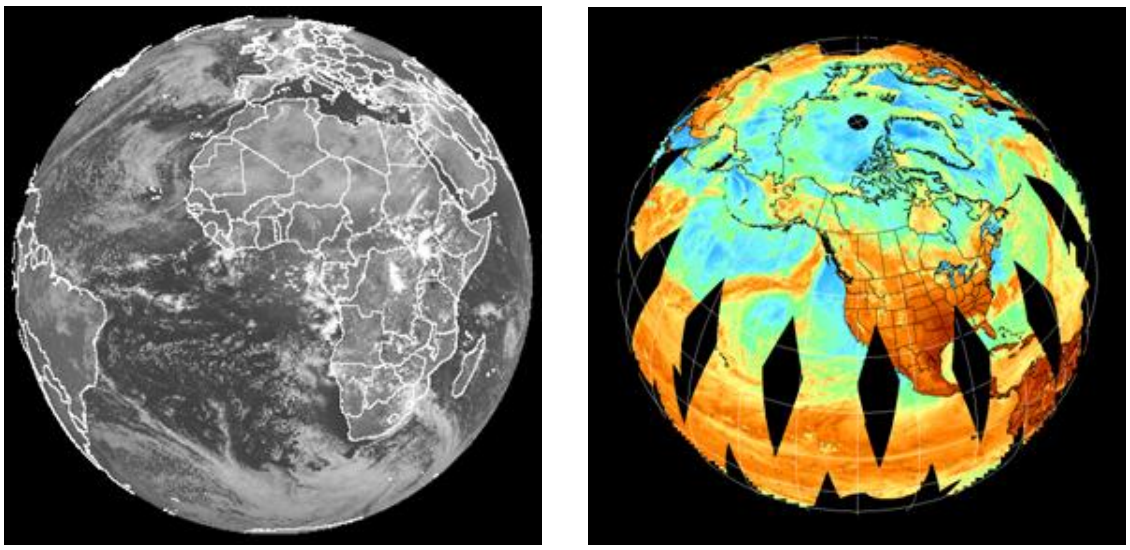


Figure 1. (Left) Coverage of the Earth as seen from a satellite in a geostationary orbit positioned at a longitude of 0E. This area is scanned typically every 30 minutes. **(Right)** Coverage of the Earth from a satellite in a low-Earth orbit, after one day of orbiting. Depending upon the scan width of the imaging sensor, the missing diamond-shaped areas can be reduced or eliminated.

A special case of a LEO orbit is the commonly-used sun-synchronous orbit. As its name suggests, the orbit of the satellite is configured to follow the same local time (i.e, clock time) and therefore maintain synchronized to the same solar illumination. By arranging the orbit inclination and altitude, the orbit can be made to precess by about one degree of longitude each day, the same rate at which the Earth revolves about the Sun. Sun-synchronous orbits are used for most environmental satellites, since it is advantageous to observe weather and other geophysical phenomena at the same local time (a notable exception is the NASA TRMM satellite which is intentionally placed in an asynchronous orbit; its local time of observation varies each day, repeating itself every 46-days over the equator. This type of orbit was especially designed to sample tropical precipitation at all local times). Similar to geostationary satellites, many LEO satellites have “direct broadcast” capability whereby dedicated ground stations capture live data as the satellite flies within range of the station tracking antenna. However the satellite is only in

range of the antenna for a short time (10-15 minutes), providing only local data coverage. For global coverage, data gathered from the entire orbit are stored onboard and typically downlinked to larger, high latitude ground stations, since the satellite is within range of these tracking antennas on each orbit. From these ground stations, these data are distributed to operational international weather centers. As a result, the latency of data from most LEO satellites is larger than for GEO satellites, depending upon the amount of data that is stored onboard, when the downlink occurs, and the distribution time. Since tropical cyclones can undergo rapid intensification or shift their movement in a matter of hours, the lowest possible data latency is critical to maximize the usefulness of these data.

c) Satellite Data Coverage

An imaging sensor fixed to view vertically down on an orbiting LEO satellite would not provide much useful information, just an image that would trace out a line under the satellite along track. Imaging sensors therefore scan a swath across the track as the LEO satellite moves forward in space. The width of the swath depends upon several factors but is done in one of two scanning patterns, either across-track scanning (Figure 2a) or conically scanning (Figure 2b). Across-track scanning is commonly used for visible-to-infrared spectrum imagers with a swath width as wide as 2500-km (wider swaths minimize the missing diamond-shaped areas in Figure 1b). They also provide the best horizontal resolution directly underneath the spacecraft. Conically scanning imagers are pointed slightly ahead of the spacecraft and spin around a vertical axis, tracing a moving circular pattern on the Earth's surface as the satellite moves. Image pixels are gathered during a portion of the forward swath of the circular pattern, as depicted in Figure 2b. Conically scanning imagers are used for microwave spectrum imagers since the imager field-of-view maintains nearly a constant incidence angle with the surface of the Earth, greatly simplifying the image interpretation. A conical scanning sensor at a typical 800-km altitude has a swath width of about 1500-km.

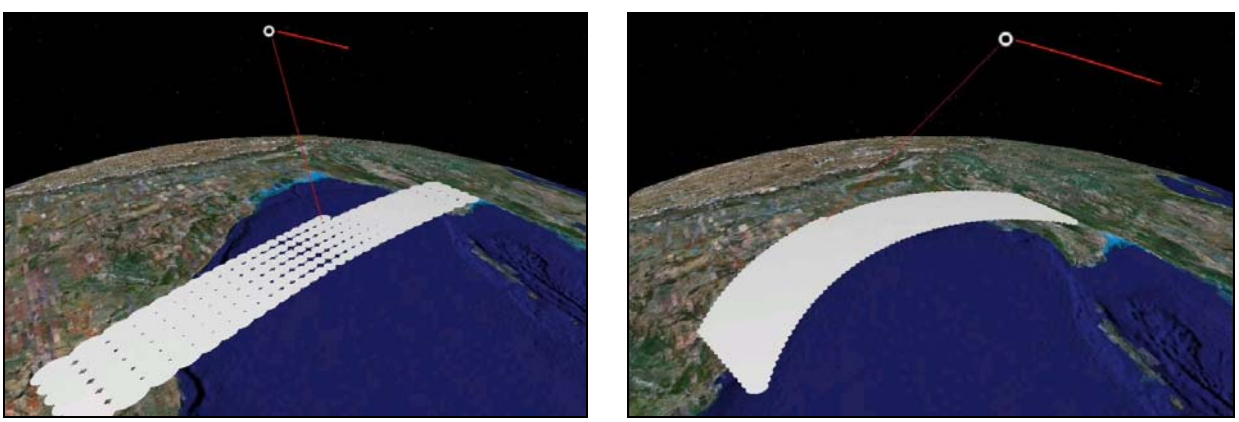


Figure 2. **(Left)** Scanning pattern of an across-track imager, as the satellite moves in space. Each white spot is a data pixel, which have the finest resolution at nadir but become more elliptically shaped near swath edges owing to Earth curvature. **(Right)** Scanning pattern of a conically-scanning imager, which gathers data during the forward swath. All image pixels have a similar elliptical shape, and this viewing geometry allows the imaging sensor to maintain a nearly constant incidence angle with the surface of the Earth.

This discussion of scan swath is important for understanding data coverage. The ideal satellite overpass would occur when the tropical cyclone was located right in the middle of the sensor swath, for maximum coverage of the area around the storm. But a wider swath is better able to "capture" more of the area surrounding a tropical cyclone when the satellite overpass lies off to one side of the storm location. We will indicate the "closest point of approach" distance for all LEO-based satellite datasets, defined as the closest distance between the satellite ground track and the storm location. To illustrate, the green line in Figure 3a shows the ground track (blue line) of a ascending overpass of the Aqua satellite, near the location of a tropical cyclone (blue-colored icon). Using the "Ruler" in Google Earth (Under "Tools" -> "Ruler"), the closest point of approach (the distance of the yellow line perpendicular to the ground track) is 157-km. The image from the eventual Aqua overpass of this storm is shown in Figure 3b. In this case, the 1400-km swath width of the AMSR-E sensor on this satellite (Figure 3b) is sufficient to cover the storm area near the cyclone. Figure 4a shows the ground tracks of an ascending DMSP F-13 satellite overpass (red line) where the closest point of approach is 849-km. In this case, the sensor swath of the SSMI imager is not wide enough to cover the area near the storm (Figure 4b).

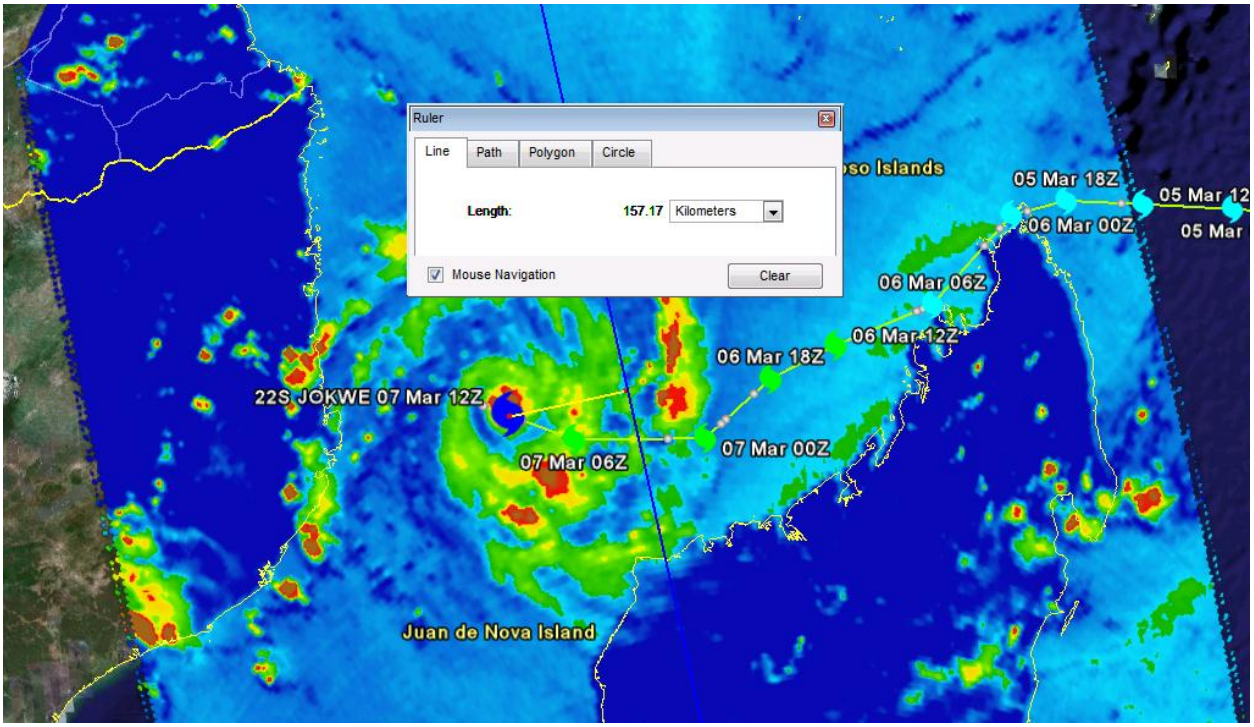
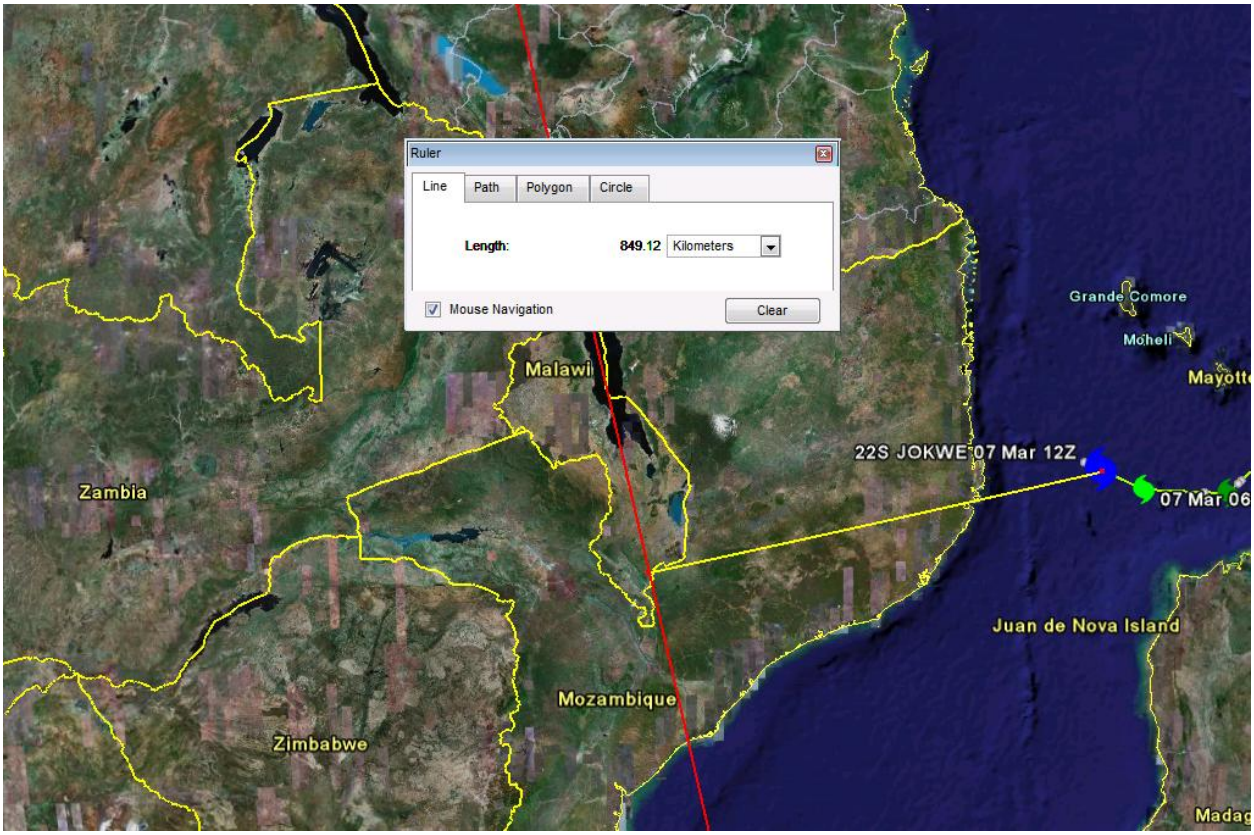


Figure 3. (Upper) Predicted ground track (blue line) from the descending overpass of the Aqua satellite as it passes near the location of tropical cyclone (blue-colored hurricane icon). The closest point of approach is 157-km. **(Lower)** Satellite image from the eventual Aqua overpass at this time. In this case, the sensor swath of the AMSR-E microwave sensor is wide enough to cover the area near the cyclone, so the overpass track is shown in a blue color.



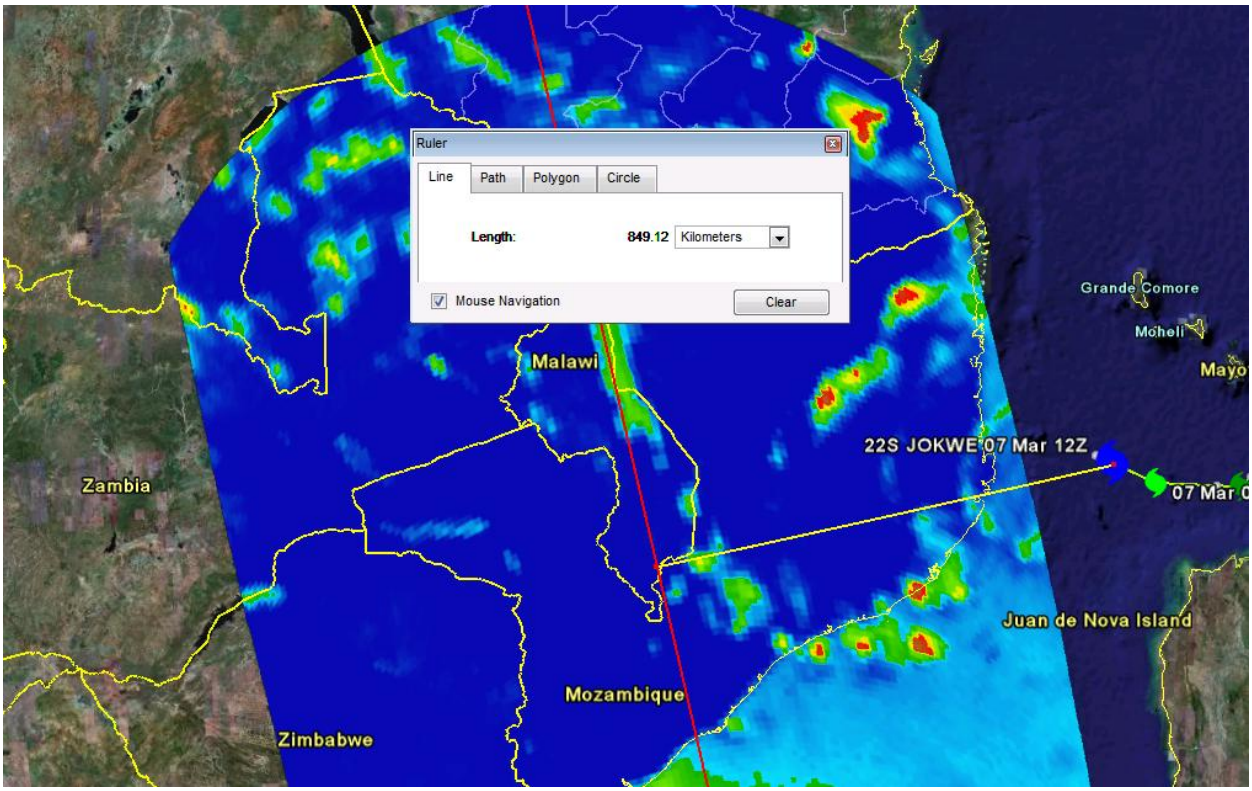


Figure 4. (Upper) Predicted ground track (red line) from the descending overpass of the DMSP F-13 satellite as it passes near the location of tropical cyclone (blue-colored hurricane icon). The closest point of approach is 849-km. **(Lower)** Satellite image from the eventual DMSP overpass at this time. In this case, the sensor swath of the SSMIS microwave sensor is not wide enough to cover the area near the cyclone, so the overpass track is shown in a red color.

These two quality factors – satellite data coverage and data latency – are key indicators of the utility of these data in this application and will be referenced below.

4. Starting the application

TC-Earth is initiated from within the NRL TC-Web application. The left frame of the TC-Web shows the number and name of active tropical cyclones in each of the six ocean basins discussed above. When a KML button KML appears next to any storm, this indicates that the TC-Earth application is available. Selecting and clicking this button will open up Earth and fly you to the region of the world where the storm is located. Once Earth has been loaded with the main level kml file, an entry for the storm name will be listed under Earth's "Temporary Places" folder. The "plus sign box" in front of this (or any other) entry means that it is a folder that can be further expanded. Clicking on this box opens up the folder to reveal its contents, as shown in Figure 5. Note that the position placemarks and the track line are both pre-selected.

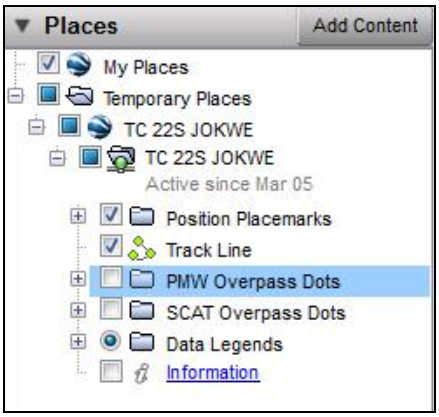


Figure 5. After the storm is opened up in Google Earth, an entry will appear as an expandable folder under the "Temporary Places" left frame. The entry will be listed by the storm number and name (e.g, TC 22S JOKWE). Opening up this folder (click on the plus sign) reveals the contents for this storm. Note that the position placemarks and the track line are both pre-selected.

a) Viewing the storm track

At this point, the storm track history will appear as a series of connected hurricane icons (the most recent storm position will have a slightly larger icon) as shown in Figure 6. The date of each position is shown (time in UTC, denoted as Z time) and the color of the hurricane icon is tied to the storm intensity (category number) at each position according to the Saffir-Simpson scale. You can toggle the position icons or the storm track on/off via the checkbox in the storm folder. For active storms, the storm track will automatically update itself every 30 minutes (the storm position is only updated every 6 hours, but the satellite data update as frequently as 30 minutes), provided that the storm track checkbox is selected.

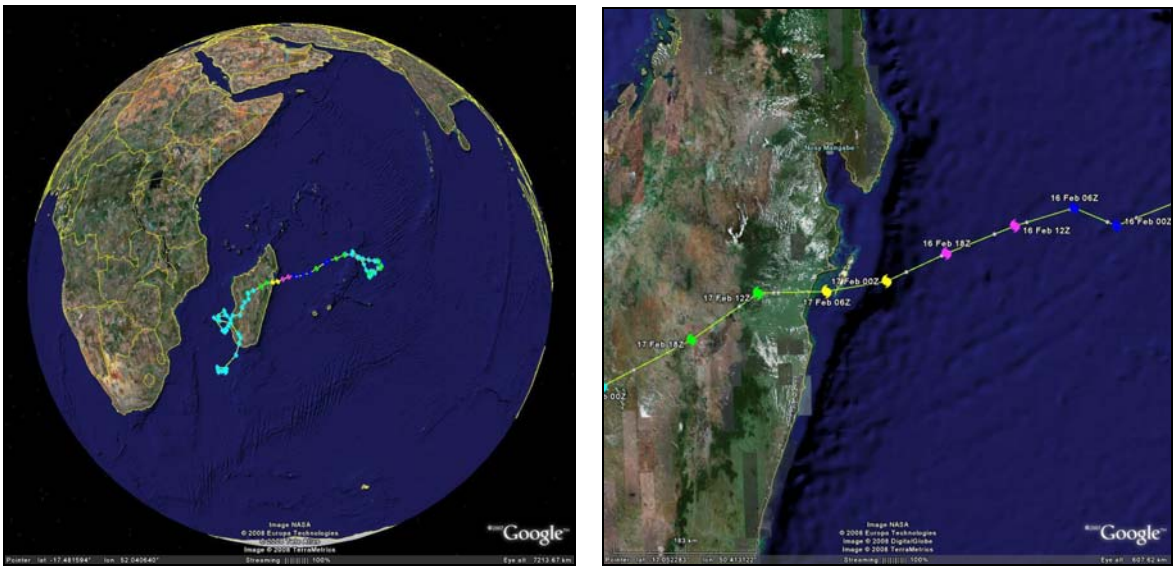


Figure 6. (Left) Track of tropical cyclone Ivan during 7-25 February 2008. **(Right)** Viewed from a lower altitude (the current storm position has a slightly larger icon that the others) where the position dates are shown. The icon color indicates storm intensity.

b) Listing satellite overpasses at each position

Each of the position icons is a placemark, which when selected opens up a popup balloon, as depicted in Figure 7. The small image thumbnail in the upper left shows the closest visible (thermal infrared at night) image relative to this position time; to the right of this is information regarding the storm intensity at this time. Below this is a tabular listing of all satellite overpasses and their associated data products available during this position time interval (i.e, between this position time and the previous position time 6 hours earlier), sorted from newest-to-oldest in time. The list of files is color-coded to quickly inform the user about two important characteristics of these satellite data. The color of the occasional horizontal lines indicates the time **data latency** of all datasets. A red line indicates that data above the line are more than 12 hours old (relative to the last update time), while yellow, blue and green indicates that data above the line are less than 12, 6, or 3 hours old, respectively. Tropical cyclones can intensify quickly, necessitating the need for the most up-to-date data.

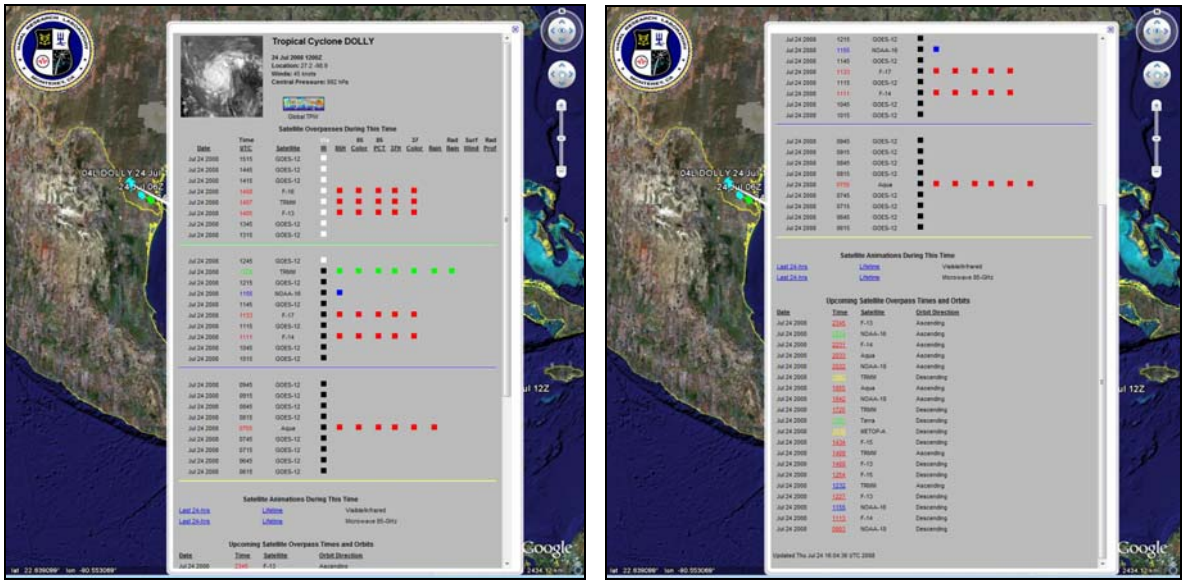


Figure 7. (Left) Popup displaying the list of satellite datasets available near the latest position of tropical cyclone Dolly in July 2008, after landfall in Texas. **(Right)** Sliding further down along the slider bar on the right side of the popup balloon, the latest animations and satellite overpass tracks of upcoming (future predicted) overpass times are shown (discussed in Sections 6 and 7).

For each line in the popup, the satellite overpass date and time, satellite name, and satellite data products are listed from left-to-right. For all LEO satellites, the text color of the overpass time and the checkbox for each data product (which is the hyperlink to the dataset) provides an indication of the satellite **data coverage**. Red text indicates that the satellite subtrack passed more than 500-km from this storm position, while yellow, blue and green indicates that the satellite subtrack passed within 500, 200 or 100-km, respectively. Therefore, the user can immediately gauge which satellite datasets possess the best overall quality in terms of timeliness and coverage. GEO satellites, by virtue of their Earth-disk coverage, always have full coverage of the storm, but the color of the text time is left black in order to distinguish GEO from the LEO

satellite overpasses. A white checkbox for a GEO satellite indicates a daytime overpass (visible image), and a black checkbox indicates a nighttime overpass (infrared image).

c) Selecting datasets to view

The popup table displays several different types of data products per satellite overpass, depending upon which sensor types are onboard each satellite. The datasets below are intended for users familiar with (at a minimum) typical visible and thermal infrared (IR) satellite imagery as commonly seen on weather-related websites or television weather. For advanced users, these various types of satellite data products are described in detail in the Appendix at the end of this document. But for many users, the most common (and easy to understand) satellite imagery datasets are the traditional visible (created during daytime) and thermal infrared (created during night time) imagery, which are available from any of the GEO satellites (whichever ones covers the storm area). These are the data that are commonly seen on weather websites, where the data may be colorized a certain way in order to highlight areas of clouds, rain, snow, etc. Figure 8 compares a visible and a thermal infrared image. As you may have noticed when looking down at clouds when flying aboard jet aircraft, taller and thicker clouds reflect more visible sunlight (appear whiter) than shallower, thinner clouds (appear darker). Oceans and most land surfaces are poor reflectors of sunlight (snow and deserts are an exception). At night, the depiction switches to a thermal infrared measurement in the 11 µm band, where the shading is closely related to the physical temperature of the cloud. Taller, thicker clouds are colder and depicted with brighter white shades; shallower clouds and land surfaces are shown in increasingly darker shades. These visible and thermal infrared (Vis/IR) geostationary satellite imagery are updated as frequently as every 30 minutes and are likely to be the most useful dataset to view the storm structure and evolution.

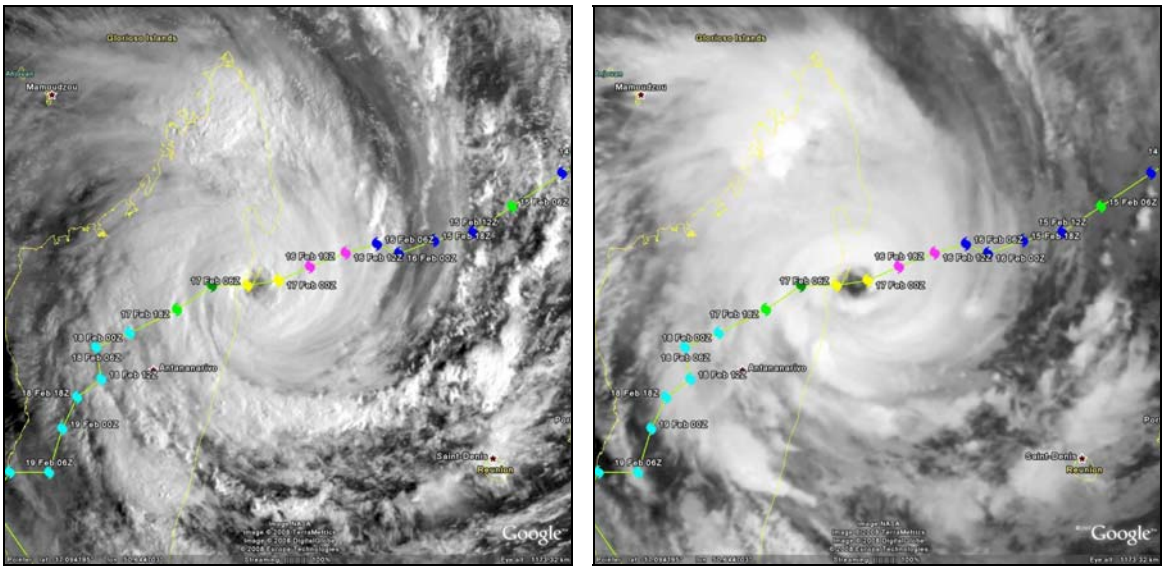
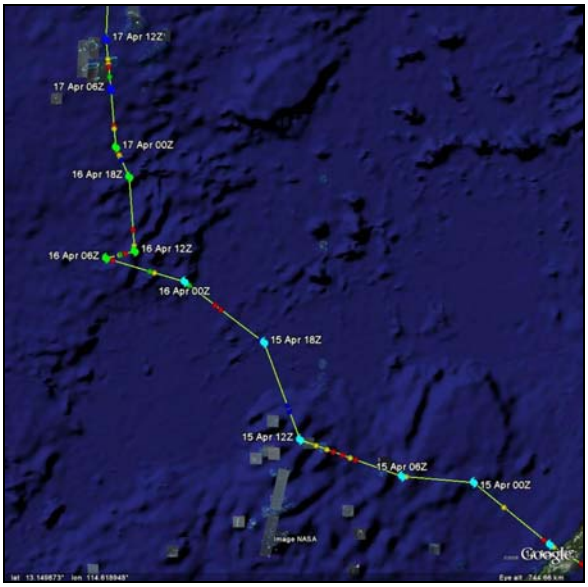


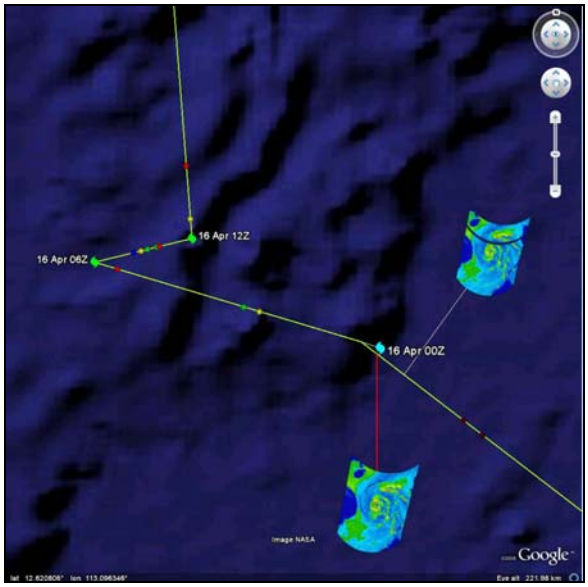
Figure 8. (Left) Visible image of Hurricane Ivan at 0430 UTC (shortly after sunrise) on 17 February 2008. **(Right)** Infrared image taken two hours earlier, at 0230 UTC.

The storm position closest in time to the satellite data time is used to set the center coordinates of the map-registration for an image size sufficient to cover the cyclone circulation and surrounding rainbands. Images larger than 500 pixels on a side are tiled for best viewing and download efficiency. Occasional overpasses of the EOS-Terra and Aqua satellites during daylight hours provide up to 250-m visible imagery (1-km infrared at night).

d) An alternate way of perusing data: Overpass Dots

In the main storm entry under the "Temporary Places" (Figure 5), there are two unselected folders, named "PMW Overpass Dots" and "SCAT Overpass Dots". Selecting either of these will bring up a sequence of small colored dots along the track, tied to the overpass times of satellites with 85-GHz passive microwave imagery (for PMW) and surface wind vector capability (for SCAT, QuikSCAT, Coriolis and METOP). Figure 9a shows the PMW dots for a segment of the track of Cyclone Neoguri (mid-April 2008, Western Pacific Ocean). The dot position is determined by interpolating the overpass time between adjacent position times, and the dot color is determined by the overpass quality as described in Section (b) above. You can mouseover these dots (i.e, slide the mouse along the storm track) and view small 150-pixel thumbnails of each image, as shown in Figure 9b. Note that if there are multiple overpasses clumped near the same time, which is often the case for the sun-synchronous satellites, Google Earth will pop up the various thumbnails with "sticks" tied back to their location along the storm track. This allows one to have a "quick look" at the time history of the data without having to load any KML links. Once you have selected a dataset that you would like to view, select (click) the thumbnail image and a small popup balloon will appear with the date and satellite time listed at the top and the same thumbnail image (Figure 9c). Click on this thumbnail and the full geolocated data will load in Earth (Figure 9d) and be listed as an entry under the "Temporary Places".





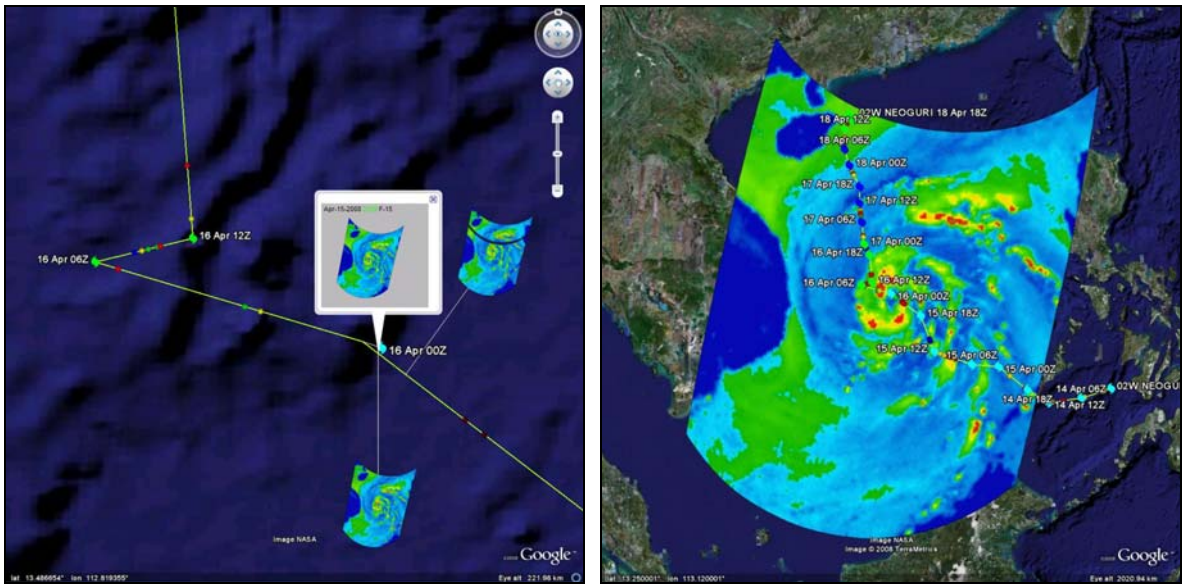


Figure 9. Viewing available satellite imagery from a sequence of satellite overpasses. **(a, Upper Left)** Storm track for Cyclone Neoguri (mid-April 2008 in the Western Pacific Ocean) with the "PMW Overpass Dots" folder selected, showing the sequence of overpass dots for satellites with 85-GHz data capability. **(b, Upper Right)** Mouseover one or more of the overpass dots shows a small thumbnail image of the imagery. This feature allows you to quickly peruse 85-GHz microwave imagery through the storm lifetime by sliding the mouse along the storm track line. **(c, Lower Left)** Selecting (clicking) any one of the thumbnails pops up a balloon with the satellite date and the same thumbnail inside. **(d, Lower Right)** To load the data in Earth, click on the image in the popup balloon. The full geolocated data will be loaded from the KML link.

5. Overlaying multiple datasets

To maximize the information that can be gathered from multiple satellite and data types, users may want to overlay one or more datasets. The visible/infrared imagery discussed above makes an ideal "background" image to use when overlaying these other satellite data types (see Appendix), for enhancing detail on the tropical cyclone intensity and structure. Here are some suggested image overlay combinations:

1) Overlay 85-GHz microwave imagery on top of nearby-time visible/infrared imagery. This will contrast the inner cloud structure of the storm (the "eye" structure) with the overall structure near the tops of the clouds. An example from tropical cyclone Ivan in 2008 is shown in Figure 10.

2) Overlay a rainrate image on top of nearby-time visible/infrared imagery to reveal the location and intensity of the surface precipitation underneath the clouds. An example is shown in Figure 11 for Hurricane Felix in 2007.

3) Overlay surface wind vectors on top of nearby-time visible/infrared imagery to contrast the cloud structure and shape with the wind speed and direction at the ocean surface. Examples are shown in Figures 12 (Hurricane Ivan) and 13 (Cyclone Ophelia in 2008).

4) (Updated only infrequently) Overlay vertical radar profiles from the TRMM and CloudSat space radars on top of nearby-time visible/infrared imagery. An example for the CloudSat space radar is shown in Figure 14, from imagery during Typhoon Sidr in the Bay of Bengal. Use Earth's navigation controls to tilt and rotate the viewing perspective along one side of the profile. If your mouse has a depressible scroll wheel or you are using a Space Navigator, you can use it to tilt and rotate at the same time. Since visible/infrared satellite images generally provide information on the horizontal structure near the tops of the clouds, this combination provides a picture of what the vertical cloud structure looks like "underneath" the top of the cloud. Combining three products together (geostationary imagery providing the large scale view of the cloud top structure, space radar providing a glimpse of the vertical cloud and precipitation structure underneath, and scatterometer data providing information on surface wind speed and direction), condense a high level of data and information content down into one single depiction. Furthermore, the user can navigate around the tropical storm from different view locations and tilt angles. **Note:** By virtue of how the radar profiles are currently processed, this option will not work well on older computer architectures (e.g., Pentium-based PCs, PowerPC Macs, single core processors, etc) or older graphics cards.

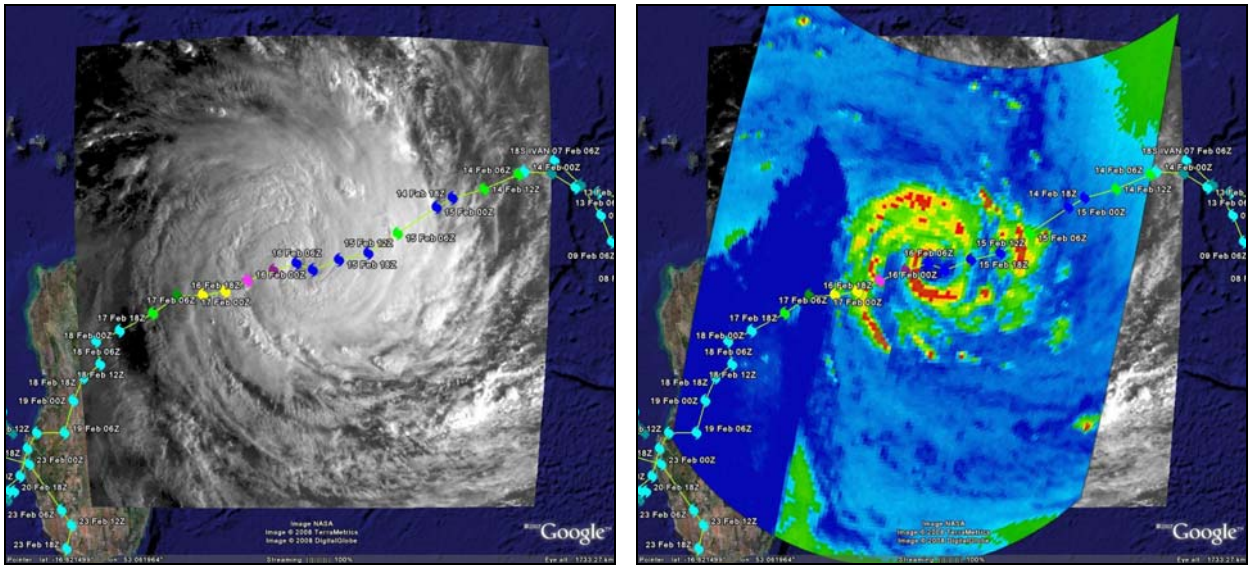


Figure 10. (a, Left) Visible satellite image of Hurricane Ivan as it approaches landfall on the island of Madagascar, from the Meteosat-7 satellite at 0330 UTC on 16 February 2008. **(b, Right)** Same image overlaid with the 85 GHz microwave imagery from the DMSP F-15 satellite at 0332 UTC. Note how the microwave imagery enhances the spiral circulation that is otherwise "hidden" underneath the visible imagery. The areas in red indicate regions of heavy convective-type precipitation and the horizontal structure of the eyewall intensity.

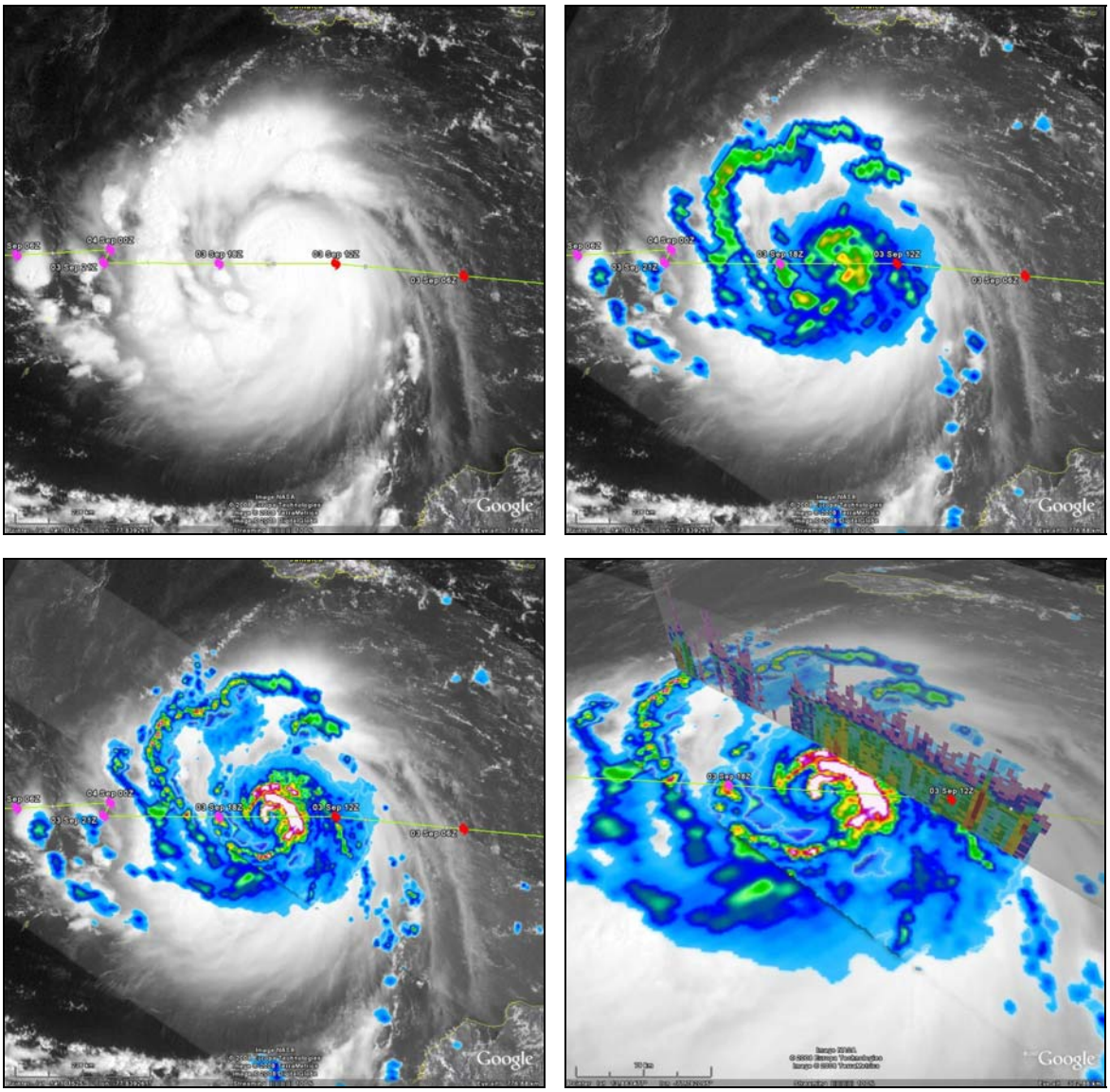


Figure 11. (a, Upper left) Infrared satellite image of Hurricane Felix in the Caribbean Sea, taken from the GOES-12 geostationary satellite at 1515 UTC on 3 September 2007. At this time, Felix had maximum winds of 125 knots (Category 4). From this image alone, the areas of maximum surface rainfall are difficult to discern. **(b, Upper right)** Same image overlaid with the surface rainfall estimated from the TRMM Microwave Imager (TMI) onboard the TRMM satellite, showing heavy rain in the southwest quadrant of the eye, as well as in the surrounding rainbands. **(c, Lower left)** Same image overlaid with the surface rainfall estimated from the Precipitation Radar (PR) onboard TRMM. The PR is capable of detecting heavier, finer scale rain structure. **(d, Lower right)** Same image with the vertical radar profile (see Appendix) from the PR shown down the middle of the TRMM ground track. Combined with the TRMM surface rainfall figures, the addition of the radar profile shows the vertical and horizontal extent of rainfall.

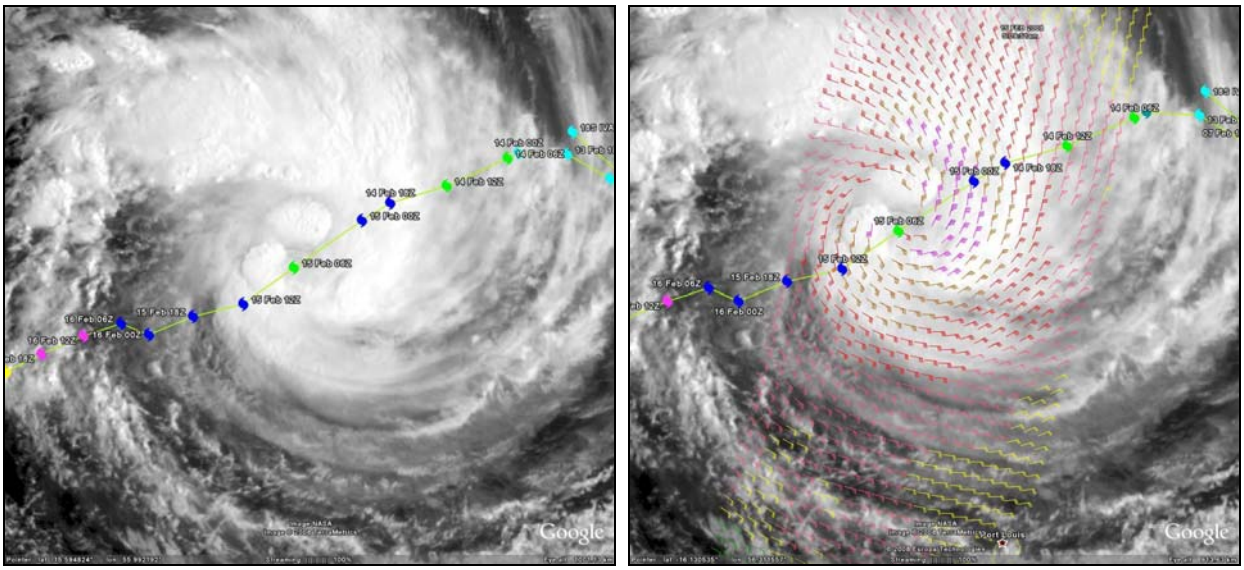


Figure 12. (a, Left) Visible satellite image of Hurricane Ivan as it approaches landfall on the island of Madagascar, from the Meteosat-7 geostationary satellite at 0530 UTC on 15 February 2008. **(b, Right)** Same image overlaid with surface wind vectors (plotted as color-coded wind barbs; see Appendix) from the Advanced Scatterometer (ASCAT) onboard the METOP-A satellite at 0509 UTC (21 minutes earlier). Note how the barbs point in a clockwise direction about the circulation center for tropical cyclones in the southern hemisphere. From the visible image of the clouds alone, it is difficult to locate the center of the low-pressure circulation; with the scatterometer data the location of the circulation is revealed with the ASCAT overlay.

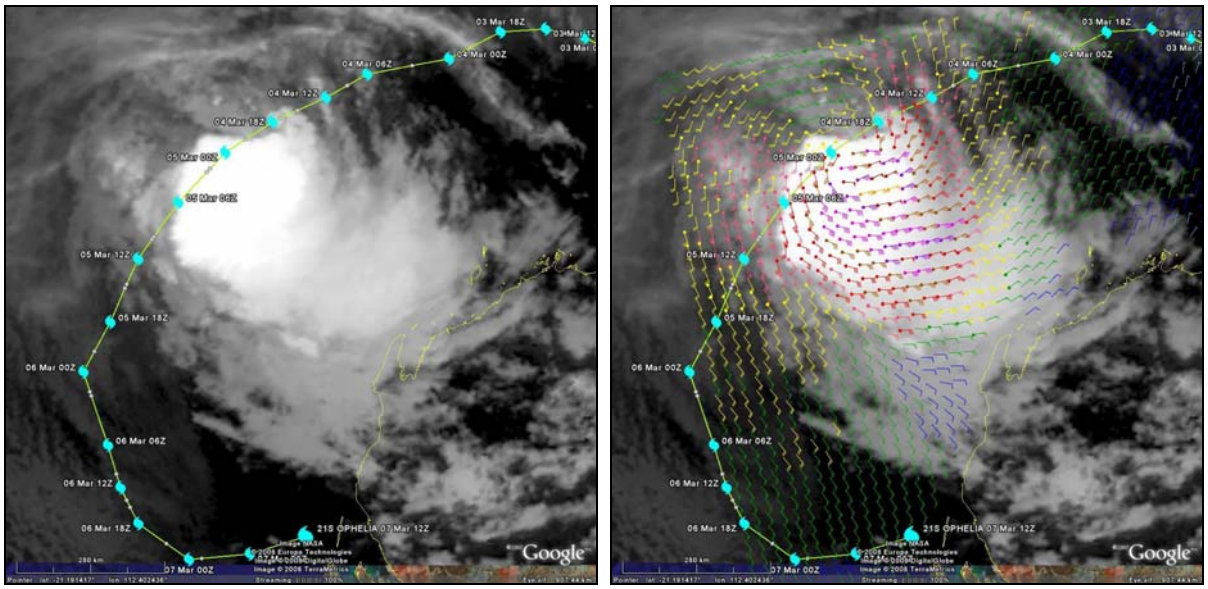


Figure 13. (a, Left) Infrared satellite image of Hurricane Ophelia offshore of northwest Australia, from the GMS-6 geostationary satellite at 2230 UTC on 4 February 2008. **(b, Right)** Same image overlaid with wind vectors from the Seawinds scatterometer onboard the QuikScat satellite overpass at 2227 UTC (see Appendix). Note how the barbs point in a clockwise direction about the circulation center for tropical cyclones in the southern hemisphere. Ophelia was a weak storm (50 knot winds, indicated by the aqua-colored position icons) and the low-level circulation center is often not discernable from cloud imagery alone, but evident from scatterometer data.

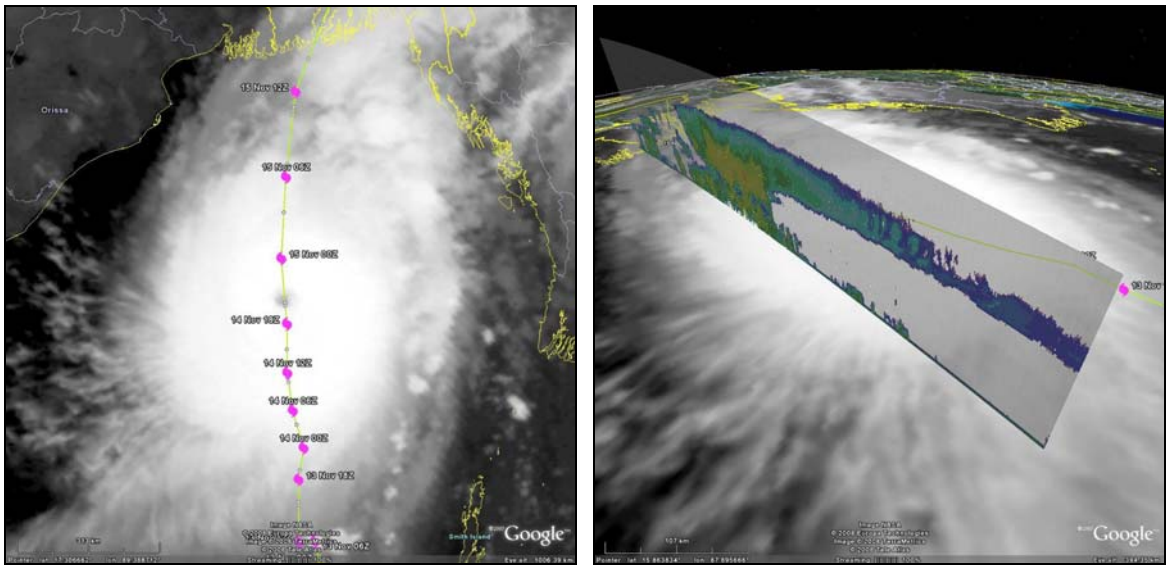


Figure 14. (a, Left) Infrared satellite image from the Meteosat-7 geostationary satellite at 2000 UTC on 14 November 2007, as Typhoon Sidr was developing in the Bay of Bengal. At this time the typhoon was a Category-4 storm with maximum winds of 130 knots. **(b, Right)** Vertical reflectivity profile (colored by reflectivity units; see Appendix) from the CloudSat spaceborne radar overpass at 2000 UTC overlaid on top of the infrared imagery, For proper vertical perspective, the image is stretched in the vertical and the top of the semi-transparent shading indicates a 20-km altitude.

Color legends are available as screen overlays and these can be accessed by expanding the folder named "Data Legends", shown in Figure 5. A radio folder item will list the available descriptive overlays, each providing a brief summary of the color scaling. Once you are finished with it, the screen overlay folder can be turned off to minimize screen clutter.

6. Image Animations

For the latest position (the position with the slightly larger icon), animations of the Vis/IR and 85-GHz microwave image sequence are available in the popup list immediately after the list of satellite datasets. There are two options for the animations:

1) A sequence of the most recent 24-hours of imagery. This option is available for the Vis/IR and 85 GHz microwave data. The previous 24 hours of imagery (relative to the most recent image time) is animated from oldest-to-newest in time.

2) A sequence of images throughout the entire storm lifetime. In this type of animation, the image movement will follow along the entire storm track. For the Visible/IR data, a previous image every 6 hours is selected and the sequence is animated from oldest-to-newest in time. For the 85-GHz microwave data, only the highest-quality overpasses in terms of coverage are selected (the more abundant NOAA and METOP overpasses are only included if the storm intensity exceeds 100 knots).

These animations are accessed by selecting and clicking the desired hyperlinks. To use the animation, first turn off all images in your "Temporary Places" (unchecking the "Temporary Places" folder will turn off visibility for all items including the storm track, which you can then re-select). Or if you don't need any of the temporary datasets, you can right click on "Temporary Places" and select "Delete Contents". Selecting any animation will bring up the first image in the sequence and the animation slider will appear in the upper part of the viewing frame, as shown in Figure 15. (**Hint**: The animation will load faster if you zoom out and view the storm from an eye altitude above 5000-km, since only the lowest level tiles will be downloaded). Select the "play" button (icon on right side of the animation slider). The animation will step through each image in the sequence as they are downloaded. This could take several minutes depending upon the download speed; once these downloads complete the animation should run smoothly. The animations option (icon on left side of animation slider) allows you to adjust the speed of the animation. To manually animate these data, select and hold down the mouse button on the lower part of the animation time indicator, and move it sideways as you desire.

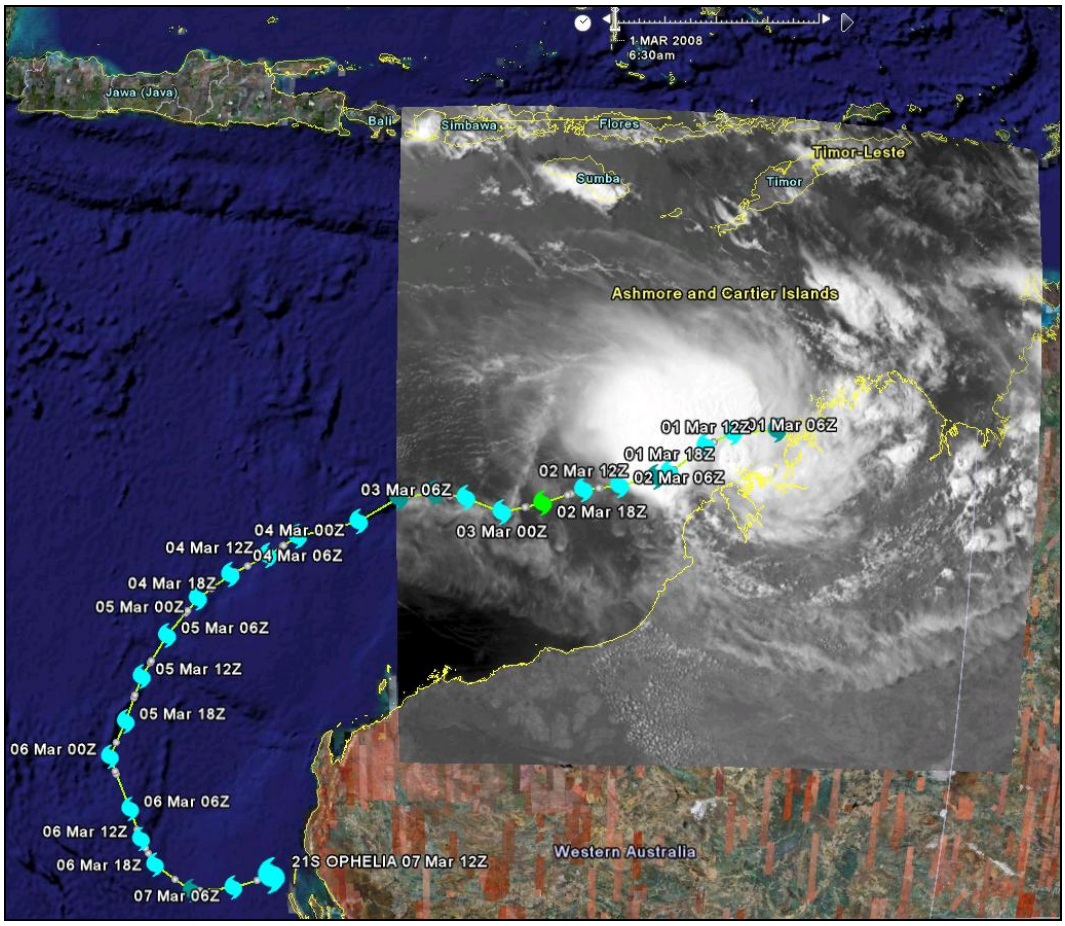


Figure 15. Animation of lifetime visible/infrared imagery from tropical cyclone Opehlia. When one the animation links is selected from within the position icon popup (shown in Figure 7), an animation item appears in the list of "Temporary Places", and the first image in the sequence appears (shown here). The animation slider (just to the right of the top center of the viewing frame) appears. The "play" button is located to the right of the slider and the animation options are located to the left.

In Google Earth 4.3, day/night shading was added as an option to the icons in the menu bar. With the "sunrise" icon selected (top of Figure 16), the animation will also include associated day/night shading for each frame in the sequence (that is, for any selected layer that has a KML time tag embedded within it). You can toggle the day-night shading on an off as desired.

The animation will automatically update itself every 30 minutes, even if you leave it running. When an update occurs, you will see the animation flash briefly and slow for a short while as only the new image(s) in the updated animation sequence are downloaded. This is an ideal way to observe the evolution of the tropical storm.

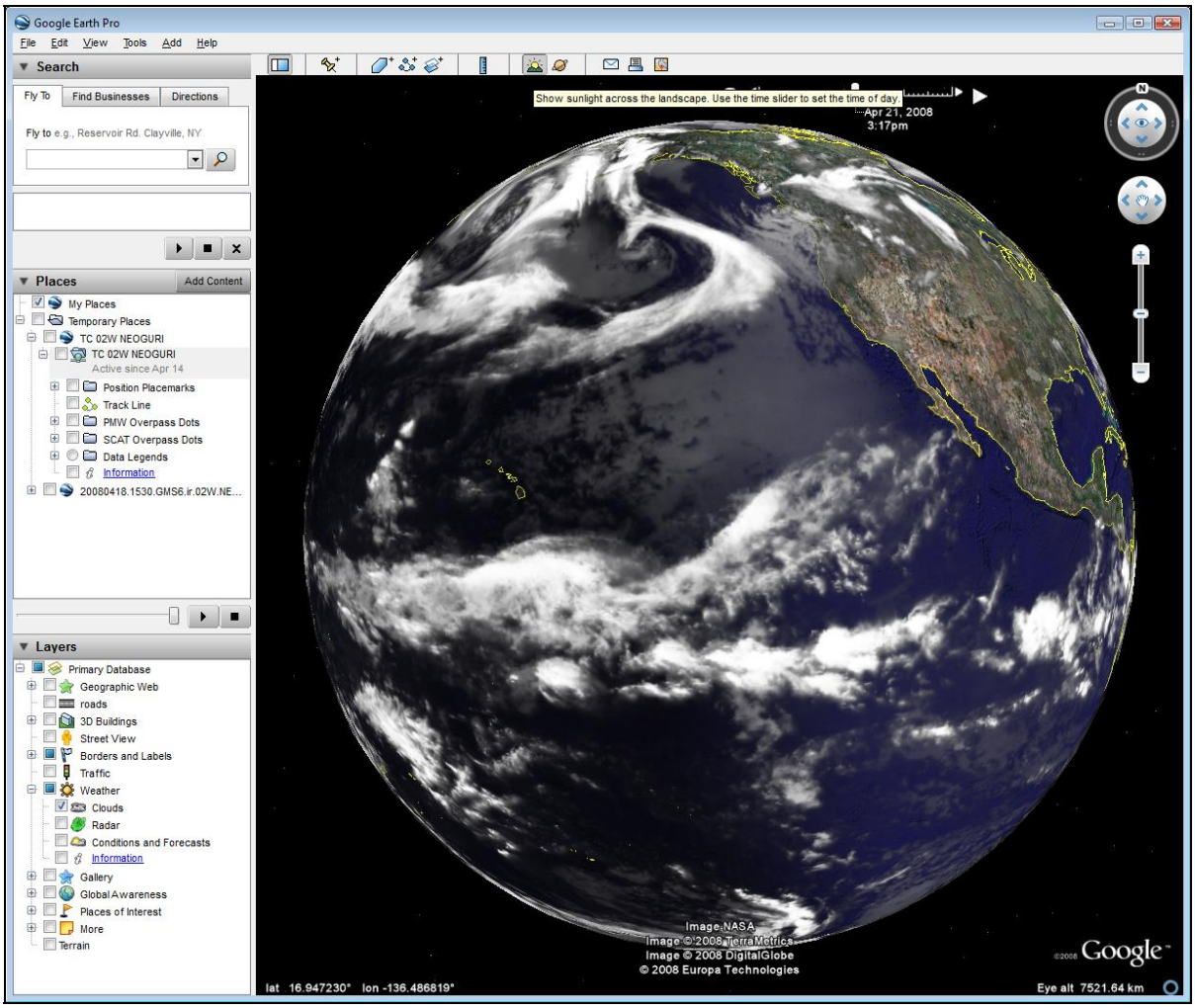


Figure 16. With the release of Google Earth 4.3 in mid-April 2008, day-night shading has been included as an icon in the top menu bar. Clicking on the "sunrise" icon turns on shading (clouds at night appear against a near-black background). You can toggle the day-night shading on and off.

7. Previewing Future Satellite Overpass Tracks

At the bottom of the popup for the latest position placemark (the slightly larger icon), there is a second list that provides the user with the predicted times of upcoming satellite overpasses, up to 12 hours into the future (relative to the time of this latest position). These predicted overpass times are useful to forecasters and other operational users who time their observations and warnings to coincide with overpass times of selected satellites. As discussed above, the color of the overpass time text is related to the quality of the overpass. Red text indicates that the satellite subtrack passed more than 500-km from this storm position, while yellow, blue and green indicates that the satellite subtrack passed within 500, 200 or 100-km, respectively. Selecting and overpass brings up the image subtrack (track line is colored as above) with arrows indicating the satellite direction (down arrows for a descending satellite overpass, up arrows for ascending) and beginning and end times of the track segment. Figure 17a shows four overpasses, one from the Terra satellite (green), TRMM (yellow) and METOP and DMSP F-14 (red). In these renditions, the track segment is placed along the actual satellite flight altitude. By tilting the Earth slightly with Earth's navigation controls, you can see the actual track in space. Note the lower orbit altitude of the TRMM satellite (402-km), as it flies "underneath" the tracks of the other three satellites (Figure 17b).

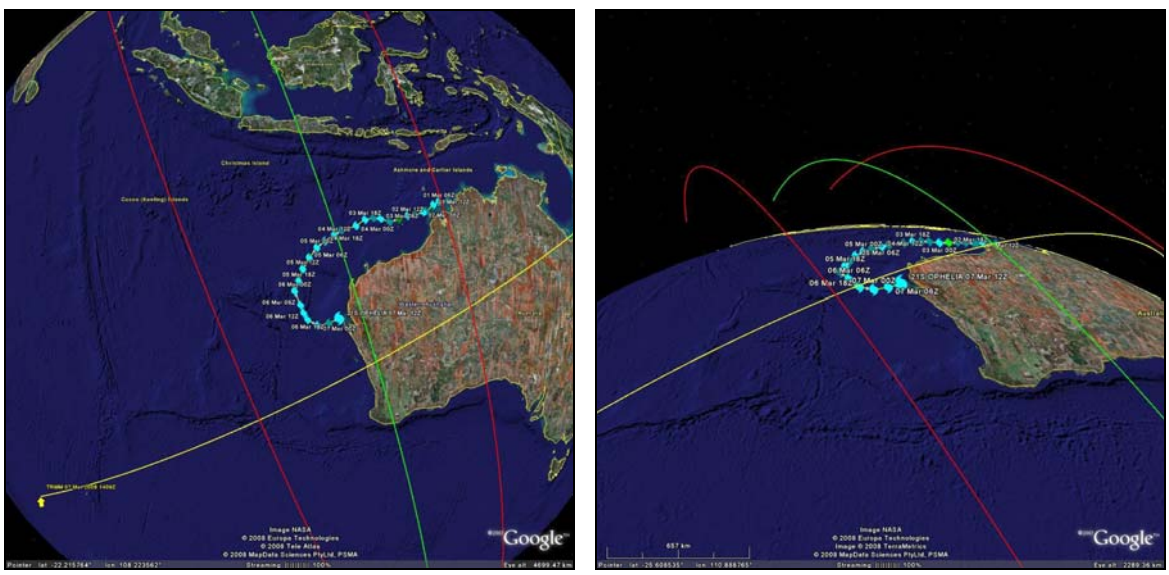


Figure 17. (a, Left) Ground track of four upcoming satellite overpasses, color-coded by closest approach point (described in Section 4c) to the latest storm position (21 UTC on 7 March 2008) of tropical cyclone Ophelia. Red indicates that the satellite subtrack passed more than 500-km from the storm position, while yellow, blue and green indicates that the satellite subtrack passed within 500, 200 or 100-km, respectively. The "down" and "up" arrows signify a descending (ascending) overpass. **(b, Right)** By tilting and rotating the Earth, you can see the actual orbital path of these satellites.

8. Optional Over-Ocean Backgrounds

The blue bathymetry backgrounds that are used as a default in Google Earth for over-water backgrounds are not particularly revealing. At the top of each popup balloon (see Figure 7),

there may be one or two small thumbnail images labeled **Global TPW** and **Global SST**. These image thumbnails are hyperlinks which when activated, change the over-ocean backgrounds. The Global SST is the global sea surface temperature (SST) data produced by the Fleet Numerical Meteorology and Oceanographic Center (FNMOC) Global High Resolution SST/Sea Ice Analysis (GHRSST), a contribution to the Global Ocean Data Assimilation Experiment (GODAE) HiRes SST project. The analysis is updated every 6 hours using AVHRR GAC satellite SST and in situ SST from ships and buoys (fixed and drifting).

The Global TPW is the global total precipitable water (TPW), produced from multi-orbit composites of the total precipitable water (TPW) from the DMSP SSM/I and SSMIS satellite sensors (currently F-13 through F-17). The composite is updated every 6 hours. Figure 18 illustrates how these background composites appear when opened in Google Earth for the over-ocean background. Note that these background images appear like any other image referred to above. If there are currently other images displayed, there is no preferred layer order and the background image may cover up the existing overpass image (this is a feature that I intend to fix in future versions). Both of these image composites are created at a 0.25-degree/pixel resolution.

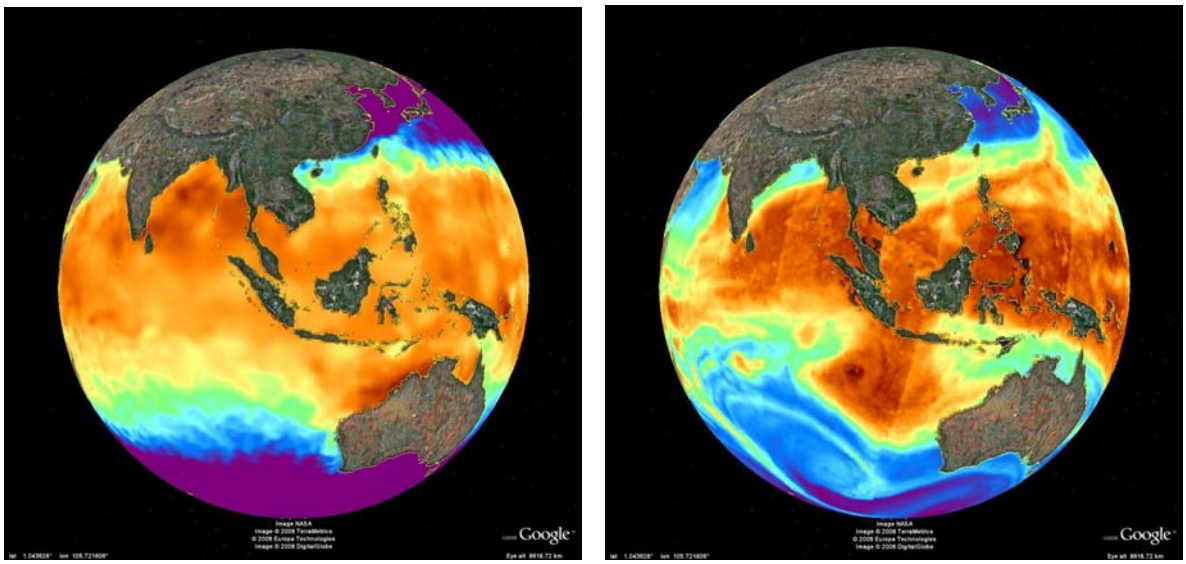


Figure 18. Optional over-ocean image overlay backgrounds available in TC-Earth. Examples from 06Z on 25 April 2008. **(Left)** Global Sea Surface Temperature (SST), scaled between 20-32 C. **(Right)** Global Total Precipitable Water (TPW) composite from multiple orbits of the SSMI and SSMIS sensors onboard the DMSP satellites, scaled between 10-65 mm. Both of these composites are updated every 6-hours.

Known Issues

1. Every dataset that is selected gets loaded under the "Temporary Places" folder and it is left to the user to save anything. Since these data are dynamic, you probably don't want to save anything. When you close out of Earth and are prompted to save these data to your "My Places" folder, select "No", else you'll end up saving a lot of data that you'll never look at again.

2. The "Weather" layer under "Layers" contains a cloud layer which, if selected, may hide part or the entire storm track. Turn off the "Weather" layer to correct this.

3. There is no mechanism in place to arrange the preferred order of the image overlays. For example, if image1 lies underneath image2 (i.e, image1 is the background and image2 is the foreground), you can bring image1 to the foreground by right-clicking on image1 in the "Temporary Places" and selecting "Revert". This will re-load image1 and place it on top of everything else.

4. The performance of this application is largely dependent upon the network speed, the type of processor and graphics card. There is no guarantee that these data will display properly, especially the radar profiles and wind vector barbs. Make sure you have the latest version of Earth installed. On older systems, some of the products will load slowly and if too many are loaded, Earth may crash unexpectedly. It is a good idea to increase the disk cache to as large as you can (2 GB is the maximum). Under Earth's "Tools" -> "Options", select the "Cache" tab, and increase this from the default provided. It is a good idea to occasionally clean out both the memory and disk cache, and to delete unnecessary contents in the "Temporary Places" folder.

5. To reduce screen clutter, turn off grids unless you need to see them. Under "View", uncheck "Grid". Same for other unnecessary layers.

6. In the position popup balloons, the color of the text in the "Time" column is chosen based upon the distance of the closest point of approach, as described in Section 4b. For the most recent position icon, the predicted future overpass times are shown. Ideally, the predicted satellite overpass time and the color of the text for the eventual satellite dataset near this time should be identical. In practice, the prediction software may have slightly out-of-date orbital information thereby places the predicted track close, but not identical to the actual overpass track. In these cases the colors of the text for the predicted and actual times may differ.

Appendix

The following selections of satellite datasets are available within the popup at each storm position. From left-to-right, these are:

1) Visible (day) and thermal infrared (night) grayscale imagery from any of five geostationary satellites (whichever covers the storm area), updated every 30 minutes, with an approximate resolution of 1-km (day) and 4-km (night). Also, finer-scale resolution visible (250-m resolution during day from channel 1) and thermal infrared (1-km resolution at night from channel 31) grayscale imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS instruments are onboard the NASA Earth Observing System (EOS) Terra and Aqua satellites. In general, taller, thicker clouds reflect more visible sunlight than shallower, thinner clouds, the more reflective the whiter the shading), whereas ocean and most land surfaces are poor reflectors of sunlight (snow and deserts are an exception). At night, the depiction switches to a thermal infrared measurement in the 11 µm band, where the shading is closely related to the physical temperature of the cloud. Taller, thicker clouds are colder and depicted with brighter white shades; shallower clouds and land surfaces are darker, as shown in Figure A1.

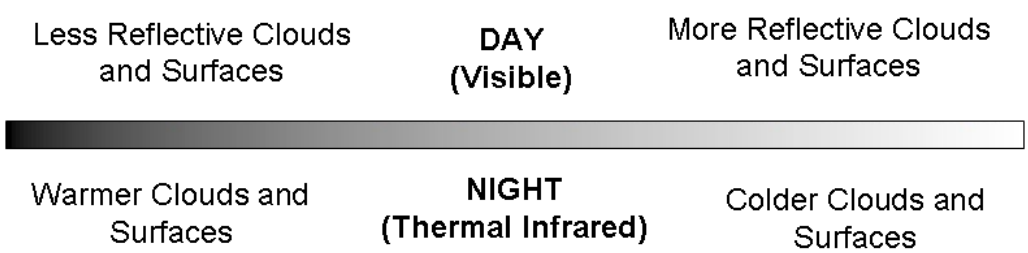


Figure A1. Grayscale shading used for the visible and thermal infrared imagery.

   a) GOES-12 is the operational NOAA east geostationary satellite located at 75W longitude.
   b) GOES-11 is the operational NOAA west geostationary satellite located at 135W longitude.
   c) Meteosat-7 is the operational EUMETSAT geostationary satellite located at 57E longitude.
   d) Meteosat-9 is the operational EUMETSAT geostationary satellite located at 0E longitude.
   e) GMS-6 is the operational JMA geostationary satellite located at 140E longitude.
   f) MODIS onboard EOS-Aqua.
   g) MODIS onboard EOS-Terra.

2) 85 GHz (H channel) microwave imagery from passive microwave (PMW) sensors onboard various low Earth-orbiting (LEO) satellites. In principle, 85 GHz observations similar to thermal infrared measurements, but the observation is more representative of processes (e.g, rainfall) inside of the clouds rather than near the tops of the clouds. The

unique spiral pattern and eye shape of a tropical cyclone is often "masked" by the presence of high altitude cirrus clouds, and often are poorly depicted in visible or thermal infrared imagery. The cirrus clouds have much less of an impact with the 85 GHz microwave measurements, so these data can be used to effectively visualize the tropical cyclone horizontal structure. In this depiction, regions of convective-type precipitation (i.e, precipitation with an ice phase) are colored with yellow-red shades and clearer skies are colored a green-blue color, as shown in Figure A2.

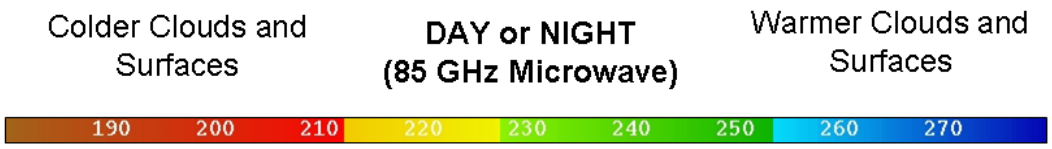


Figure A2. Color scale used to assign colors to the 85 GHz blackbody brightness temperatures.

a) The Special Sensor Microwave Imager (SSMI and SSMIS) onboard the Defense Meteorological Satellite Program (DMSP) satellites, F-13 through F-16.
b) The Advanced Microwave Scanning Radiometer (AMSR-E) onboard EOS-Aqua.
c) The TRMM Microwave Imager (TMI) onboard the NASA Tropical Rainfall Measuring Mission (TRMM). TMI, SSMI, and AMSR-E scan conically with resolution ranging from 5-15 km.
d) The Advanced Microwave Sounding Unit (AMSU) and the similar Microwave Sounding Unit (MHS) onboard the NOAA (NOAA-15 through NOAA-18) and EUMETSAT METOP satellites. AMSU and MHS scan across-track with a resolution of 16-km at nadir.

3) 85 GHz color composite (RGB composite). This is a red-green-blue (RGB) color image enhancement that has proven popular with the tropical cyclone community. This image enhancement is created by scaling the 85-GHz polarization-corrected temperature (PCT) between 310-220K (i.e, inverted), the 85H channel between 240-300K, and the 85V channel between 270-290K. These three scaled values are then used, respectively, as input to the red, green and blue channels of an image enhancement. The 85 color images are created for the same sensors as the 85H imagery.

4) 85 GHz PCT. The 85-GHz polarization corrected temperature (PCT) is created by the linear relation 85PCT= 1.818*85V – 0.818*85H. The 85PCT image is set to transparent when 160 > 85PCT > 260K. The 85-PTC images are created for the same sensors as the 85H imagery.

5) 37 GHz (H channel). This image is created by scaling the 37H channel between 170-270K. The 37H images are created for the same sensors as the 85H imagery, with the addition of the WindSat sensor onboard the Coriolis satellite.

6) 37 GHz color composite (RGB composite). This is a red-green-blue (RGB) color image enhancement that has proven popular with the tropical cyclone community. This image enhancement is created by scaling the 37-GHz polarization-corrected temperature (PCT) between 280-260K (i.e, inverted), the 37V channel between 180-300K, and the 37H channel between 160-300K. These three scaled values are then used, respectively, as input to the red, green and blue channels of an image enhancement. The 37-GHz polarization corrected temperature (PCT) is created by the linear relation 37PCT= 2.18*37V – 1.18*37H. The 37 color images are created for the same sensors as the 85H imagery, with the addition of the Coriolis-WindSat sensor.

7) Rainfall rate color imagery. PMW sensors and radars are especially useful for gathering information on aspects of the Earth's hydrological cycle, such as precipitation, snow, ice cover, water vapor. Since these sensors provide information about the vertical liquid and ice content of clouds, they can be used to estimate precipitation rate. In these depictions, areas with precipitation rates under 0.1 mm hr^{-1} are shown with a thin white transparency so the sensor swath coverage can be identified.

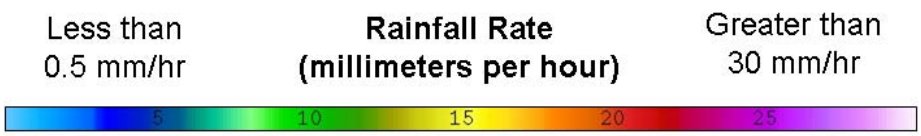


Figure A3. Color scale used to assign colors to rainfall rate imagery.

a) The AMSR-E onboard EOS-Aqua (swath width of about 1400 km)
b) The TMI onboard TRMM (swath width of 800 km)
c) The Precipitation Radar (PR) onboard TRMM (narrow swath width of 220-km, but with a horizontal resolution of 4-km).

8) Surface wind vectors (wind speed and direction) plotted as traditional wind barbs and colored according to wind speed. Wind barbs are the traditional symbol to show both wind speed and direction where the wind speed is always given in knots (1 knot= 1 nautical mile per hour= 1.15 miles per hour= 1.85 km/hr). These sensors depend upon the presence of capillary waves that are set up when strong winds blow across an ocean surface. A scatterometer measures sends a radar pulse and measures the reflected power from several different look angles; these can be processes to retrieve the wind speed and direction. A microwave polarimeter relies upon the same phenomena, but measures the polarized thermal emission upwelling from a wind-roughened ocean surface. Both types of sensors are adversely affected by the presence of rainfall, which disturbs the ocean surface signal and may lead to improper retrievals of wind speed and direction. In these data, the presence of rain is denoted with a small circle near the tip of the wind barb.

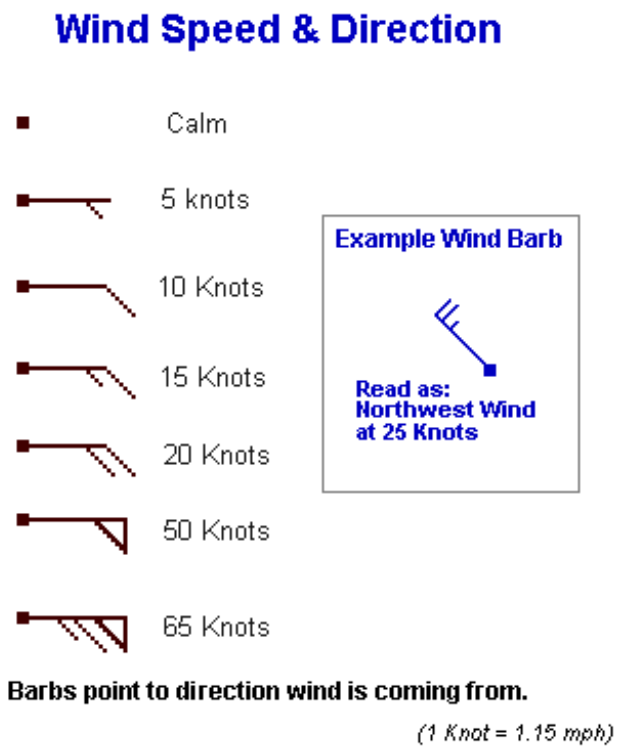


Figure A3. Interpretation of wind barbs.

a. The Seawinds scatterometer onboard the NASA QuikSCAT satellite.
b. The WindSat passive microwave polarimetric radiometer onboard the NRL Coriolis satellite.
c. The Advanced Scatterometer (ASCAT) onboard the EUMETSAT METOP-A satellite.

9) Occasional (updated days to weeks late) vertical radar reflectivity profiles from two different spaceborne radar systems. Unlike ground-based radars, these radars provide vertical profiles of radar reflectivity with a resolution of 250-m in the vertical, from the surface up to approximately 20-km altitude. In recent years, the successful launch of advanced research satellite/sensor systems such as the joint United States/Japan Tropical Rainfall Measuring Mission (TRMM, launched in 1997) and the NASA CloudSat satellite (2006) have deployed the first spaceborne radar systems. The Precipitation Radar (PR) onboard TRMM provides vertical profiles (250-meter vertical resolution) of precipitating clouds (i.e, sensitive to precipitation-sized rain drops) from the 402-km orbit altitude of TRMM. CloudSat, while providing a similar vertical resolution, orbits at a higher orbit (800 km) and transmits at a higher frequency (94 GHz), which is sensitive to much smaller cloud drops, but is also adversely affected by attenuation of larger, precipitation-sized drops. Together, these spaceborne radar sensors provide the capability to gather information on the 3-dimensional structure of rain and clouds, and are well-suited to layer and combine with visible, infrared and passive microwave satellite imagery.

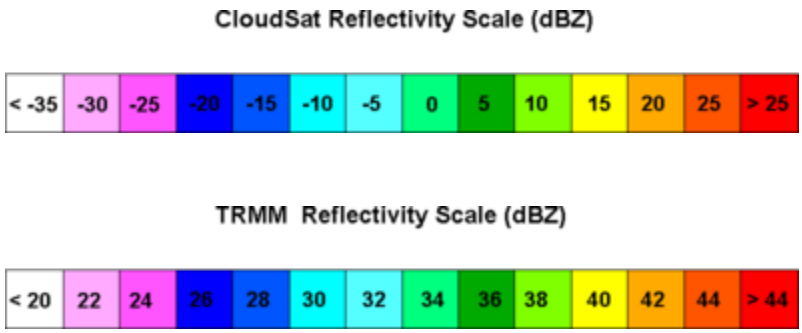


Figure A4. Colors used to assign to radar reflectivity bins for the TRMM and CloudSat spaceborne radars.

a) The NASA CloudSat (95 GHz cloud radar), which flies in the A-Train constellation at approximately the same time as EOS-Aqua. CloudSat gathers a vertical profile every 1.1-km along the satellite track.
b) The PR (14 GHz precipitation radar) onboard TRMM. Unlike CloudSat, which is a single "trace" of reflectivity under the satellite track, the PR scans a narrow (220-km width) area across-track with vertical profiles spaced about 4-km apart.

All of these satellites except TRMM orbit the Earth in a near-polar, sun-synchronous orbit. That is, the local time of ascending node (LTAN; the local time of the satellite as it crosses Earth's equatorial plane from the southern to northern hemisphere) is fixed. As a consequence, the local ascending and descending times are 12-hours apart. In reality, orbit maneuvers need to be applied if a fixed LTAN is to be maintained. Typically, the satellite is designated as a "morning" or "afternoon" satellite, depending upon the local time of day when it flies overhead. For example, NOAA-17 (2201 LTAN) and 18 (1336 LTAN) are classified as morning and afternoon satellites, respectively. TRMM is the only one of all of these satellites which flies in a non-sun-synchronous orbit; its local observation time moves from day to day with a repeat cycle of 46 days at the equator, specially configured to capture the daily cycle of precipitation.