Chapter 10
Assessing Hurricane Intensity Using Satellites

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Abstract Tropical cyclones spend most of their life cycle over the tropical and subtropical oceans. Because of the lack of in situ data in these regions, satellite observations are fundamental for tracking and estimating the intensity of these storms for real-time forecasting and monitoring climate trends. This chapter reviews methods for estimating tropical cyclone intensity from satellites, including those based on visible, infrared, and microwave instruments. Satellite intensity estimates are transitioning from subjective to objective methods, and new instruments on the next generation of NOAA low-earth orbiting and geostationary satellites hold promise for continued improvement in satellite analysis of tropical cyclones.

10.1 Introduction

The large loss of life and unprecedented damage caused by US landfalling hurricanes in the 2000s (Lili 2002; Isabel 2003, Charley, Frances, Ivan, Jeanne 2004; Dennis, Katrina, Wilma 2005; Ike 2008) raises the question of whether the Atlantic hurricane climate is changing. This question has considerable societal and economic implications for residents along the US gulf and east coasts and in other coastal regions around the globe. Emanuel (2007) showed a high correlation between decadal increases in Atlantic sea surface temperatures (SST) and an integrated measure of Atlantic basin tropical cyclone activity called the power dissipation index (PDI). This correlation suggests that the recent changes in hurricane activity may have a connection with global warming.

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The question of whether the hurricane climate is changing is complicated by two main factors, and recent observational and modeling studies have sometimes produced conflicting results (Knutson et al. 2010). First, tropical cyclone (TC) activity in the Atlantic (and other regions as well) undergoes significant natural variability on annual and multi-decadal time scales (Kossin et al. 2010). Second, the observing systems for measuring TC activity have varied extensively in the last century (Landsea et al. 2010). Before the mid-1940s, the primary source for TC information was ship reports. Aircraft reconnaissance became available in the mid-1940s, low-earth orbiting (LEO) satellites in the mid 1960s, and operational geostationary satellites in the 1970s. In addition, the instrumentation from aircraft reconnaissance has varied considerably, and this data was routinely available only for the Atlantic and western North Pacific through 1987. After 1987, west Pacific TC reconnaissance was discontinued. Thus, it is not always obvious whether long-term TC increases are physical or are due to improvements in the ability to monitor them.

Because TCs spend most of their lifetime over the tropical and subtropical oceans and the limited availability of in situ and aircraft observations, satellite data is fundamentally important for the analysis and forecasting of TCs. In fact, just a few years after the launch of the first meteorological satellite (TIROS-1) in 1960, methods began to be developed to estimate TC intensity from satellite imagery (Hubert and Timchalk 1969). These early attempts were not completely satisfactory, but about a decade later the very successful Dvorak method was developed (Dvorak 1975). In this chapter, the use of satellite data for estimating TC intensity is described. Satellite data also have many other TC applications, including position and structure analysis and atmosphere and ocean numerical forecast model initialization, but these topics are beyond the scope of this chapter. Accurate TC intensity estimation is important for both short-term forecasting and for monitoring changes in global TC activity.

This chapter begins with a description of the Dvorak intensity estimation technique, which is still a cornerstone of operational TC analysis around the globe. The intensity of a TC is quantified as the maximum sustained surface wind speed associated with the storm. Another indicator of TC intensity is the minimum sea-level pressure near its center. Newer methods that make use of passive microwave sensors are also presented. General methods for satellite wind estimation and their application to TCs are also briefly described. This chapter concludes with a summary of how forecasters combine TC information from many sources and a look toward future satellite capabilities.

10.2 The Dvorak Tropical Cyclone Intensity Estimation Method

The Dvorak technique estimates tropical cyclone intensity using satellite imagery. It was one of the first innovative applications of meteorological satellite imagery, and it is still widely used today at tropical cyclone forecast centers throughout the world (Velden et al. 2006). The Dvorak technique was developed in the early 1970s by Vernon Dvorak and his colleagues at NOAA NESDIS.

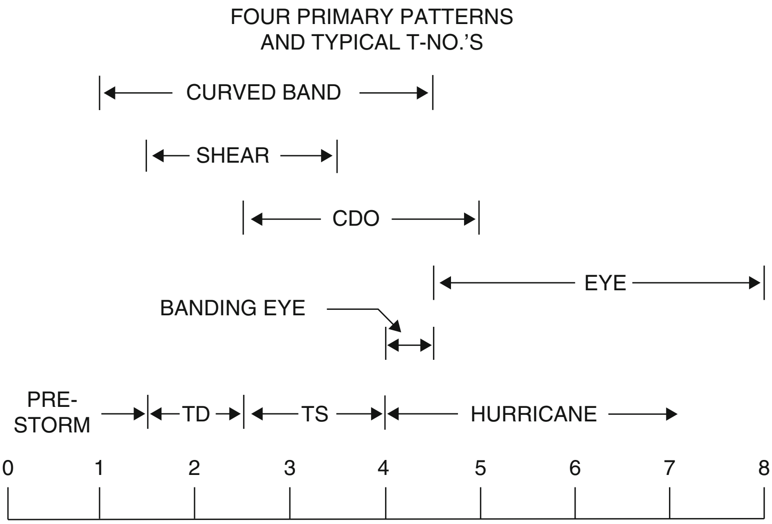


Fig. 10.1 The primary Dvorak cloud patterns in relation to T-number and tropical cyclone intensity ranges

10.2.1 *Operational Dvorak Technique*

The Dvorak technique (Dvorak 1984) primarily uses satellite observed cloud patterns and infrared (IR) cloud top temperatures to estimate intensity, with independent methods for visible and IR satellite imagery. It uses an intensity unit called a T-number in increments of ½ ranging from T1 to T8. The Dvorak T-number intensity scale is normalized according to typical observed daily changes in intensity (one T-number per day). T2.5 is the minimal tropical storm intensity (18.0 m/s), T4.0 is minimal hurricane intensity (33.4 m/s), T6.0 has a wind maximum of 59.1 m/s, and T8.0 approximates a record maximum intensity (87.4 m/s).

The cloud patterns in the Dvorak technique are divided into the four basic patterns in Fig. 10.1 (curved band, shear, central dense overcast, and eye), with a fifth sub-pattern called a banded eye. With weaker intensities, the analysis is usually based on either the curved band pattern or the shear pattern. Using the curved band analysis, the extent to which a spiral shaped band of deep convective clouds surrounds the tropical cyclone center determines the intensity. The shear pattern refers to the cloud pattern observed when broadscale vertical wind shear induces a distinctly asymmetric cloud pattern with respect to the tropical cyclone low-level circulation center. The degree of deep convective cloud displacement due to the vertical shear decreases with intensification.

As a TC intensifies, the cloud pattern typically evolves into what is called a central dense overcast (CDO), which describes the deep convective clouds that surround the center. As intensification continues, an eye is observed within this central dense overcast. The eye is the familiar cloud-free or cloud minimum area

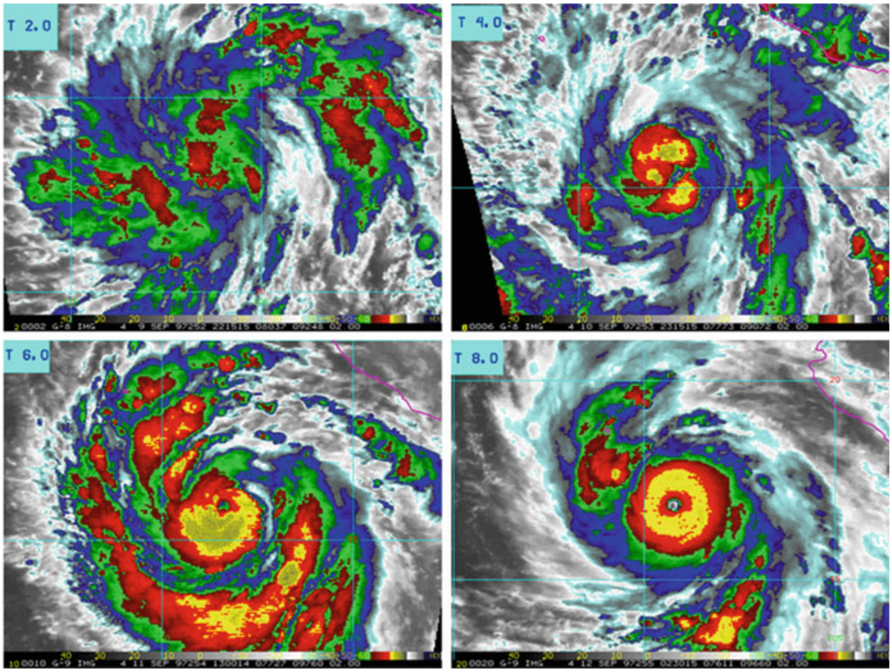
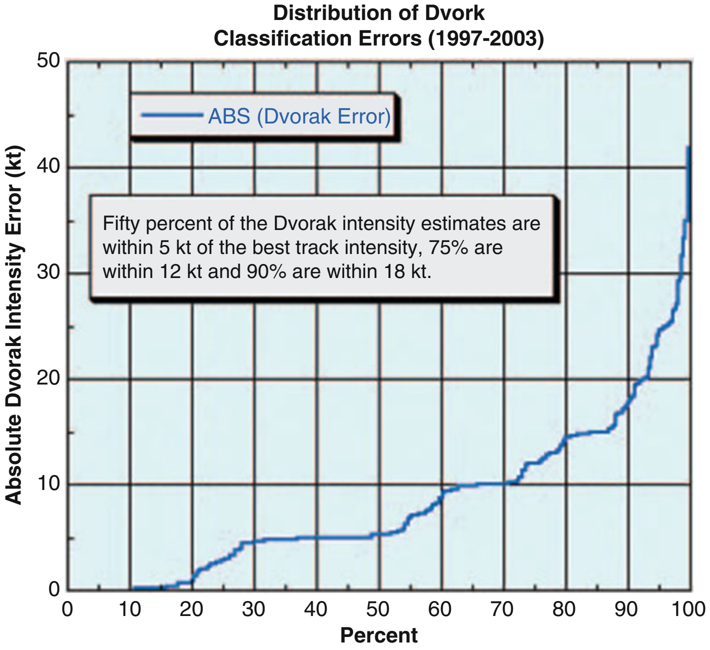


Fig. 10.2 Enhanced IR images of Hurricane Linda with Dvorak intensities T2, T4, T6, and T8. Hurricane Linda was located in the eastern North Pacific, southwest of Mexico, during 9–17 September 1997

associated with the lowest pressure at the tropical cyclone center. The eye is surrounded by a circular area which has the strongest winds within very deep clouds and heavy rain, known as the eyewall. The Dvorak technique analyzes visible features and IR temperatures of the eye and the surrounding deep clouds to assign the intensity. In general, the Dvorak tropical cyclone intensity increases as the eye gets warmer and better defined, and the surrounding clouds get colder and more symmetric. A continuous very cold circular ring of cloud tops generated by the eyewall along with a warm eye temperature indicates an intense tropical cyclone. Enhanced IR images of Dvorak intensities T2, T4, T6, and T8 are shown in Fig. 10.2 with Hurricane Linda that was located in the eastern North Pacific in September 1997.

An analysis of errors associated with Dvorak intensity estimates in comparison with the “best track” values is shown in Fig. 10.3. The best track is determined by the post-storm analysis of all available information, including aircraft intensity estimates, and is considered ground truth. Figure 10.3 shows that the Dvorak maximum wind estimates are normally accurate to within 5–10 kt but can sometimes be much larger. Knaff et al. (2010) performed a systematic analysis of the errors and biases of the Dvorak intensities. The results show that some of these biases are systematic and can be corrected, which would lead to further improvement of the operational Dvorak method.



Fifty percent of the Dvorak intensity estimates are within 5 kt of the best track intensity, 75% are within 12 kt and 90% are within 18 kt.

Fig. 10.3 Errors of the Dvorak tropical cyclone intensity estimation technique (From Velden et al. 2006)

10.2.2 Improved Objective Dvorak Approaches

Following Dvorak's original work, research and development efforts have been focused on replicating and refining the Dvorak approach with objective and automated routines using the IR temperatures (Velden et al. 2006). Automated Dvorak techniques give reliable results that are quickly updated as the latest IR satellite image becomes available, and the tropical cyclone intensity data supplement the general use of satellite data for analysis and forecasting.

Initial automated techniques were analogous to the operational Dvorak technique's enhanced IR (EIR) method (Dvorak 1984; Zehr 1989; Velden et al. 1998). The original goal of using computer-based objective methodology to achieve the accuracy of the operational Dvorak technique was accomplished, however, with important limitations. The automated routines could only be applied to storms at greater than minimal hurricane intensity. Also, a user-located storm center was needed. With continued research and development, the advanced objective Dvorak technique (AODT) emerged (Olander et al. 2004). The most recent version of the objective algorithm progression is the advanced Dvorak technique (ADT). Unlike the earlier techniques that attempt to mimic the operational technique, ADT is focused on revising and extending the method beyond the original application and constraints. The ADT is fully automated for real-time analysis and continues to be improved (Olander and Velden 2007). Automated center finding algorithms are also under development (Wimmers and Velden 2010).

10.3 Satellite Microwave Intensity Estimation Techniques

In parallel with applications of visible and IR imagery such as the Dvorak technique, microwave observations from LEO satellites provided important observations of tropical cyclones in the 1970s and 1980s (Kidder et al. 2000). Microwave data have two main advantages over visible and IR images: (1) microwave radiation penetrates clouds; (2) Microwave radiation is sensitive to a wide variety of geophysical parameters, such as temperature, water vapor, cloud liquid water, cloud ice water, rain, and surface wind speed.

Microwave sensors can be divided into the two basic categories of imagers and sounders. Similar to IR and visible imagery, microwave imagery provides information about atmospheric and cloud properties due to the interaction with the upwelling radiation. Sounders measure microwave radiation in a range of frequencies centered about an atmospheric absorption band to provide vertical profiles of atmospheric moisture. TC intensity estimation techniques from microwave sounders have generally been more successful than those from microwave imagery. These are described first, followed by attempts to utilize microwave imagery.

10.3.1 Microwave Sounder Applications

The first operational microwave soundings were obtained from the microwave sounding unit (MSU) on TIROS-N, beginning in 1978, after successful demonstration on NIMBUS-5 earlier that decade. Shortly after this data became available, techniques to estimate TC intensity began to emerge (e.g., Kidder et al. 1978). An advantage of sounding methods compared to the Dvorak technique is that they have a firmer physical foundation. The minimum surface pressure near the center of a tropical cyclone is directly related to the vertical atmospheric temperature profile above that point through the hydrostatic equation. The minimum sea-level pressure has a strong relationship with the maximum surface wind through the horizontal momentum equations. To a reasonable level of approximation, these equations are diagnostic. For example, in the case of steady circular flow that occurs in strong tropical cyclones above the boundary layer, the wind and pressure field are related through the gradient wind equation.

A rather severe limitation of the early TC estimation techniques from the MSU was the 150-km footprint size of the measurements. This is much larger than the scale of the tropical cyclone eye, so the very warm temperatures in the eye cannot be resolved. This situation improved considerably beginning in 1998, when the advanced microwave sounding unit (AMSU) with its improved resolution began

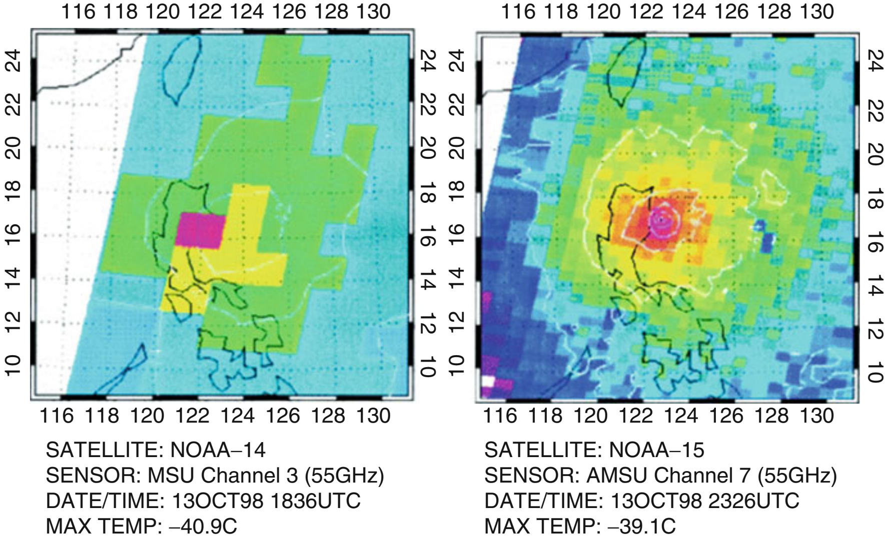


Fig. 10.4 An illustration of the improvement in spatial resolution of the AMSU over the MSU for Typhoon Zeb from the western North Pacific (From Kidder et al. 2000)

observing tropical cyclones. A comparison of the resolution of the MSU and AMSU is shown in Fig. 10.4 for Typhoon Zeb in the western North Pacific. The horizontal footprint of AMSU-A is about 50 km near nadir.

Observations and high-resolution modeling studies of tropical cyclones show that the warm core is a maximum near the storm center and the scale of the warm core increases with height due to the tendency for outward sloping eyewalls. Also, the strongest warm anomaly relative to that outside of the storm is a maximum in the middle and upper troposphere (e.g., Hawkins and Imbembo 1976; Stern and Nolan 2012). Based on this observed structure, two approaches have been taken to estimate TC intensity from AMSU. In the first approach, brightness temperatures from AMSU channels that sense the upper troposphere are used directly to estimate the warm core (Spencer and Braswell 2001; Brueske and Velden 2003). The characteristics of the warm core are then related to the TC intensity. In the second approach, temperature retrieval algorithms are applied using all of the AMSU-A channels to provide a three-dimensional temperature structure. Using an upper boundary condition from a large-scale analysis, the hydrostatic equation is integrated downward to provide the pressure field at each vertical level. The pressure gradient can then be calculated, and the wind field is determined from an appropriate approximation of the horizontal momentum equations. This method was applied by Demuth et al. (2004), assuming radially symmetric temperature and wind fields relative to the storm center, so that the gradient wind equation could be used. Figure 10.5 shows an example of the temperature anomaly and wind speed estimated by this technique. This figure shows that this retrieval method can also be used to provide information about the horizontal and vertical structure of a storm.

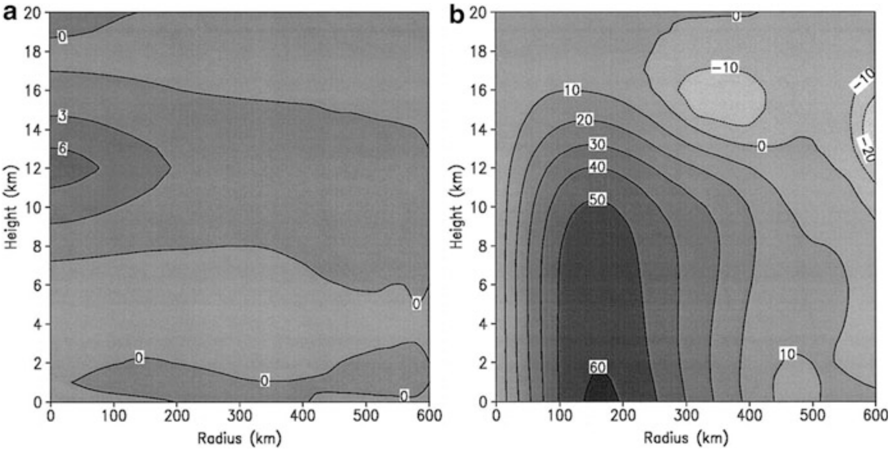


Fig. 10.5 Radial-height cross sections for Hurricane Gert on 16 Sept. 1999 of AMSU-retrieved (**a**) temperature anomalies (8 °C), showing the warm core at a height of approximately 12 km, and (**b**) gradient winds (kt), showing that the MSW occurs at approximately 175 km from the storm center (From Demuth et al. 2004)

Although the retrieved wind structure in Fig. 10.5 is qualitatively similar to a tropical cyclone with cyclonic tangential winds decreasing with height and a larger scale anticyclone at upper levels, the inner core is still not represented well. The low-level radius of maximum wind is about 175 km, which is much too large, and the retrieved maximum wind of about 60 kts is much lower than what was observed for Hurricane Gert at this time. To help correct for the lack of resolution, a statistical bias correction is applied to several parameters from the retrieved fields (Demuth et al. 2006) to improve the accuracy of the method. A scale correction is also applied to the AMSU retrieval method described by Brueske and Velden (2003). That algorithm also makes use of the AMSU-B moisture channels, which have a footprint size about 1/3 that of AMSU-A, to provide an eye-size estimate. The eye-size information is used to help correct for the low resolution of the AMSU-A channels. Both of the TC intensity estimation techniques described above have been used operationally by the National Hurricane Center and the Joint Typhoon Warning Center for the past several years. The average accuracy of the AMSU methods is not quite as good as the Dvorak method, especially for very small cyclones, but it provides an independent estimate of intensity.

10.3.2 Microwave Imagery Applications

Microwave imagery has been available from LEO satellite systems for the past few decades, including Special Sensor Microwave/Imager (SSMI), Special Sensor Microwave Imager Sounder (SSMIS), Tropical Rainfall Measuring Mission (TRMM)

Microwave Imager (TMI), and Advanced Microwave Scanning Radiometer-EOS (AMSR-E). As described above, channels from the AMSU-B sounder can also be used for imagery applications. The microwave imager instruments have much higher spatial resolution than the sounder data and provide detailed information about cloud and rain structure below the cloud top. Figure 10.6 shows an 85-GHz microwave image from SSMI for Hurricane Celia in the eastern North Pacific and the corresponding color-enhanced GOES IR (channel 4) image. The microwave imagery shows more clearly the cloud organization below the cirrus canopy in the IR image.

Despite the usefulness of microwave imagery for qualitative interpretation of tropical cyclone structure, a quantitative algorithm for intensity estimation with sufficient accuracy has yet to be developed. Bankert and Tag (2002) described a microwave imagery technique based on a nearest neighbor approach that could be fully automated. However, the average errors were about twice as large as those from the Dvorak technique. The use of microwave imagery for TC intensity estimation remains an area of active research.

10.4 Other Wind Estimation Techniques

Wind estimates from satellites have application to many phenomena in addition to tropical cyclones. Wind vectors can be estimated in the atmosphere by tracking features in subsequent images from geostationary satellites. This technique can also be applied at high latitudes with polar-orbiting imagery, since the temporal coverage from those satellites is much higher there (Dworak and Key 2009). Development of feature track wind algorithms began shortly after the availability of the first satellite observations, and improvements continue to be made (e.g., Velden and Bekda 2009).

Surface winds over the ocean can also be estimated from scatterometers on LEO satellites. These techniques are described in more detail in Chap. 8. The scatterometer winds have proved to be very useful for tropical cyclone intensity and structure analysis.

The AMSU retrieval technique described in Sect. 10.3 can be generalized to provide three-dimensional estimates of the horizontal wind. For that application, the gradient wind balance assumption is replaced by the more general nonlinear balance equation (Bessho et al. 2006). The three-dimensional AMSU winds are useful for TC structure analysis and are also being applied to other phenomena, including the atmospheric response to the Gulf Stream (O'Neill et al. 2010).

The three wind estimate techniques (feature track winds, scatterometer winds, and generalized AMSU retrievals) can all be used for tropical cyclone intensity estimation. However, low-level feature track winds are usually not available near the center of tropical cyclones due to the cirrus canopy. The scatterometer signal can attenuate at very high wind speeds, and there are some complications due to rain contamination and the footprint size. The generalized AMSU winds also have a limitation due to the instrument resolution. Thus, these techniques have application to TC intensity estimation, but generally can provide a lower bound estimate, and are used in combination with other information.

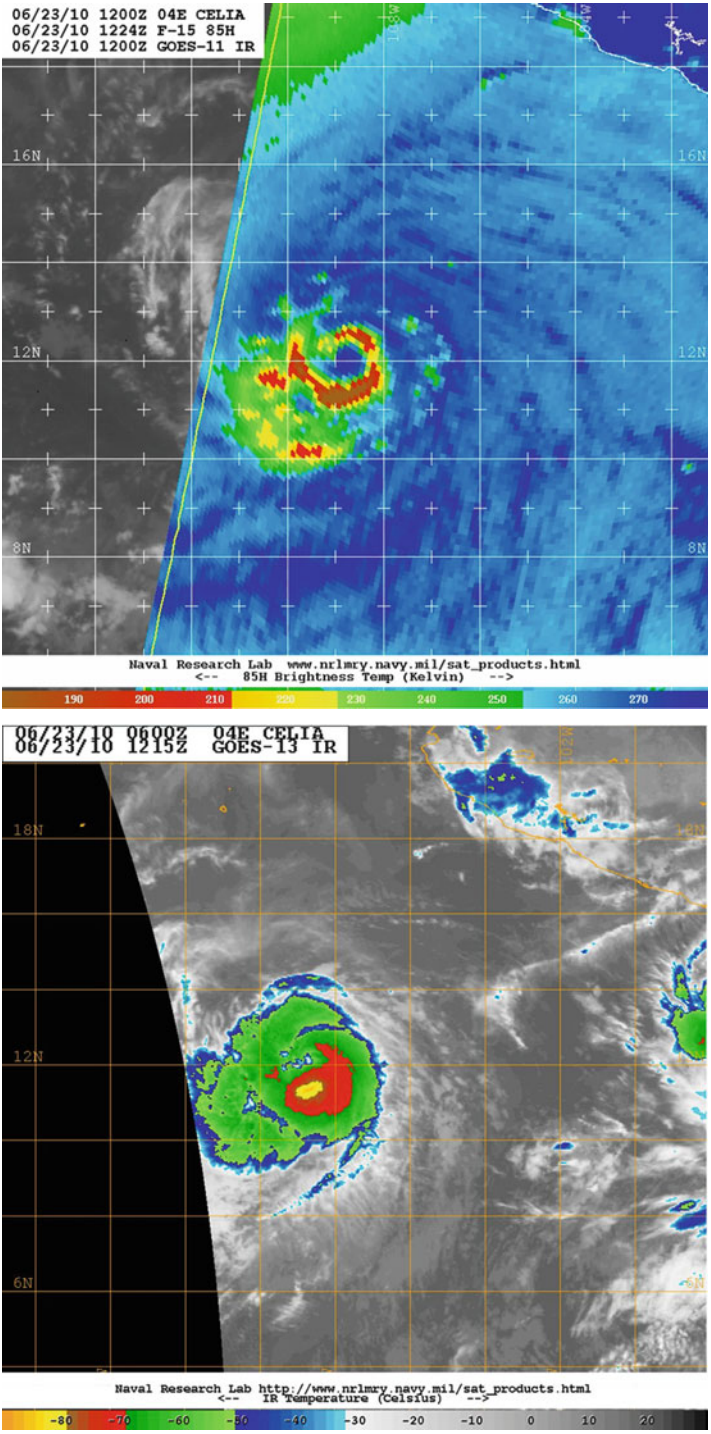


Fig. 10.6 85 GHz (*top*) and GOES channel 4 IR (*bottom*) image of Hurricane Celia at 12 UTC on 23 June 2010

10.5 Forecaster Applications

Hurricane forecasters and analysts assign intensity to tropical cyclones by using all available information. In addition to the satellite data, aircraft observations provide important intensity information, with more direct measurements of central pressure and maximum wind. At times, surface and ship observations also provide critical intensity data. Since the critical aircraft and surface data are not always available, but more directly measure the intensity, they are also needed for validation and refinement of the satellite intensity estimates.

Because each of the satellite TC intensity estimate techniques has their limitations, they are usually used in combination. The methods that use geostationary data have better temporal resolution and can be used to detect short-term trends. The methods that use LEO data are compared to the geostationary-based estimates when they are available, and forecasters make a subjective estimate of the TC intensity. Methods are also being developed to objectively combine satellite-based intensity estimates, using a satellite consensus (SATCON). These methods take advantage of the strengths and weaknesses of each method to provide an optimal TC intensity estimate (Herndon et al. 2010).

10.6 Future Outlook

The next decade should provide new opportunities for improving satellite-based intensity estimates. The next-generation GOES satellite beginning with GOES-R (expected launch date of late in 2015) will include an Advanced Baseline Imagery (ABI). The ABI will include 16 channels, with improved spatial, temporal, and radiometric resolution. The ABI has the potential to improve the existing Dvorak technique and lead to new methods that make better use of the multispectral imagery.

The next-generation NOAA polar-orbiting satellite will include an Advanced Technology Microwave Sounder (ATMS), which will have improved resolution when compared to the AMSU. As described in Sect. 11.3, the horizontal resolution of the AMSU is still coarse relative to the scale of the TC eye. The satellites will also include a hyperspectral IR sounder, which can be used in combination with the ATMS to provide more accurate temperature soundings. Although the IR sounding capabilities are primarily limited to clear regions, it may be possible to get accurate soundings in the eyes of storms with well-defined eyes. The ATMS and high spectral resolution Cross-track Infrared Sounder (CrIS) are now available on the recently launched Suomi National Polar-orbiting Partnerships (S-NPP), and preliminary results show great potential for utilizing this new data to improve the satellite estimates of tropical cyclone position, intensity, and structure.

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