15A.6 # ENHANCED TROPICAL CYCLONE MONITORING WITH MODIS AND OLS

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1. INTRODUCTION

Tied intrinsically to the poorly observed oceanic environment, tropical cyclones (TCs) pose inherent characterization, tracking, and forecasting challenges. Here, perhaps more clearly defined than with any other environmental phenomenon, satellite remote sensing offers fundamental information bearing direct and immediate relevance to life and property. In 1997, the Naval Research Laboratory in Monterey, CA launched the Tropical Cyclone Web Page (TC Webpage; www.nrlmry.navy.mil/tc_pages/tc_home.html) as a comprehensive and near real-time asset for the tracking and assessment of TCs occurring worldwide (Hawkins *et al*., 2001). Its unique consolidation of multi-sensor and multi-platform applications blending optical and microwave spectrum with scatterometer and spaceborne radar digital datasets yields a powerful tool in estimating storm structure, path, intensity.

This paper describes the recent additions to the TC Webpage of high spatial resolution imagery (250 m true color) from the Moderate-resolution Imaging Spectroradiometer (MODIS) sensors on board NASA Terra and Aqua, and nighttime low-light imagery (measurement of clouds reflecting moonlight) from the Operational Linescan System (OLS) on board the Defense Meteorological Satellite Program (DMSP). The MODIS data is shown to provide superior characterization of convective bursts within the eyewall and observes mesoscale circulation patterns within the eye (barring central-dense-overcast conditions) as they relate to current storm intensity and short-term trends. The nighttime capability from OLS provides another means to resolving low-level circulation (e.g., by revealing low cloud patterns otherwise poorly resolved at night via conventional infrared imagery) particularly for dissipating systems. Used in concert with the full suite of TC Webpage passive optical/microwave and scatterometer tools, these new additions improve our ability to monitor and prepare for one of nature's most powerful forces.

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2. HIGH RESOLUTION MODIS IMAGERY

High spatial resolution (250 m at nadir) true color imagery from MODIS provides a detailed and eye-appealing view of the Earth's weather. The intuitive nature of true color imagery stems from its ability to reproduce to first order the color response of the cone cells of the human retina by way of three narrow-bandwidth visible-spectrum channels in the blue, green, and red. The procedure results in imagery that is reminiscent of color photography, or in this case, what an astronaut might observe from orbit. Compared to panchromatic (single, wide-band) or false color (composite of varying spectral bands) satellite imagery, true color presents details of a complex scene, particularly the land background, at markedly reduced ambiguity. As a result, both novice and expert analysts of satellite imagery gravitate naturally to true color renditions whenever available.

In addition to its qualitative benefits, combining high spatial resolution with true color offers additional and distinct advantages over single-band or other false color composites in terms of analyzing the terrestrial impacts found in the wake of severe weather events. Over land, true color provides additional capabilities to assess flood zones and damage to foliage. Over water, examples include changes in the structure of shoals (e.g., due to storm surges) and enhanced water turbidity (e.g., rainwater runoff). Here, brightness contrast information provided from broadband sensors is often insufficient to differentiate various scene constituents that are readily distinguishable through natural coloration.

Producing MODIS true color imagery at 250 m spatial resolution involves three main pre-processing steps: 1) synthesizing 250 m resolution for bands 3 (blue; 500 m native resolution) and 4 (green; also 500 m native resolution) based on band 1 (red; 250 m native resolution), 2) applying an atmospheric correction to the blue, green, and red bands to remove molecular scatter (limb brightening) from the imagery, and 3) projecting the swath data to a georeferenced grid. With assistance from (T. Haran and K. Knowles) of NSIDC, researchers at the University of Wisconsin-Madison Space Science and Engineering Center (L. Gumley) and the NASA

Goddard Space Flight Center's MODIS Rapid Response Team (J. Descloitres and J. Schmaltz) have made publicly accessible a package for performing the above operations on the MODIS data (the source code is provided at ftp.ssec.wisc.edu/pub/IMAPP/MODIS/TrueColor/. As will be shown in examples to follow, 250 m resolution reveals fine-scale details of TC structure, including embedded "hot towers" of convection and mesoscale vortices within the eye.

3. OLS NIGHTTIME VISIBLE IMAGERY

In general, infrared satellite measurements of the earth and atmosphere provide extremely useful and complementary information to visible spectrum data. However, there are limitations in terms of what information the infrared can provide on cloud properties (due to signal saturation) and even coverage (the problem being low clouds whose temperatures are similar to the thermal background). Detection of the latter is important to the tracking of decaying or strongly-sheared TC systems at night, where the true center of circulation may be defined only through the spiral pattern of low cloud bands. Despite being in a dissipating stage, significant winds (exceeding 25 kt in some cases) associated with these storms can pose a hazard to sea craft and impact Navy operations. In addition, these storms may regenerate under favorable environmental conditions (e.g., re-entering an area of warmer waters, or exiting an area of strong vertical sheer), making their accurate 24-hour tracking of critical importance.

Methods exist for detecting low cloud at night via spectral property differences between 3.9 and 11.0 μm window bands (e.g., Ellrod 1995, and applied specifically to TCs by Lee 2000). The approach works best for small particle size distributions where the scattering at 3.9 μm leads a depressed brightness temperature with respect to the 11.0 μm (where the single-scatter albedo of the latter is near unity). However, the signal is not consistent for all low clouds, particularly those occurring in pristine environments having characteristically larger effective particle sizes reducing scattering at 3.9 μm, or near the tropics where higher absorption by water vapor at 3.9 μm requires a more "aggressive" brightness temperature difference threshold which still might not detect the low clouds present. In this case, visible light reflection may provide the only viable means for their detection.

The Defense Meteorological Satellite Program's (DMSP) Operational Linescan System (OLS) is capable of overcoming this problem in part by sensing cloud reflection of moonlight when available on the nighttime side of the earth. This provides an appealing counterpart (and in some instances, augmentation) to daytime visible imagery applications. The emission from moonlight typically is several orders of magnitude smaller (roughly 1 million times fainter) than daytime scenes, necessitating the use of a photomultiplier tube (PMT) for adequate signal amplification. The OLS also includes a single infrared window (11μm) channel, enabling the identification of optically thick high clouds.

The OLS was designed specifically for cloud imaging (used by Air Force meteorologists in support of nephanalysis production). It operates over an extremely large dynamic range of illumination, but provides only coarse radiometric resolution (6-bit and 8-bit for the visible and infrared channels, respectively). A dynamically adjusting on-board gain (to avoid saturation while traversing highly variable light scenes) that is not reported as part of the telemetry further limits the quantitative utility of these data. The global-area-coverage data (available in archive since 1992 at the National Geophysical Data Center) are provided at a "smooth mode" resolution of ~2.7 km. A fine mode (0.56 km pixels) is also available via direct broadcast. Since the declassification of these military satellites in 1972, researchers have been able to demonstrate applications of the OLS in a number of areas (foremost among these being the monitoring of human activities; e.g., Croft (1973, 1987) and Elvidge et al. (1997,1999)). Here, we demonstrate the OLS utility in revealing TC structures by moonlight that cannot otherwise be seen via infrared imagery.

4. AUTOMATED TC PROCESSING SYSTEM

The new MODIS and OLS processing has been added to the suite of applications produced by the TC Webpage automated processing system (APS), a user-friendly graphical user interface which broadcasts near real-time satellite of tropical storms occurring worldwide. Global MODIS datasets from Terra and Aqua are obtained via the Near Real-Time Processing Effort (Haggerty et al. 2003), and global OLS datasets (currently, from DMSP constellation members F-13 through F-16) are obtained via Fleet Numerical Meteorology/Oceanography Center. Typical latencies for both datasets are of the order 2-4 hr.

Storm locations (center points) as defined by tropical cyclone warning centers (e.g., National Hurricane Center in Florida and the Joint Typhoon

Warning Center in Hawaii) are obtained through the Automated Tropical Cyclone Forecast (ATCF) system (Sampson and Schrader 2000). The APS loops over all active storms, checks for corresponding satellite coverage, and launches post-processing scripts to produce both imagery products and research datasets. The various imagery products (including standard visible/infrared from geostationary sensors, passive microwave-derived wind, water vapor, and storm structure, active microwave-derived surface winds and rainfall) are delivered to the TC Webpage to form a complementary, co-registered overview of storm structure, position, and intensity. The following section presents examples of the new capabilities brought to the table by the recent additions of MODIS and OLS.

5. EXAMPLES

The examples to follow illustrate several new TC Webpage capabilities afforded by MODIS high resolution and OLS nighttime visible imagery products. For OLS nighttime examples, an almanac was consulted to determine the dates of near full-moon phases during the 2001-2005 hurricane seasons. Based on these dates, the TC Webpage online archive was interrogated to identify potential storm cases illustrating specific benefits of the nighttime visible light dataset. The OLS data for a subset of these cases were then retrieved via the National Geophysical Data Center online archive system, and processed according to the low/high cloud OLS enhancement algorithms described in Miller et al. 2005 and Lee et al. 2006. MODIS data were retrieved from the NASA Distributed Active Archive Center (DAAC), and processed according to the method described in Section 2.

5.1 *TCs by Moonlight*

Nighttime visible observations in reflected moonlight (when available) enhance TC storm position fixing particularly in the decaying stages of a storm, where environmental shear may have destroyed or displaced the upper level circulation with respect to the near-surface circulation. In Fig.1, conventional infrared imagery (upper panel) is hard-pressed to discern the low-level circulation remnants of Hurricane Flossie. The lower panel, which uses moonlight to depict low clouds in yellow and infrared emission to depict high clouds in blue, reveals this low level circulation (including a still-defined eye) off the coast of Baja California. Also worth noting is the presence of thin, high clouds atop thick lower level clouds (as noted). Combining quantified nighttime visible information with established thin cirrus detection techniques (e.g., using either the 11-12 or 3.9-11 μm brightness temperature differences) would therefore allow for a cloud-overlap detection algorithm entirely analogous to the daytime techniques described by Pavolonis and Heidinger (2004).

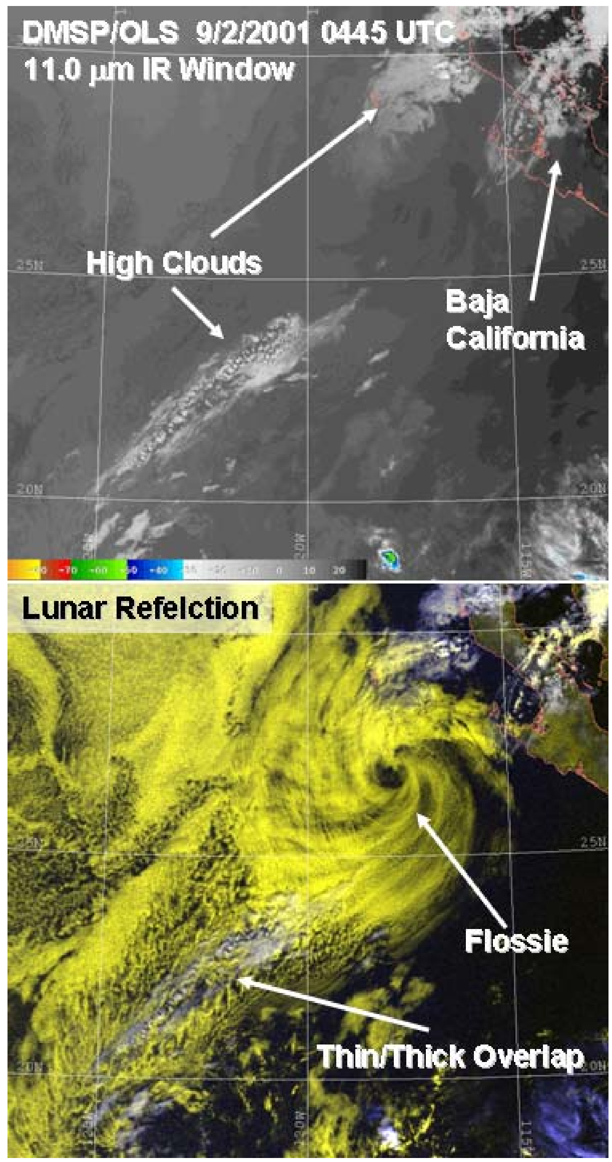

Figure 1. Infrared imagery (top) gives little indication of the low-level circulation associated with the remnants of Flossie, which are revealed using moonlight reflection (bottom). An area of thin cirrus overlapping low clouds is also noted.

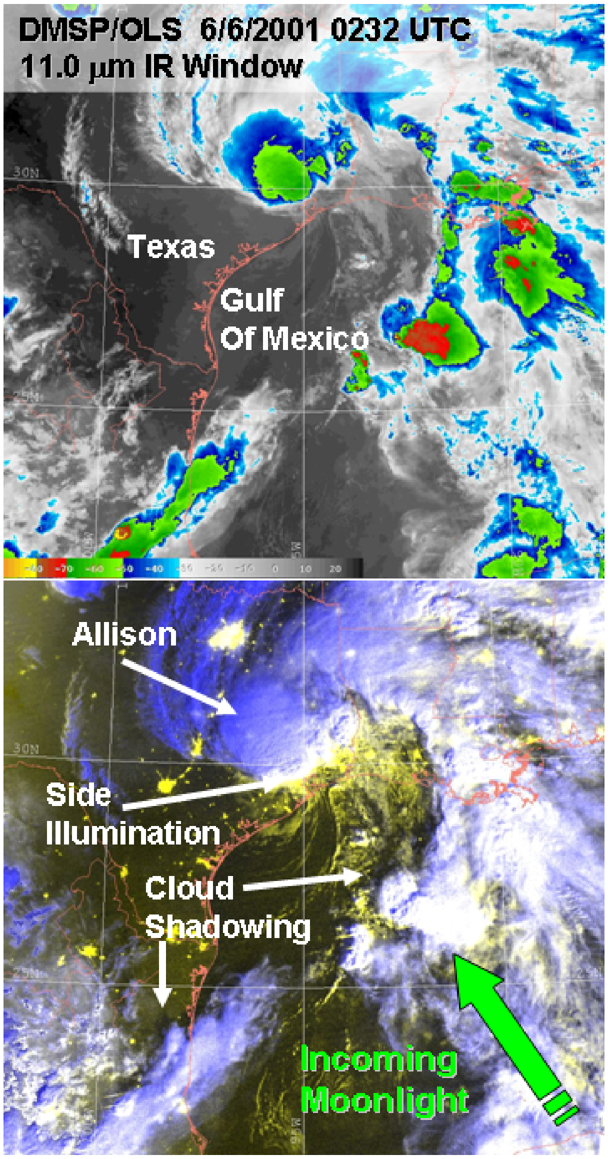

Figure 2. Low elevation angle moonlight entering from the southeast illuminates the sides of convective clouds associated with Hurricane Allison and casts shadows on the land/ocean.

Fig. 2 is a nighttime view of Hurricane Allison making landfall along the Gulf Coast in June of 2001. While moonlight provides additional information on the low-level rain bands (particularly in the southern quadrants), this example was included primarily to highlight the role played by lunar geometry. At the time of this pass, the moon is in the southeastern sky and preferentially illuminating the southeastern sides of cloud structures. Here, the side illumination of the northern quadrant convective complex is shown in white tonality (a combination of cold brightness temperatures in the blue "color gun" and strong visible light reflection in the green and yellow guns of this three-color composite). Shadows extend to the northwest of several high cloud structures, suggesting that cloud height retrievals based on satellite/lunar geometry can be conducted analogous to the same techniques used during the day, particularly in regions of moon-glint and over reflective land backgrounds.

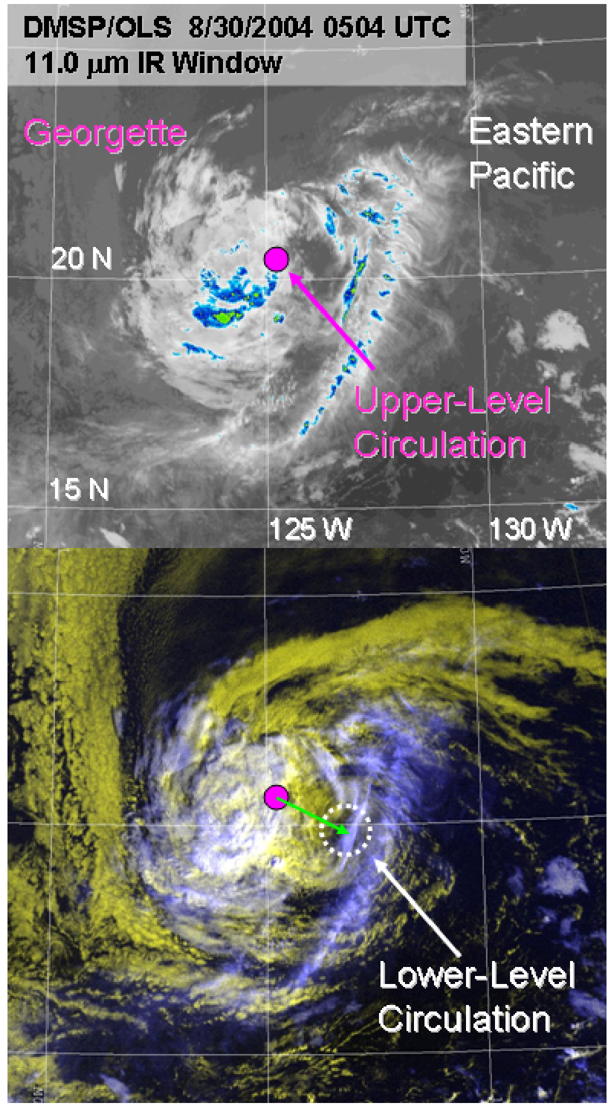

Figure 3. Demonstrating the utility of moonlight in revealing the center of lower level circulation for the remnants of Georgette.

Figs. 3 and 4, corresponding to the remnants of Hurricanes Georgette (2004) and Iselle (2002), respectively, demonstrate the benefits of nighttime visible light measurements to determining storm position in less organized systems. In the case of Georgette, the upper-level circulation (as inferred from the infrared imagery) is displaced significantly (approximately 2 degrees) from the lower-level circulation. Similarly, the asymmetric structure of

Iselle places an IR-only based storm center west of the center of circulation by roughly 1.5 degrees. These displacements are significant when considering that these storms still harbor strong winds and can on occasion redevelop into more powerful storms if they move into more favorable environmental conditions.

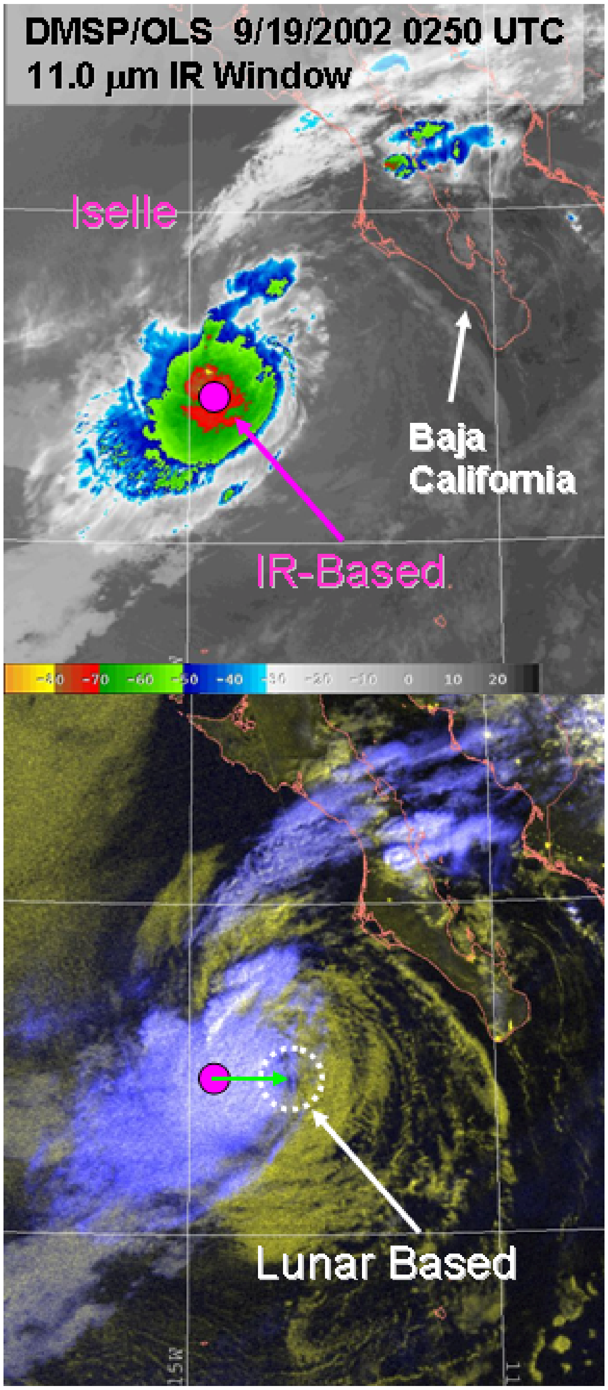

Figure 4. Storm fixed based IR features can lead to significant discrepancies for asymmetric systems such as shown here for Iselle, off the coast of Baja California.

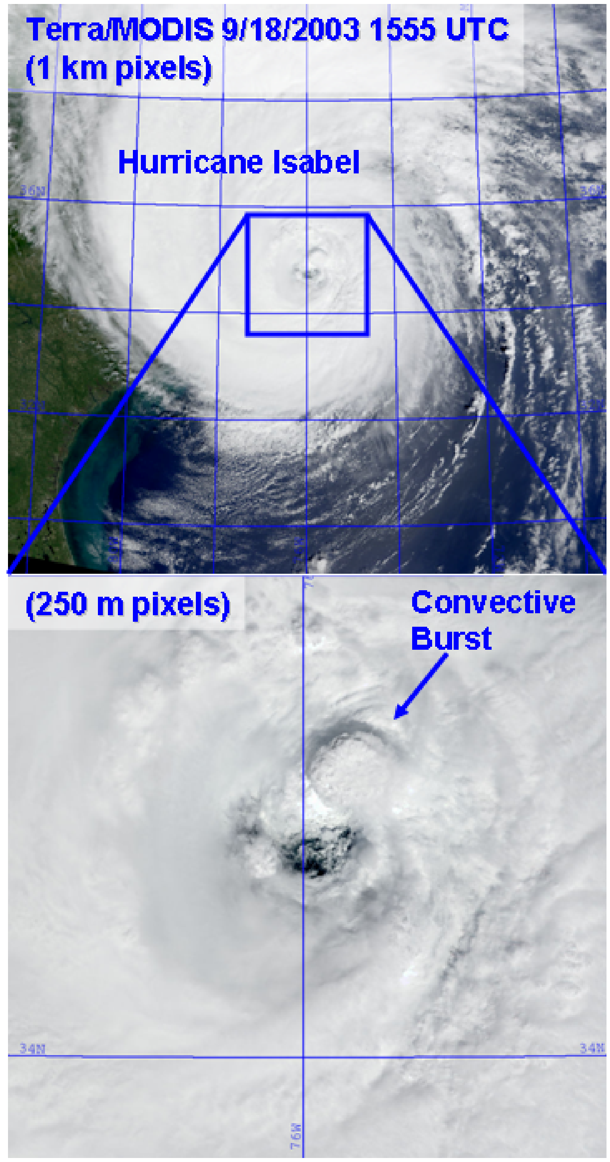

Figure 5. MODIS 250 m imagery captures a convective burst in progress on the northeastern quadrant of Hurricane Isabel. These events have been linked to rapid intensification.

5.2 *Fine-Scale Eyewall Structure*

The high spatial resolution available from MODIS enables close inspection of fine-scale features of TCs which may provide unique information on current intensity and short-term trends. Fig. 5 illustrates the phenomena of convective hot towers occurring in the eyewall of Hurricane Isabel (2003). Zooming in from storm-scale to eyewall-scale resolution reveals a pronounced and isolated convective burst on the northeast portion of the eyewall (note the shadow cast to the north by the overshooting cloud top). Kelly et al. 2004 demonstrate how such anomalous cells can be harbingers to rapid TC intensification. Simpson et al. 1998 consider the role of such isolated hot towers in subsequent TC organization. Here, the 250 m MODIS imagery resolves potentially valuable details in support of both studies.

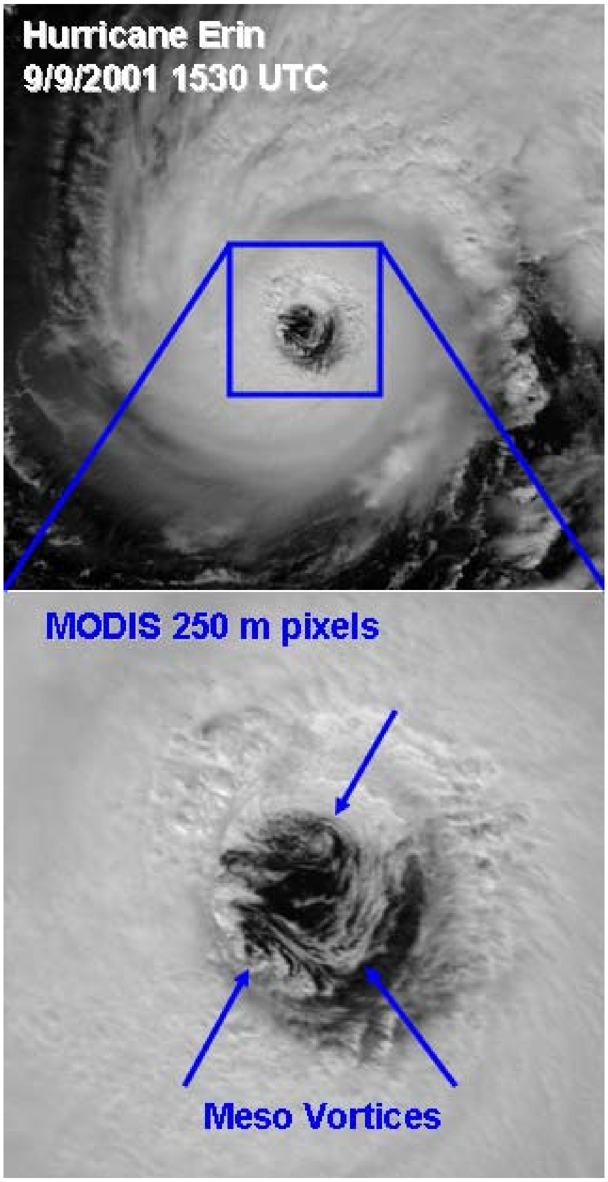

Figure 6. Mesoscale vortices reveled within the eye of Hurricane Erin using 250 m resolution MODIS imagery.

When central dense overcast conditions do not occur and a clear view of the eye itself is available, additional information related to TC development can be gleaned from the high resolution MODIS imagery. Fig. 6 shows examples of at least three mesovortices occurring inside the eye of Hurricane Erin in 2001, as revealed by the low level cloud patterns readily apparent with MODIS. Recent research has related the characteristics of inner-eye circulations to hurricane intensity (e.g., Kossin and Schubert 2001, Kossin et al. 2002, and Montgomery et al. 2002). The features are largely indiscernible from conventional 1 km visible imagery.

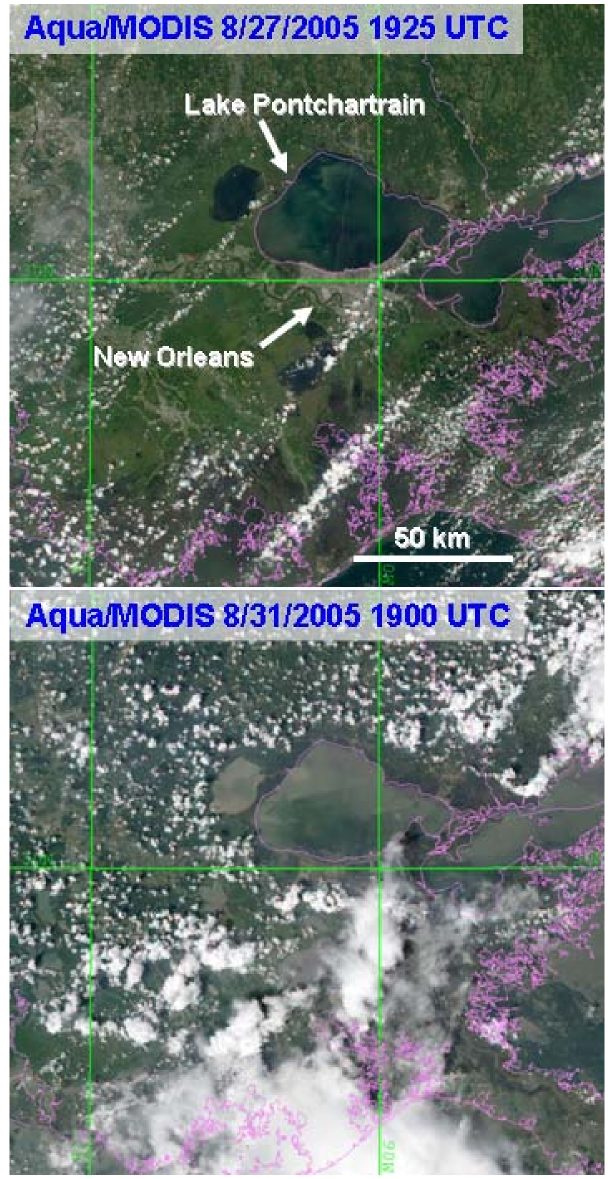

Figure 7. Before (top) and after (bottom) view of New Orleans area depicting the widespread destruction of Hurricane Katrina and the muddied waters of Lake Pontchartrain.

5.3 *Post-Storm Reconnaissance*

In addition to improving the characterization of active storms, the MODIS/OLS day/night capabilities provide new capabilities in terms of post-storm analyses of impacted land/littoral zones. The 250 m resolution MODIS imagery in Fig. 7 captures the widespread flooding throughout the New Orleans area associated with Hurricane Katrina (2005). The top panel shows a view of the region two days prior to Katrina's landfall, and the lower panel shows the same area two days after landfall. Most notable are the muddied waters of Lake Pontchartrain and surrounding water bodies.

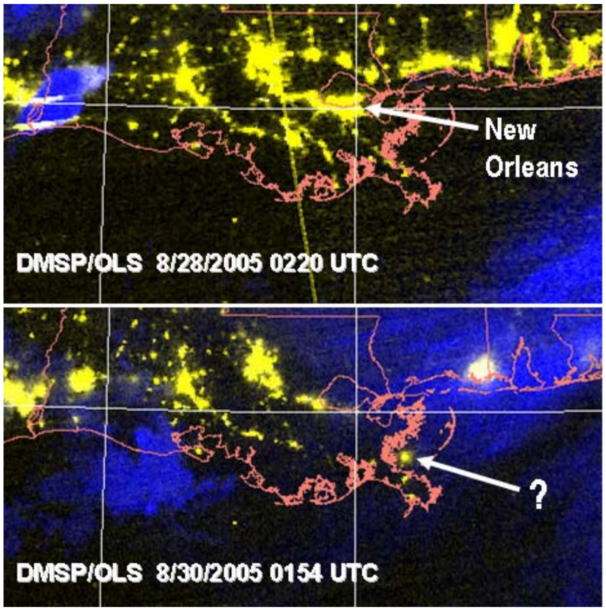

Figure 8. City lights in and around the New Orleans area before (top) and after (bottom) the landfall of Katrina.

The OLS nighttime observations paint an even more poignant picture of the impacts Katrina had on human life. The top panel of Fig. 8 shows the New Orleans area roughly 34 hr prior to landfall (the first indications of the storm's cirrus shield are shown as blue clouds in the southeast). Bright yellow patches are major metropolitan areas, with New Orleans designated by a white arrow. The bottom panel shows the same region about 12 hr after landfall. Widespread power outages as a result of the winds and flooding account for the absence of lights over a substantial region, including the entire city of New Orleans. The source for the "new light" (pointed out in the lower panel by a question mark) offshore the southeastern Louisiana coastline is not known, but could be the lights produced by sea vessels conducting search and rescue operations.

6. SUMMARY

To research and operational entities alike, the TC Webpage serves as an important resource for timely, value-added satellite imagery characterization of active and archived TCs worldwide. The capability to characterize these storms during both day and night has been augmented by the inclusion of OLS nighttime and MODIS high resolution daytime imagery.

In the coming years, the capabilities demonstrated here based on separate satellite systems (DMSP, Terra/Aqua) will be provided on a single sensor. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) era will feature among its sensor suite the Visible/Infrared Imager/Radiometer Suite (VIIRS). VIIRS will incorporate and augment sensor technologies and data acquisition techniques currently available from the OLS, AVHRR, and MODIS heritage sensors in providing a superior, integrated observing system. In addition to high resolution true color rendering capability, VIIRS will include the "Day/Night Band" (DNB)—based on the DMSP-OLS but featuring notable improvements in spatial/radiometric resolution, calibration, and dynamic range of sensitivity (e.g., Lee et al., 2006). The NPOESS Preparatory Project (NPP), scheduled for launch in 2008, will offer a first look at the capabilities of the VIIRS sensor. The first NPOESS satellite is slated for launch in the ~2012 timeframe.

7. ACKNOWLEDGEMENTS

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