NOTES AND CORRESPONDENCE

Nighttime Observation of Sheared Tropical Cyclones Using GOES 3.9-μm Data

THOMAS F. LEE

Naval Research Laboratory, Monterey, California

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ABSTRACT

This note discusses a Geostationary Operational Environmental Satellite product that can reveal the low clouds associated with tropical cyclones at night. It is based on a pixel-by-pixel difference of the longwave (10.8 μm) and shortwave (3.9 μm) brightness temperature fields. This product is compared with daytime visible images from the same satellite and passive microwave images from the Tropical Rainfall Measuring Mission Microwave Imager and the Defense Meteorological Satellite Program Special Sensor Microwave/Imager. Implications for weather analysis and forecasting are discussed for weak and shearing systems.

1. Introduction

Longwave infrared imagery, one of the mainstays of tropical cyclone monitoring from satellites, is an effective tracer of cirrus and the tops of tropical convection. However, over weak tropical cyclones these images can mislead an analyst because they do not show low clouds well. Visible images, on which low clouds appear prominently due to reflected solar radiation, are therefore invaluable supplements to infrared images during the daytime. Visible images have the further advantage that thin cirrus is translucent, allowing limited observation of near-surface clouds that are obscured by cirrus on infrared images. However, visible images also have a disadvantage: they show high, middle, and low cloud decks in very similar gray shades, complicating the ability of the user to observe low cloud structure independently.

At night, visible images are not available, forcing reliance on infrared images that do not show the lower layers of the tropical atmosphere well. Even infrared image enhancements that target the brightness temperatures associated with stratus often fail to depict these clouds unambiguously. In real-time monitoring efforts, the first visible image of the day often reveals important information about storm structure that was missing during the previous night. There are several problems with infrared images. First, abundant tropical water vapor partially obscures the view of the satellite of stratiform clouds even when higher clouds are absent. Second, low clouds contrast poorly with the slightly warmer sea surface. Third, low clouds contrast poorly with thin cirrus, which, due to transmission of warmer radiances from below, often assumes brightness temperatures of 0°C or above.

This note will discuss a nighttime enhancement for liquid water clouds for use in the Tropics. The tropical low cloud enhancement (TLE) is scaled differently from similar products developed for the midlatitudes (Dostalek et al. 1997; Lee et al. 1997) to account for abundant tropical water vapor. In two of the three case examples the TLE image will be compared to images from satellite passive microwave instruments: the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I). Passive microwave images are useful for comparison because cirrus clouds are transparent at these frequencies, allowing an unobscured view of low clouds. In addition, passive microwave images show low clouds well against the sea surface, unlike infrared images. Finally, microwave images can show convective precipitation directly, a capacity that adds useful context to the discussion.

2. Background and processing

Using National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer data, several studies employed the shortwave (3.7 μm) infrared channel in conjunction with the longwave (10.8 μm) infrared channel to detect the presence of nighttime low cloud that would otherwise match the thermal surface background (Eyre 1984; d'Entremont 1986;

Corresponding author address: Thomas F. Lee, Naval Research Laboratory, 7 Grace Hopper Avenue, Monterey, CA 93943-5502.
E-mail: lee@nrlmry.navy.mil

d'Entremont and Thomason 1987; Yamanouchi and Kawaguchi 1992). Developed for midlatitude or polar regions, all of these techniques exploited the distinct emissivities of stratiform clouds at the two wavelengths. The new Geostationary Operational Environmental Satellites (GOES), which contain the requisite infrared channels, allow these applications to be used extensively with much broader spatial and temporal refresh (e.g., Ellrod 1995; Lee et al. 1997; Dostalek et al. 1997). Such ''fog,'' ''stratus,'' or ''low cloud'' products are routinely generated for regions within the United States and are now used in forecasting operations over land and coastal areas. This paper demonstrates this technique over tropical cyclones, where GOES coverage is excellent. Using low-resolution GOES Sounder data, Ellrod (1993) illustrated a prototype of this application.

The longwave–shortwave brightness temperature difference (LSBTD, 10.8–3.9 μm) forms the basis of nighttime processing. The range of the LSBTD over low clouds depends on a number of factors, most significantly droplet size within the cloud and the amount of absorbing water vapor between the clouds and the satellite. This difference is usually positive over low clouds because longwave (10.8 μm) brightness temperatures (near blackbody cloud emissivity) exceed those in the shortwave (3.9 μm) channel (cloud emissivity less than blackbody). Background features, such as cloud-free land and ocean surfaces, usually have values of LSBTD near or slightly below zero, enabling contrast between low cloud and background on images. Over the United States, where droplet size is relatively small [continental cloud condensation nuclei (CCN) regime], the LSBTD ranges from about 2 to 6 K and is scaled over this range on most operational images. Over the midlatitude oceans away from coastlines (generally larger droplets, marine CCN regime) the LSBTD tends to be smaller, about 1–2 K. Over the tropical oceans above low clouds, differential water vapor attenuation roughly neutralizes the effects of cloud emissivity mentioned above, so that LSBTD values hover around 0–1 K. Fortunately, cloud-free ocean in the Tropics is associated with LSBTD values near -2 or -3 K, enabling contrast between low clouds and the sea surface on TLE images.

Ice clouds, particularly those that are optically thin, generate nighttime values of LSBTD of the opposite sign ($\sim<-3$ K) from low stratiform clouds. These negative differences result from two effects: first, greater cloud transmissivity in the shortwave window versus the longwave window, and, second, interchannel differences over partially cloud-filled ''mixed pixels'' (Dozier 1981). The negative values of the LSBTD over ice clouds produce strong contrast with low stratiform clouds on TLE images. Thick cirrus and cumulonimbus produce spurious LSBTD values associated with increased shortwave channel noise at low temperatures (Yamanouchi and Kawaguchi 1992; Ellrod 1995).

A linear display of the LSBTD image is not optimal, so an enhancement curve was developed for the Tropics

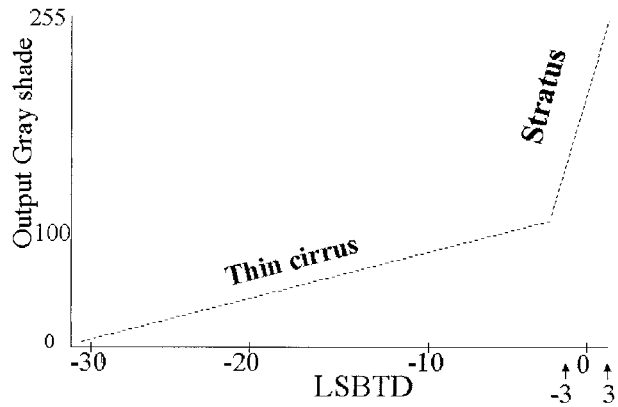

FIG. 1. Graph of enhancement used for TLE. LSBTDs of -30 to -3 K are mapped to output gray shades of 0–100. LSBTDs of -3 to $+3$ K are mapped to 101–255.

(Fig. 1) that ''stretches'' the range of values from -3 to $+3$ K that corresponds to low cloud and cloud-free sea surface. The higher values within this temperature range represent low cloud (whites); the lower values represent the sea surface (grays). This enhancement is the basis for TLE imaging. The broader range of values from -30 to -3 K is ''compressed'' into the lowest and therefore darkest output values. This procedure gives thin cirrus a dark gray or black appearance on the enhanced image. The noisy values at low shortwave temperatures appear as speckles on the TLE image and mark thick cirrus and cumulonimbus.

3. Case examples

a. Nighttime observation of eastern Pacific Tropical Depression 5, 1997

A longwave infrared image of Tropical Depression 5 off the Mexican coast (position: 15.4°N, 114.6°W; intensity: approximately 25 kt) shows very little detail over the storm center (Fig. 2a). A convective band appears prominently to the south. Using this image alone a forecaster would have great difficulty in fixing the position of the storm. A BD enhancement (Dvorak hurricane enhancement; Fig. 2b), a stepwise linear infrared enhancement often used in tropical cyclone monitoring, improves the view of the system compared to the unenhanced view. Still, there are difficulties in interpreting the BD image correctly, especially for users who are not experts. Specifically, the low clouds near the storm center blend in with the sea surface and the thin cirrus to the north, complicating the interpretation of any of these features on the basis of gray shade alone.

The TLE image provides an improved view (Fig. 2c). The low clouds (white) can easily be distinguished from the sea surface and from ice clouds. Furthermore, the image can be used to distinguish thin cirrus (black or dark gray) from thick ice clouds (speckled). The speckled cloud band on Fig. 2c at 10°N suggests deep con-

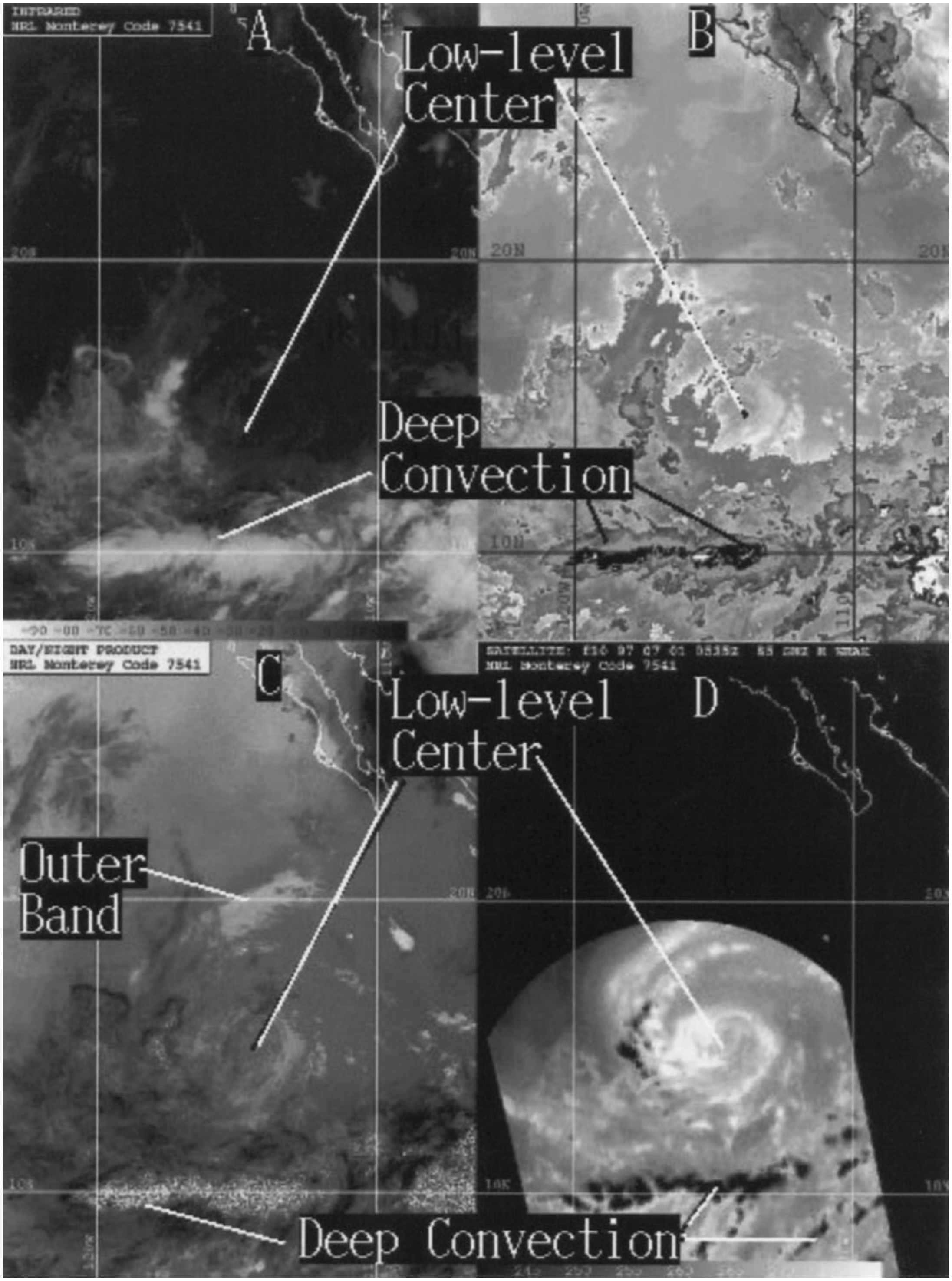

FIG. 2. Eastern Pacific Tropical Depression 5, 0530 UTC 1 Jul 1997 (nighttime): (a) *GOES-9* longwave infrared, (b) *GOES-9* longwave infrared BD enhancement, (c) GOES TLE enhancement, and (d) SSM/I 85-GHz (horizontal polarization), linear display from 240 to 280 K.

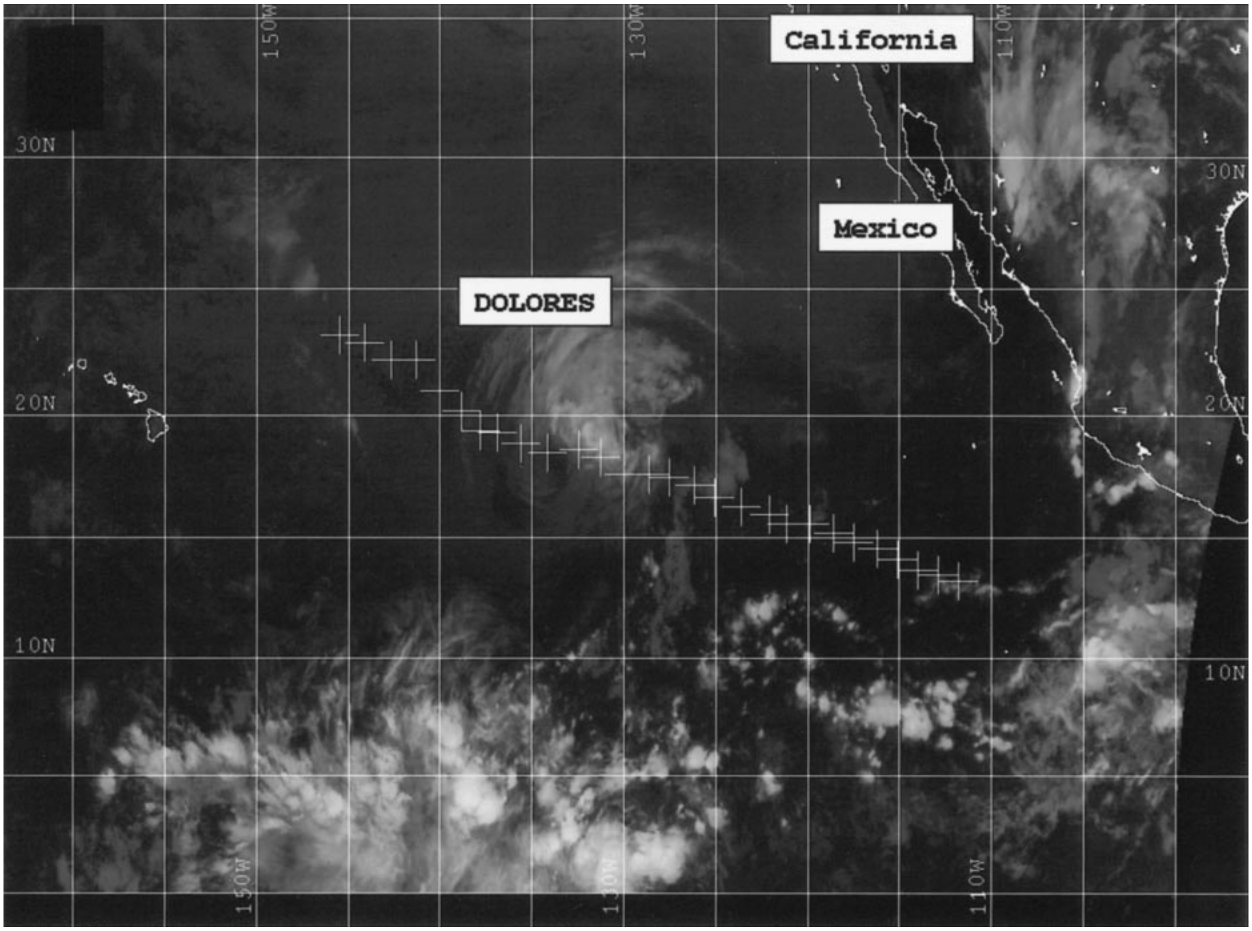

FIG. 3. Track of Dolores overlayed on longwave infrared *GOES-9* image at 1030 UTC 10 Jul 1997. Crosses indicate locations of Dolores over its lifetime.

vection. Figure 2d, an SSM/I view (85 Ghz, horizontal polarization) at nearly the same time, suggests the presence of convective precipitation (black, indicating low brightness temperatures) in this cloud band (Negri et al. 1989). It also shows the cloud water of the low-level center to the north in bright white.

b. Hurricane Dolores in the eastern Pacific, 1997

On 5–12 July 1997 Dolores moved across the eastern Pacific toward the west (crosses shown in Fig. 3), weakening later in the period. On 9 July the hurricane weakened to a tropical storm, and on 10 July it was downgraded to a tropical depression. The infrared satellite view on 10 July 1997 shows most of the high cloudiness from Dolores to the north of the track of the storm. This phenomenon, common in eastern Pacific storms, is caused by vertical shear.

Over a 21-h period, this effect can be observed in an afternoon daytime visible image, two nighttime TLE products, and a morning visible image the next day (Figs. 4a–d). The first visible image (Fig. 4a) shows the storm moving into a large area of stratus clouds to the north. Directly north of the tropical cyclone lies a clear band in the stratus, a phenomenon often observed in visible satellite images as eastern Pacific storms move into the stratus-covered waters of the eastern Pacific. Figure 4b, the TLE product shortly after dark the same day, shows the high cloud canopy (black) detaching from the circulation of the lower cloudiness (white). The black gray shades of the cirrus canopy suggest that this cloud deck is thin and unlikely to overlay any precipitation. Figure 4c, the TLE image 5 h later, shows the same trend. The clear band seen in Fig. 4a is apparent in Fig. 4c as well. The image from the following morning (Fig. 4d, visible) shows the remnants of convection in the northeast portion of the tropical cyclone, while the low-level portion increasingly merges with the ambient stratus field.

c. Tropical Storm Arlene in the Atlantic, 1999

On 19 June 1999 Arlene was undergoing significant vertical shear (position: 31.6°N, 62.6°W; intensity: ap-

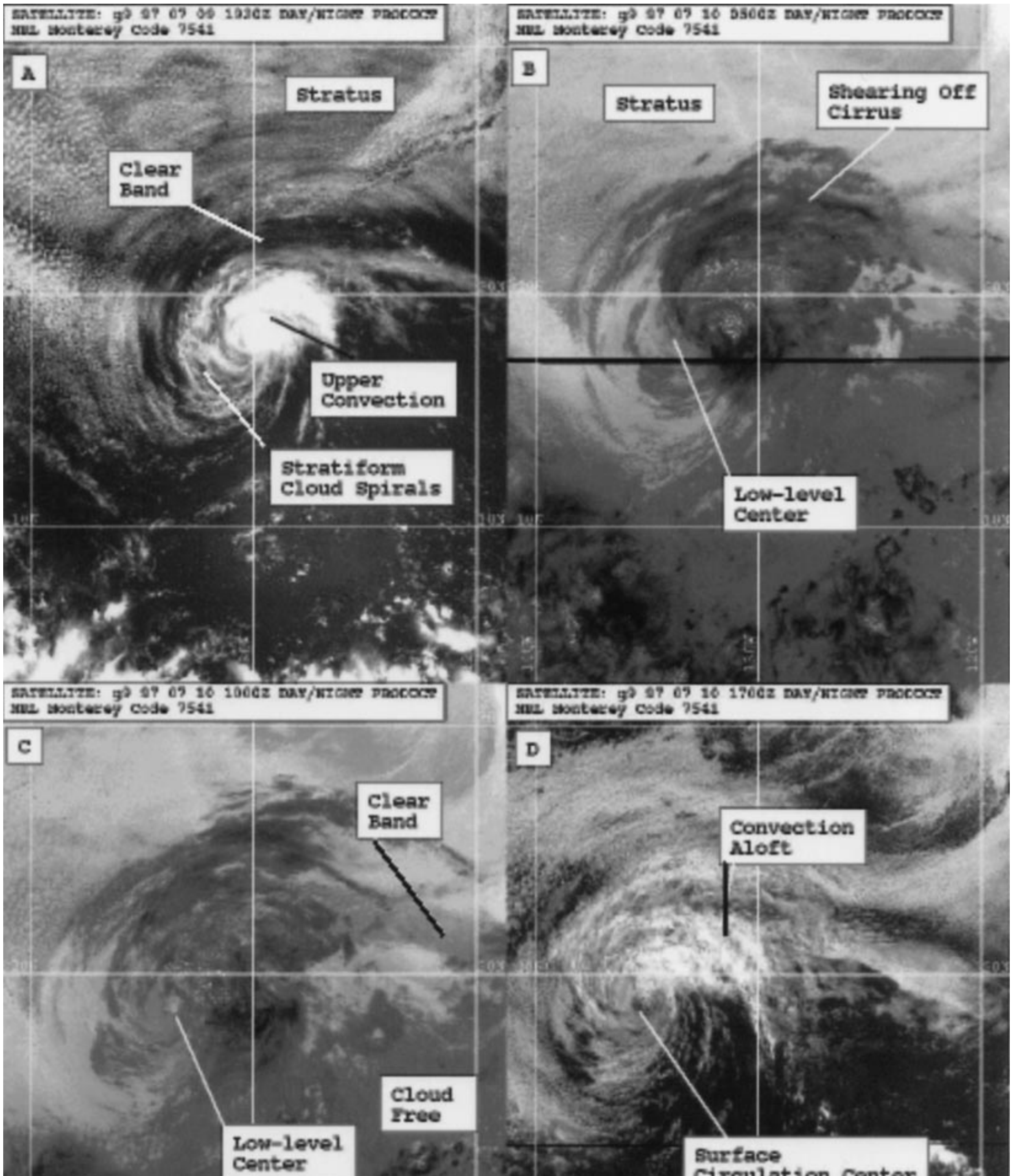

FIG. 4. Hurricane Dolores, Jul 1997: (a) *GOES-9* visible image at 1030 UTC 9 Jul, (b) *GOES-9* nighttime TLE image at 0500 UTC 10 Jul, (c) *GOES-9* nighttime TLE image at 1000 UTC 10 Jul, and (d) *GOES-9* visible image at 1700 UTC 10 Jul 1997. Annotations of ''surface circulation center'' and ''low-level center'' are intended as reference points for the viewer and do not represent actual fixes of storm position.

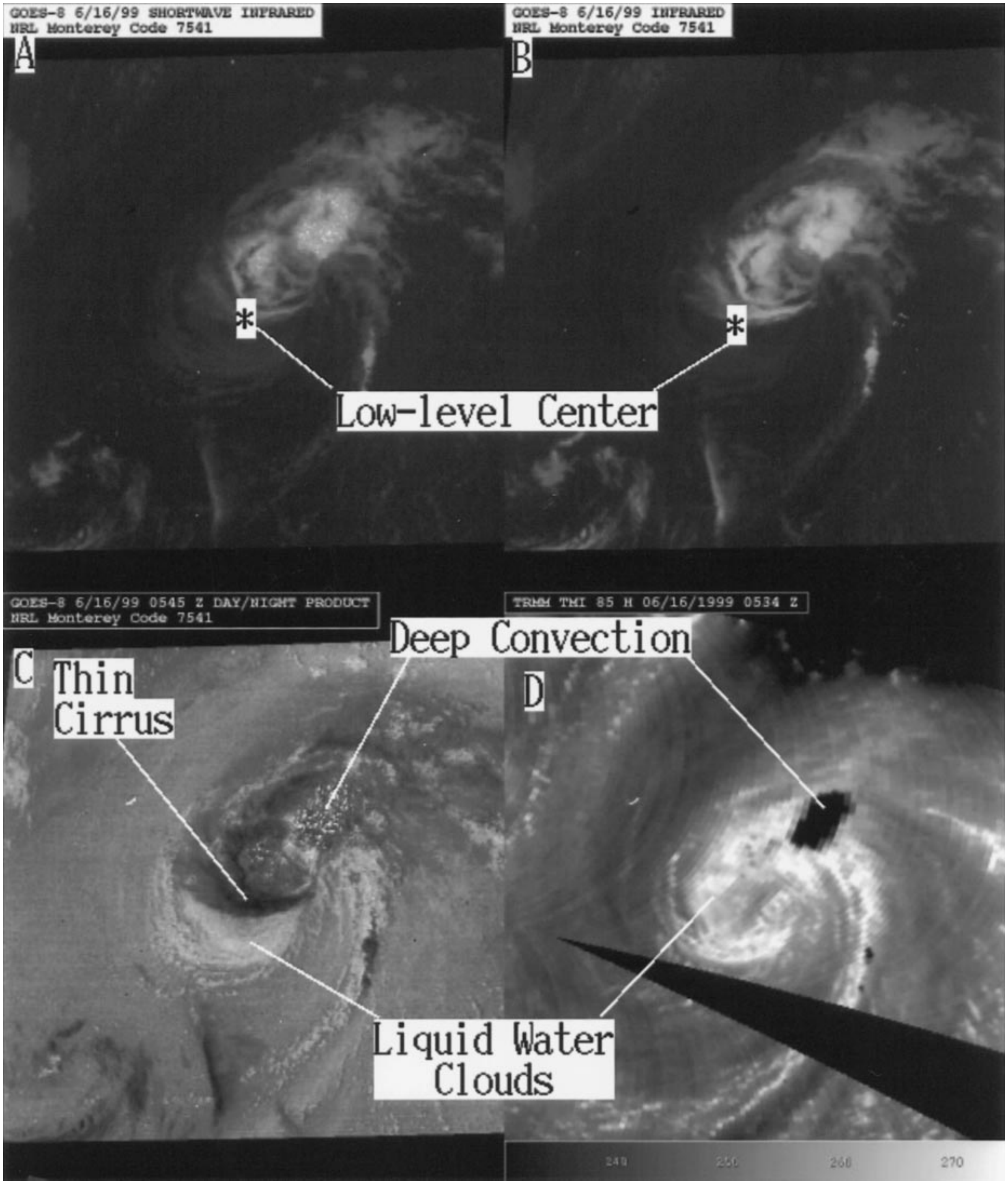

FIG. 5. Hurricane Arlene, 0530 UTC 16 Jun 1999 (nighttime): (a) *GOES-10* longwave Infrared, (b) *GOES-10* shortwave infrared, (c) GOES TLE image, and (d) TRMM TMI 85 GHz (horizontal polarization). Annotations of ''low-level center'' are intended as reference points and do not represent actual fixes of storm position. Each of the panels above is about 1200 km on a side.

proximately 45 kt). The shortwave infrared (Fig. 5a) and the longwave infrared images (Fig. 5b) both show a circulation in the high cloud field. However, lack of thermal contrast near the surface prevents the easy identification of low clouds in either image. The TLE image (Fig. 5c) reveals the low-level stratiform center distinctly as white in contrast to a gray sea surface to the south and west. Thin cirrus just to the north (annotated in Fig. 5c) obscures a portion of this low cloud center. Speckles suggest a thick cirrus cloud or cumulonimbus to the northeast. Figure 5d shows the corresponding 85-GHz (horizontal polarization) image from the TRMM TMI imager (Kummerow et al. 1998; Simpson et al. 1998). Since this frequency is unaffected by cirrus, the entire low cloud circulation (white) can be easily observed. The black spot in the northeast quadrant of the storm indicates the presence of convection (low brightness temperatures shown as black). This corresponds to the speckled area on the TLE image (Fig. 5c).

4. Discussion

Over tropical cyclones there is often some limited infrared contrast between low clouds and the ocean background. Thus, an experienced operator on a satellite workstation can usually enhance an infrared image to arrive at a product that resembles the TLE image to some degree. However, the TLE image requires no interactive processing and can be distributed automatically via the Internet and other similar means. Furthermore, the TLE image often can be used to distinguish between water- and ice-phase clouds, a capability impossible from single-channel infrared enhancements.

The TLE image is generally a good nighttime substitute for visible images. However, there is an important difference in appearance between the two types of images. On the TLE image thin cirrus appears dark gray or black, while on visible images thin cirrus is white. This makes it easier to distinguish cirrus from low clouds on TLE images than on visible images. Sequences of images (e.g., Figs. 4a–d) can be easily combined into loops that can show low-cloud circulations in and around tropical cyclones 24 h a day. This capability is an improvement over the traditional reliance on visible images during the daytime and infrared images at night, because the continuity of low cloud features is not lost from day to night. Another potential application of the TLE images is the production of automated low-level wind vectors at night in regions of sheared tropical cyclones, which could also help locate the storm centers.

The speckles that mark thick cirrus or deep convection often delineate regions of precipitation, though not reliably. In strong, unsheared storms, the TLE image allows the analyst to distinguish between the dense overcast surrounding the eye (speckled) from thin cirrus (dark gray) on the periphery.

5. Summary and conclusions

This paper has discussed a simple technique to enhance low clouds associated with weak or shearing tropical cyclones at night. Based on the difference of the GOES shortwave and longwave channels, images were demonstrated that show low clouds as white, thin cirrus as black, convection as speckled, and the ocean background as gray. Series of these images, combined with visible images during the daytime, permit the uninterrupted viewing of storm evolution not before possible. Qualitative validation of these GOES products was performed with TRMM and SSM/I 85-GHz images. Less affected by cirrus than the GOES infrared channels, these passive microwave images offer an unprecedented opportunity to view low clouds and convection in the tropical marine atmosphere.

A real-time demonstration of the GOES TLE product appears on the Naval Research Laboratory's satellite Web page.[1]

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[1] To view the NRL satellite imagery online, visit http://kauai.nrlmrv.navy.mil/sat_products.html and click on ''GOES Color Composites Loops and Images.'' On the lower row of images, the TLE image appears in red, the GOES water vapor image appears in green, and the GOES infrared image appears in blue. Click on the color images to zoom. Zooming also gives an option to see the TLE images in black and white (low cloud option).

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