Satellite-based Microwave Observations of Tropopause-Level Thermal Anomalies: Qualitative Applications in Extratropical Cyclone Events

CHRISTOPHER S. VELDEN

Cooperative Institute for Meteorological Satellite Studies, Madison, Wisconsin

(Manuscript received 17 April 1992, in final form 4 August 1992)

ABSTRACT

The evolution of upper-tropospheric thermal patterns associated with extratropical cyclone events is often not well represented by the conventional observational network, especially in marine situations. In this paper, a potential tool for qualitatively analyzing tropopause-level thermal structure and variations based on remotely sensed microwave data from satellites is examined. Specifically, warm anomalies associated with tropopause undulations in upper-tropospheric waves are captured in imagery from the 54.96-GHz channel of the Microwave Sounding Unit (MSU) onboard the current series of NOAA polar-orbiting satellites. Examples of this imagery during selected western North Atlantic cyclone events are presented, and the potential usefulness of these observations in analysis and forecasting is discussed.

1. Introduction

Forecasting extratropical cyclogenesis remains one of the most challenging aspects of operational meteorology, even though the past decade has witnessed some significant advances in our observation and understanding of these events. Rapidly developing cyclones over the western North Atlantic Ocean are a good example. These storms are often accompanied by severe weather conditions causing a variety of economic disruptions along the densely populated northeast coast of the United States (Kocin and Uccellini 1990). In addition, these storms can adversely affect maritime travel due to the accompanying strong winds and waves.

Many recent observational studies have yielded new insights into the evolution of these cyclones (e.g., Sanders and Gyakum 1980; Bosart 1981; Gyakum 1983; Bosart and Lin 1984; Kocin and Uccellini 1984; Uccellini et al. 1984, 1985, 1987; Manobianco 1989a; Wash et al. 1992). At the same time, the development of numerical models has progressed to the point of being able to reproduce many of the observed synoptic and mesoscale features associated with these systems (e.g., Chang et al. 1982; Anthes et al. 1983; Nuss and Anthes 1987; Orlanski and Katzly 1987; Reed et al. 1988; Manobianco 1989b; Kuo and Low-Nam 1990).

Many of these studies and others suggest that upper-tropospheric processes can play a crucial role in surface cyclogenesis. For example, the existence of transient upper-level troughs preceding the development of surface cyclones has been documented (Sutcliffe and Forsdyke 1950; Sanders and Gyakum 1980; Sanders 1986; Rogers and Bosart 1986). The relationship between these troughs and surface cyclogenesis in terms of local concentrations of potential vorticity (PV) is discussed in Hoskins et al. (1985). Bleck (1990) forwarded these concepts to demonstrate how they could successfully be used in practice to show that extratropical cyclogenesis can be interpreted as a mutual amplification of juxtaposed PV perturbations. An observed tropopause fold and associated stratospheric extrusion of high PV air was identified by Uccellini et al. (1984, 1985) as having played a role in the deepening of the President’s Day storm in 1979. In another study, Gyakum (1983) asserted (based on limited aircraft observations) that the QEI storm had an upper-level warm core characteristic of hurricanes, and a similar feature was present in a case study of a rapidly deepening North Pacific storm (Reed and Albright 1986).

These and other observational and theoretical studies (e.g., Elsberry and Kirchoffer 1988; Hirschberg and Fritsch 1991a,b) show that the evolution of the upper-tropospheric structure and thermal response during surface cyclogenesis needs to be well observed and documented. Unfortunately, in most of the studies cited, conclusions about the influence of upper-level processes were hindered by analysis uncertainties owing to the sparsity of observations, especially in explosively deepening marine events. Initial analysis errors can also lead to large numerical model forecast errors (Reed et al. 1988; Sanders and Auciello 1989; Mullen and Baumhefner 1989; Kuo and Low-Nam 1990). High-
level commercial aircraft reports and satellite-derived cloud-motion vectors provide some quantitative information over this region; however, both of these types of observations are mainly restricted to single levels, and horizontal coverage is limited. Satellite soundings offer information in cloud-free regions, but are of questionable value in large-scale precipitating weather systems. Analysis of field experiment data collected during the Genesis of Atlantic Lows Experiment (GALE, Dirks et al. 1988), the Canadian Atlantic Storms Project (CASP, Stewart et al. 1987), and the Experiment on Rapidly Intensifying Cyclones in the Atlantic (ERICA, Hadlock and Kreitzberg 1988) will provide crucial information. However, even in these enhanced-observation field experiments, only a very limited description of the broad evolution of the upper-tropospheric (above 300 mb) and lower-stratospheric structure over marine areas was achieved.

In operational practice, cases of marine cyclogenesis are monitored primarily by visible and infrared satellite pattern-recognition techniques, along with analyses and diagnostic output from numerical guidance systems. In this paper, an additional analysis tool is presented. Space-borne passive microwave radiometers are capable of penetrating the thick cirrus cloudiness that often accompanies extratropical cyclones, and measuring the upper-tropospheric large-scale thermal patterns. Imagery from specifically designed sounding channels can be used qualitatively to describe the evolution of these thermal patterns during cyclogenesis. Specifically examined in this study is imagery from the 54.96-GHz channel of the Microwave Sounding Unit (MSU, described in section 2) on board the current series of NOAA polar-orbiting satellites, which is shown to delineate upper-tropospheric/lowertropospheric temperature anomalies associated with tropopause undulations during extratropical cyclone events. These undulations are commonly observed in synoptic-scale baroclinic waves, and have been physically linked to the cyclogenesis process (for a discussion, see Hirschberg and Fritsch 1991a,b).

Several sequences of MSU imagery during selected extratropical cyclone events in the western North Atlantic are presented in section 3. Since this data is available in real time (or near-real time) to most of the world’s major meteorological forecast centers, the potential operational value of this product as an analysis and forecast tool is discussed. This paper focuses on the qualitative aspects of the observations, to alert forecasters to the availability and potential usefulness of the imagery itself. It will be shown that the imagery can be used not only as an analysis tool, but also to validate operational model performance. In a research mode, obtaining this type of information could be crucial to model-based evaluations of the relative importance of upper-level processes during cyclogenesis. Future studies will examine the potential quantitative uses of this information, as discussed in section 4.

2. Data description and availability

The MSU is a space-borne microwave radiometer with four spectral channels in the 50–58-GHz oxygen absorption band (Smith et al. 1979). The 54.96-GHz channel, examined in this paper, is most sensitive to variations in the upper-tropospheric/lower-stratospheric thermal field. Due to weighting function characteristics (Fig. 1), the radiance measurements of this channel represent a broad layer-average brightness temperature, with peak energy emitting from near the tropopause level (i.e., 100–400 mb). Attenuation of the signal from cloud and precipitation is minimal since hydrometeors at this level are mainly in the form of ice, which has little effect on outgoing radiation at this frequency. Therefore, upper-level thermal features in the extensive cloudy regions of extratropical cyclones can be observed. The horizontal resolution of the individual footprints at nadir is around 110 km. Observations from this channel have proven useful in a variety of applications including a study of a frontal zone (Grody 1980), convective storms (Grody 1983), and tropical cyclones (Velden 1989; Velden et al. 1991).

The normal operational satellite observing network includes two NOAA polar-orbiting satellites, each making two passes over a given location each day. This implies that MSU observations of a given meteorological feature can be attained on a 6-hourly basis. As a comparison, observations from the Nimbus-7 Total Ozone Mapping System (TOMS), which has been used in previous studies to infer tropopause variations in extratropical cyclone events (Shapiro et al. 1982; Uccellini et al. 1985; Reed and Albright 1986; Man-
obianco et al. 1991), are only available once per day (at most). The future of operational TOMS data availability is in question, whereas the fleet of NOAA satellites is scheduled to continue at least through the 1990s. Beginning around 1995, the NOAA satellites will carry an advanced MSU instrument (AMSU), which will have greatly increased horizontal resolution (i.e., 40 km).

3. Applications

Several examples of the MSU imagery are presented to demonstrate the potential applications of this data in extratropical cyclone analysis and forecasting situations. Since the operational usefulness of this product will be maximized over the data-sparse marine areas, cases of western North Atlantic cyclogenesis are examined. Applications of these observations in cyclogenesis events over other regions (such as the eastern North Pacific and western coast of the United States) will be discussed in a future publication.

NOAA satellite passes were collected during four cases of North Atlantic extratropical cyclones. Two of the cyclones exhibited a prolonged rapid deepening phase, one case was characterized by slow deepening with a short rapid deepening phase, and the final cyclone represents a case that did not appreciably deepen. Two of the cases (1 and 4) were randomly selected, with the data collected and processed in real time on the University of Wisconsin McIDAS. The other two cases (2 and 3) were taken from ERICA Intensive Observational Periods (IOP) 4 and 5, and were postprocessed from archive tapes.

a. 28–29 December 1989, explosive cyclogenesis

On 28 December 1989, a relatively weak 1004-mb low was situated off the coast of New England. During the next 36 h, the storm exhibited explosive development and reached a minimum pressure of 948 mb (surface pressure information was obtained from the NMC operational hemispheric analyses). Figure 2 shows a sequence of 54.96-GHz MSU imagery during this event (all imagery is shown in a Mercator projection). The time period covered by this sequence is approximately 28 h, during which time the surface low deepened 50 mb. The extent of the data coverage with each satellite overpass is shown by color coding the imagery (to emphasize the storm, only passes over and near the cyclone are presented; neighboring overpasses upstream or downstream of the storm are not shown). Each color shade in Fig. 2 represents one degree of brightness temperature warmer than the domain-mean brightness temperature represented in blue. The blockiness appearance to the imagery is due to the relatively coarse horizontal resolution of the observations.

The MSU imagery reveals that a relatively weak, small-scale warm anomaly (indicated in green) is evident at the initial time (1800 UTC 28 December) when the surface low was forming. This anomaly is situated to the southwest of the surface low. Twelve hours later (0600 UTC 29 December), the imagery shows a strengthening of the warm anomaly coincident with a large drop in central pressure of the surface low. The warmest pixel in the satellite image is located in the southwest corner of the yellow area. Ten hours later, at 1600 UTC 29 December, the surface cyclone has rapidly deepened further to 964 mb. The MSU-depicted warm anomaly has expanded and strengthened considerably (the black pixel to the immediate northeast of the surface low is missing data, as is the black bar to the south and east of the surface low in panel 4). By 2200 UTC 29 December, the surface low was analyzed at 954 mb, and the accompanying MSU warm anomaly appears even stronger. At this point, the center of the upper-level anomaly is still not quite vertically aligned with the surface low (and the cyclone deepened another 6 mb after this time).

Evidence will be presented later that suggests that the MSU-depicted warm-anomaly signature is a reflection of a lower tropopause in the center of the associated upper-level trough (the descended portion of a tropopause undulation as described by Hirschberg and Fritsch 1991a,b). Since the 54.96-GHz MSU observations represent a layer-averaged brightness temperature with peak radiances emitting from the tropopause region, an extrusion of relatively warmer stratospheric air into the troposphere will be depicted by a high (warm) brightness-temperature anomaly in the imagery. In terms of "PV thinking," this warm anomaly also represents an upper-level potential vorticity maximum, since the warmer stratospheric air contains relatively higher values of PV. Hirschberg and Fritsch (1991a) discuss the relationship between upper-level temperature and PV perturbations, and show from their analysis of a cyclogenesis case study that the fields are highly correlated (see their Figs. 9 and 16). The MSU-depicted warm anomaly can thus be interpreted as a signature of a positive upper-tropospheric PV anomaly, which Hoskins et al. (1985) have proposed as a mechanism for surface cyclogenesis given a proper phasing of the PV anomaly with a low-level baroclinic zone. In the present case, the descending portion of the tropopause undulation is strikingly evident in the MSU imagery (Fig. 2), and increases dramatically in horizontal scale during the period.

Of particular note, the warmest MSU pixels (denoting the center of the upper-level potential vorticity perturbation) remain situated well to the west-southwest (upstream) of the analyzed surface low during rapid deepening. This "upshear vertical tilt" is consistent with quasi-geostrophic surface development concepts and potential vorticity anomaly phasing relationships (Hoskins et al. 1985; Elsberry and Kirchoffer 1988; Warrenfeltz and Elsberry 1989; Bleck 1990). In terms of differential thermal advections, Hirschberg
and Fritsch (1991a,b) argue that, under favorable lower-tropospheric conditions, maximum surface development will take place under regions of strong warm-air advection in the upper troposphere/lower stratosphere in advance of the upper-level warm anomalies. Jusem and Atlas (1991) concur with this reasoning and further quantify the advective effects in terms of the pressure tendency derived from a numerical simulation of cyclogenesis. Since the NMC-analyzed upper-level winds during the rapid development in this case were generally from the southwest, and applying the foregoing concepts, the MSU imagery shows that the upper-level anomaly remains favorably juxtaposed with the surface low for continued development.

Also of note is that the strengthening of the surface low and the upper-level warm anomaly appears nearly coincident in time in this case. Examination of an overpass (not shown) 12 h earlier than the first panel in Fig. 2 indicates an MSU-depicted warm anomaly located over the eastern United States of about equal strength to that in the first panel. This suggests that upper-level trough amplification took place mainly coincident with, rather than prior to, the explosive surface cyclogenesis in this particular case.

b. 4 January 1989, ERICA IOP 4, explosive cyclogenesis

One of the most explosive western North Atlantic extratropical cyclogenesis events to occur in recent history took place during the ERICA field experiment in 1989 (Hartnett et al. 1989). This cyclone deepened 56 mb on 4 January, and a deepening rate of 24 mb per 6 h is estimated to have occurred between 0900 and 1500 UTC. Imagery of the 54.96-GHz MSU from four NOAA satellite overpasses on 4 January is shown in Fig. 3.

At 0000 UTC 4 January (panel 1), a pronounced warm anomaly is evident in the MSU imagery. The surface low was deepening over the coastal waters of the Carolinas at this time (surface low positions and central pressures were obtained from a postanalysis of the IOP, documented in the ERICA Field Phase Summary). Examination of MSU imagery (not shown) 12 h previous to this time (valid at 1200 UTC 3 January) revealed only a weak (one degree of brightness temperature) warm anomaly located over the north-central United States. In contrast to the first case presented, the MSU observations suggest this to be a case of an upper-level system amplifying prior to the period of extreme surface development, which took place over the next 24 hours.

The imagery on 0000 UTC 4 January shows an extension of warmer air (gold color) equatorward from southern Pennsylvania into North Carolina. This signature is consistent with documented cases of extrusions of relatively warm, high PV stratospheric air into the middle troposphere prior to rapid surface development (e.g., Uccellini et al. 1985; Boyle and Bosart 1986; Reed and Albright 1986; Whittaker et al. 1988). The Cape Hatteras soundings on 4 January coincident with this imagery seem to support this finding (Fig. 4). Significant warming (4°–6°C) occurs in the 200–450-mb layer between 0000 and 0600 UTC (special 3-hourly launches were in progress during this ERICA IOP), with a maximum (nearly 7°C) around 400 mb.

It was previously contended that the brightness-temperature anomalies depicted in the MSU image sequences represent upper-level warm anomalies in the descending portion of tropopause undulations associated with upper-level troughs. At 0000 UTC, the warm anomaly is situated over the eastern U.S. radiosonde network, allowing for an adequate conventional analysis of the event and an independent verification of the MSU signal. Selected upper-level temperature analyses from the NMC RAFS for this time are shown in Fig. 5. The warm anomaly is apparent in the 300-, 250-, 200-, and 150-mb analyses, with the closest match to the MSU imagery (panel 1 of Fig. 3) at 250 mb. As mentioned earlier, the MSU signal actually represents an upper-level layer. To approximate this, a vertically averaged (200–300-mb) temperature perturbation (averaged temperature minus averaged map-mean temperature) is calculated from the NMC analyses and shown in Fig. 5f. Although the NMC analyses do not depict the small-scale variations in the MSU warm-anomaly signature, the general location and pattern are a close match. The magnitude of the observed (analyzed) anomaly is about twice that of the anomaly depicted in the MSU image (6°C vs 3° MSU brightness temperature). This channel of the MSU is sensing more of the atmosphere (vertically) than the volume just containing the anomaly (200–300 mb), as shown by the weighting function in Fig. 1. Since the image represents the total contribution of energy into the sensor, the anomaly magnitude may appear as a volumetrically smoothed representation of the true anomaly. This

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**FIG. 2.** A sequence of four MSU 54.96-GHz brightness-temperature images during case 1. The four time periods are indicated under each panel. Each color corresponds to one degree of brightness temperature above the domain-mean brightness temperature represented in blue. Warm anomalies are depicted by the green to yellow to gold to red to black colors, which indicate increasingly warm brightness temperatures. The "L" on each panel represents the analyzed position of the surface low, with the central pressure indicated in mb. (The black pixel to the northeast of the low in panel 3 and the black bar to the southeast of the low in panel 4 are missing data.) The times in each panel have been abbreviated (e.g., 18 UT represents 1800 UTC).

**FIG. 3.** Same as Fig. 2 except for case 2.
emphasizes the fact that the MSU imagery, if examined in a qualitative manner as presented here, might best be utilized to follow the warm-anomaly development and trends. Attempts to further quantify these data will be a subject of future work.

Six hours later, at 0600 UTC 4 January, the surface low has deepened to 979 mb and is located to the east of the MSU warm anomaly. A slight increase in the strength of the warm anomaly (about 1/2 degree) is noted through an examination of the MSU digital values (not indicated in the imagery shown in Fig. 3, which is color coded at 1° intervals). Strong west-southwest winds were present in the upper levels (200-400 mb) at this time. This placed the surface cyclone, located just downstream of the warm anomaly, under a region of strong upper-level warm advection. Subsequent to this time, extreme rapid deepening of the surface low commenced.

By 1300 UTC 4 January, the surface low was analyzed at 952 mb, and a dramatic increase in the warm-anomaly signature has occurred (a greater-than-2° increase in just 7 h). The warmest MSU observation remains located just upstream of the surface low, but the distance has decreased somewhat. In the next MSU image at 2300 UTC 4 January, the surface low and warmest MSU pixel are collocated, indicating that an occlusion stage has been reached. No further deepening of the low occurred after this time. The MSU anomaly has considerably expanded in size, with an associated increase in strength of about 1.5 degree compared with the 1300 UTC imagery.

As mentioned earlier, unlike the first case presented, an identifiable and developing upper-level signature existed prior to the surface low development. However, very much like the first case, rapid development of both the surface low and the upper-level warm anomaly signature appeared to occur simultaneously. Again, the position of the warm-anomaly maximum (and by association, the attending warm advection or PV advection maximum) relative to the surface cyclone center seems to lend information on future development (Elsberry and Kirchoffer 1988; Warrenfeltz and Elsberry 1989; Bleck 1990; Hirschberg and Fritsch 1991c). For this product to be useful as an analysis tool, accurate positioning of the surface low would be needed for a proper diagnosis of the juxtaposition between the MSU warm-anomaly center and the low. In this case, the ERICA data provided accurate positioning. In operational practice, this is not always so easy. However, careful analysis of conventional data and interpretation of satellite imagery in most cases should suffice.

Another practical application of this imagery is in model verification. Real-time monitoring and assessment of model performance is an important operational consideration. Given the sparsity of observations over the Atlantic, the application of the MSU imagery in real-time validation of model upper-air thermal patterns can be especially valuable in forecasting marine cyclones. An example from the ERICA IOP 4 case is shown in Fig. 6. The NMG 24-h forecast of the surface low position and strength valid at 0000 UTC 5 January was quite good given the extreme nature of the event. It should be noted that the model was initialized when the upper-level features contributing to the explosive development were over the east coast of the United States, and well captured by the special ERICA upper-air observations. The forecasted surface low (solid "L" in Fig. 6) was just south of the postanalyzed verifying position (dashed "L"), and 17 mb underpredicted. Even though the NMG underpredicted the minimum sea level pressure, over 70% of the rapid deepening was captured in this unusually intense case.

Also shown in Fig. 6 is the NMG 24-h forecast of
the 300-mb temperature field (which is used here to approximate the upper-level layer-averaged temperature pattern as depicted by the MSU imagery). The imagery verifies that the NGM forecast of the upper-level thermal patterns in this case was quite good. The forecast warm-anomaly maximum is located just south
purposes. Future research will attempt to identify the optimum model layer-mean temperature analysis that best correlates to the MSU imagery, so that forecasters may also use the imagery to more accurately verify model forecasts of the warm-anomaly strength.

c. 19–20 January 1989, ERICA IOP 5, slow development followed by brief rapid deepening

This case is used as an example of a poorly forecasted event. In contrast to the ERICA IOP 4 case, a preexisting low-level disturbance was situated over the Gulf Stream off the east coast of the United States, and developed slowly in advance of an approaching upper-level wave. The MSU imagery for this case is shown in Fig. 7. Unlike the ERICA IOP 4 case, the upper-level wave does not show characteristics of amplification as it approaches the East Coast. In fact, the size of the warm anomaly actually decreases slightly from 0000 to 1800 UTC on 19 January (panels 1–4), while the strength remains essentially constant (each gray shade represents one degree of brightness temperature above the domain mean). After 1800 UTC 19 January, a short burst of rapid deepening of the surface low takes place, with a deepening rate of 18 mb per 6 h observed between 2100 UTC 19 January and 0300 UTC 20 January. This is just about the time that the surface low became juxtaposed under the leading edge of the MSU warm anomaly signature (panels 4–5). An increase in the strength of the MSU anomaly is noted at 2300 UTC 19 January as rapid deepening was under way. Unfortunately, the next three overpasses of the storm (near 0600, 1200, and 1700 UTC 20 January) were not available from archives. By 2200 UTC 20 January (final panel), the storm had occluded and filled slightly to a central pressure of 970 mb (after having reached a minimum of 965 mb around 0600 UTC 20 January). By this time, the warm anomaly was about one degree stronger than 24 h earlier, and situated directly over the surface low, confirming the occlusion.

In contrast to the previous case, the NGM forecast of this event was quite poor, as shown in Fig. 8. The NGM 24-h forecast of the surface low, valid at 0000 UTC 20 January, indicates a weak 997-mb center located to the south of the verifying 980-mb center. Clearly, rapid deepening was not predicted by the NGM in this case. As indicated by the 24-h forecast of 200-mb temperatures, an upper-level warm anomaly is predicted, but the MSU imagery implies that the forecast position of this anomaly is much too far to the north. More important, the juxtaposition of the forecast surface low with the upper-level warm anomaly is not conducive to rapid development. With west-southwest winds dominating the upper levels at this time, the forecast surface low is not situated under a forecasted region of strong upper-level warm advection (or potential vorticity advection). Conversely, the imagery and the location of the analyzed surface low indicate
a favorable juxtaposition for development, which was occurring at this time.

Not all cyclogenesis events are governed purely by upper-level processes and/or the proper superposition of these features relative to the surface cyclone. However, evidence is mounting that a favorable upper-level environment is a necessary precursor for explosive development (e.g., Sanders 1986; Hirschberg and Fritsch 1991a,b; Wash et al. 1992), and this imagery can provide a way to monitor the evolution (and model forecasts) of that environment over data-void regions.

There is some question as to whether the warm anomalies depicted in the MSU observations might in some cases be enhanced by effects from strong latent heat release associated with precipitation processes in these events. Such is the case with 54.96-GHz MSU depictions of tropical cyclones (Velden 1989; Velden et al. 1991). Evidence was presented earlier from radiosondes and model analyses that suggested that the MSU anomaly signature was primarily the reflection of a lower tropopause in an associated upper-level trough. This is further confirmed by an examination of infrared (IR) satellite imagery. Figure 9 shows the MSU warm anomaly overlain on a coincident IR image at 2200 UTC on 19 January. Clearly, the MSU warm-anomaly signal is disassociated (upstream) from the main comma cloud and strongest convection, where the maximum latent heating would be expected. Many other cases examined also yielded this result. Ventilation from strong upper-level winds characteristic of extratropical cyclones prevents massive amounts of vertically transported heat to become accumulated in the upper levels over the surface depression, as is the case in tropical cyclones (Gray and Shea 1973).

d. 16–18 April 1989, nonexplosive development

In contrast to the aforementioned explosive-type events, a case of relatively weak cyclogenesis is presented. The minimum central pressure observed with this storm was 997 mb. It should be noted, however, that the storm was embedded in a large-scale 1026-mb
Fig. 8. 24-h forecast of the 200-mb temperature field from the NGM model valid at 0000 UTC 20 January, overlain on the corresponding MSU imagery (2200 UTC 19 January). The contour interval is 3 deg C. The solid "L" indicates the forecast position of the surface low, while the dashed "L" shows the analyzed position. Corresponding central pressures are also indicated (mb).

ridge, meaning that the surface pressure anomaly was moderately intense.

Figure 10 shows a sequence of 54.96-GHz MSU imagery during this event. The images are approximately 12 h apart and cover a 36-h period. The MSU imagery for this case reveals that an upper-tropospheric warm anomaly is present even with this relatively modest surface cyclone. The central pressure of the surface low at 1200 UTC 16 April was 1001 mb, and had been dropping at a rate of 2 mb per 6 h during the previous 18 h after forming a day earlier over the midwestern United States. The MSU warm anomaly is partially depicted on the western edge of the overpass at this time (panel 1), with the deepening surface low situated just downstream. By 0000 UTC 17 April, the low has deepened 3 mb further, but the upper-level warm anomaly has quickly caught up with it as indicated by the collocation of the warmest MSU pixel. As discussed earlier, this superposition suggests that an occlusion has occurred, and further intensification would not be expected. Examination of the next two time periods at 1200 UTC 17 April and 0000 UTC 18 April confirms that the surface low remained near 997 mb and vertically aligned with the upper-level warm anomaly. Note also that the intensity of the MSU warm anomaly remains nearly constant in this case, in contrast to the rapidly developing storms presented earlier.

The orientation (in a horizontal sense) of the upper-level warm anomaly (trough) is another characteristic feature whose evolution can be monitored. Operational forecasters know from experience that certain trough configurations are more conducive to explosive cyclogenesis. For example, the MSU warm-anomaly signature in case 3 presented earlier (Fig. 7) exhibits a northwest-to-southeast orientation (a so-called negative tilt), especially later in the event when rapid deepening was occurring. This trough configuration is more favorable for upper-level diffuseness and cyclone development (Sutcliffe and Forsdyke 1950). By contrast, in the nondeveloping case 4, the orientation of the long axis of the anomaly appears to be mainly north-northeast to south-southwest through the period. This so-called positive tilt is not an optimal configuration for upper-level diffuseness and is less likely to support subsequent explosive surface development.

4. Discussion

The intent of this paper is to bring awareness to forecasters and researchers of potentially valuable satellite observations of the upper troposphere/lower stratosphere in cyclogenesis events. Examples of 54.96-GHz MSU imagery from NOAA polar-orbiting satellites are presented during selected cases of cyclogenesis in the western Atlantic. Although the number of cases examined is limited, the imagery reveals several interesting things:

1) A qualitative presentation is made of the large-scale, upper-level thermal pattern evolution. Characteristic of this pattern is a warm anomaly, which can be used to infer the position, size, orientation, and relative strength of the descended portion of the associated tropopause undulation. Most important, the tendencies of these parameters can be followed by examination

Fig. 9. Overlay of MSU and GOES IR imagery at 2200 UTC on 19 January. Only the warm-anomaly portion of the MSU imagery is shown.
of the sequenced imagery that is nominally available at 6-h intervals.

2) In those cases of rapid cyclogenesis, the prolonged juxtaposition of the downstream portion of the MSU-depicted warm anomaly with the surface low appears related to the period of rapid deepening. Conversely, the superposition of the MSU warm-anomaly maximum with the surface low center indicates an occlusion stage has been reached, marking the cessation of the development phase.

3) In the three cases of explosive cyclogenesis that were examined, the MSU warm signature strengthened concurrently with the rapid deepening phase of surface cyclogenesis, indicating these observations may be best used in a nowcasting framework, although, in case 2 (ERICA IOP4), the warm anomaly increased in size and strength preceding the development of the surface low off of the East Coast, suggesting trough amplification was occurring prior to the rapid surface cyclogenesis. In fact, a possible stratospheric extrusion feature was suggested in the imagery (and supported by nearby radiosonde data) just prior to rapid development.

4) Forecaster confidence in operational model performance can be enhanced in real time by matching model-based forecasts of upper-level thermal fields with the verifying MSU imagery. This application can also extend to the research community, to help support conceptualizations and verify model-based evaluations of the relative importance of upper-level processes in rapid cyclogenesis events.

It is interesting to compare panel 4 of Fig. 10 with panel 6 of Fig. 7. The MSU warm anomalies are very similar (a close examination of digital values indicates that the case 3 anomaly is about 0.4°C warmer), yet the accompanying surface-low central pressures are quite different (997 mb in case 4 vs 970 mb in case 3). From a purely hydrostatic standpoint, this might seem unreasonable, since both cases represent an occlusion stage, with the centers of the warm anomalies superposed directly over the respective surface cyclones. It must be remembered, however, that the storm in case 4 is embedded in an anomalously high 1026-mb surface ridge, which accounts for much of the difference (i.e., the surface anomalies should be compared rather
than the minimum sea level pressures). In addition, lower-tropospheric thermal structure differences could account for some of the inconsistency. It is entirely possible that a low-level warm-core seclusion (characteristic of strong wrapped-up maritime systems; Shapiro and Keyser 1990) was present in case 3, which would help support a lower surface pressure. By contrast, NMC analyses indicate a deep lower-tropospheric layer of cold air over the weaker cyclone in case 4. This serves to illustrate that the MSU-observed upper-tropospheric characteristics are just one piece (albeit a seemingly important one) of the development puzzle. Therefore, from an operational perspective, it would appear the MSU imagery could be best utilized in conjunction with other observations, analysis tools, and conceptual models, rather than as a stand-alone technique.

The preceding comparison also illustrates that care should be taken in regard to single image interpretation. It is physically reasonable to observe surface lows of different intensities supported by warm anomalies (upper-level troughs) of equal strength. As shown earlier, it is the proper juxtaposition and not just the absolute magnitude of the MSU warm anomaly that appears important to surface development. The four cases examined suggest that the optimum nowcasting utilization of the MSU observations might result from monitoring the evolution of the warm anomalies (through image sequences) with respect to the surface low positions. For example, the evolution of the warm anomalies up to the time of the preceding comparison took two very different paths. In case 4, the MSU warm-anomaly signal was fairly constant in the 24 h prior to the imagery in panel 4 of Fig. 10. In case 3, the MSU warm anomaly increased by 2° in the 33 h preceding the imagery in panel 6 of Fig. 7. The central pressure of the two corresponding surface lows started out nearly equal (compare panel 1 of Fig. 10 with panel 3 of Fig. 7); however, the time sequence of MSU imagery correctly suggests deepening in one case (case 3) and not the other (case 4).

The case studies presented in this paper suggest that the MSU signatures can be useful analysis tools and may contribute to improved nowcasting of rapidly deepening oceanic events. It is obvious that many more cases need to be examined to generalize some of the aforementioned findings into conceptual guidelines for operational use. In addition, it seems appropriate to try and integrate this information into existing satellite conceptual models and classification schemes developed for rapid cyclogenesis events (e.g., Smigielsky and Elrod 1985; Young et al. 1987; Spayd 1988; Browning 1990; Smigielsky and Mogil 1991; Weldon and Holmes 1991).

From a research standpoint, numerous case studies and modeling simulations have suggested that upper-tropospheric processes can play a key role in rapid sur-face cyclone development, which is especially prevalent over marine areas. However, analysis uncertainties due to the lack of conventional observations in these oceanic events have hindered investigations aimed specifically at determining the mechanisms responsible for the rapid cyclogenesis. The 54.96-GHz MSU data appear to offer some information that may help to ameliorate this problem. This would especially be true if the information were presented in a quantitative manner (such as atmospheric temperature profiles). The NOAA operational satellite retrieval method does incorporate the MSU information, but it is uncertain whether the retrieval scheme makes optimum use of the data in this application (in fact, retrievals are not attempted in precipitating areas). Inherent errors in the inversion process of converting radiances to atmospheric profiles may dampen the full extent of the anomalies observed in the radiance data (imagery) alone. The operational retrievals over oceanic areas are incorporated into the NMC hemispheric analyses; however, it is unclear how much of the satellite information is retained by the analysis scheme, which contains inherent smoothing that may also act to dampen the MSU-observed anomalies. Perhaps the use of the MSU information in this application could be optimized from a direct assimilation of the MSU radiances into the analysis scheme (Eyre and Lorenc 1989).

Given the sparsity of data over the Pacific Ocean upstream from the U.S. mainland, the potential applications of the MSU observations in storms approaching the West Coast is being investigated. NOAA satellite passes were collected during the recent STORM-Fronts Experiment Systems Test (STORMFEST, STORM Project Office 1991). Part of the STORMFEST observational network included an array of special radiosonde sites along the West Coast designed to capture the upstream environmental-flow conditions preceding incipient weather systems affecting the central United States. These data, along with special research aircraft observations, will be employed in future studies to aid in the interpretation and increased understanding of the physical processes responsible for the MSU signatures.

Qualitative satellite interpretation techniques remain an integral part of operational forecasting. The MSU observations offer a new perspective on the evolution of strong cyclones. Horizontal resolution limitations will be significantly improved when the Advanced Microwave Sounding Unit (AMSU) is deployed on NOAA satellites in the mid-1990s. The AMSU should provide increased detail of the upper-level thermal structure evolution during cyclogenesis events.

Acknowledgments. The author wishes to thank Paul Hirschberg, Lynn McMurdie, Steve Koch, Louis Uccellini, William Smith, and the reviewers for their comments and encouragement.
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