Satellite-Derived Integrated Water Vapor and Rain Intensity Patterns: Indicators for Rapid Cyclogenesis

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ABSTRACT

Rapidly deepening cyclones in midlatitudes are characterized by large cloud shields and abundant condensation qualitatively evident in infrared and visible satellite images. With the availability of passive microwave measurements from polar-orbiting satellites, it is now possible to characterize rapidly deepening cyclones quantitatively in terms of integrated water vapor and precipitation intensity. In this study, fields of integrated water vapor, integrated water vapor anomaly (defined as the observed water vapor content minus the monthly mean water vapor content at the particular location), and rainfall intensity index derived from the Special Sensor Microwave Imager (SSM/I) on the F-8 satellite of the Defense Meteorological Satellite Program are examined for 12 North Atlantic rapidly deepening and 11 North Atlantic non–rapidly deepening storms that occurred during the 1988 and 1989 winter months. By correlating concurrent 6-h deepening rates with the satellite-derived parameters for a region within 550 km of the surface low pressure center, signatures of rapid cyclogenesis are identified in the SSM/I fields. Maximum water vapor anomaly and average precipitation index have correlations with concurrent 6-h deepening rates of 0.56 and 0.55, respectively. The correlations improve dramatically when two outliers are removed, becoming 0.68 and 0.70, respectively. These results indicate that, although most rapidly deepening cyclones have high water vapor anomaly and stronger precipitation index than non–rapidly deepening cyclones, there are storms that deepen rapidly in the absence of high water vapor anomaly or heavy precipitation. In addition, occasionally there are storms that have exceptionally high water vapor anomalies yet do not deepen rapidly. In these unusual cases, it is suggested that atmospheric water vapor and condensation play a secondary role and that dynamical processes are dominant.

1. Introduction

Extratropical storms that deepen in excess of 24 mb in 24 h normalized to 60°N (Sanders and Gyakum 1980) or in excess of 10 mb in 6 h (Hadlock and Kreitzberg 1988) are considered to be rapidly deepening cyclones. Storms of this strength most commonly occur in marine climates in the vicinity of warm ocean currents, such as the Gulf Stream or the Kuroshio, but some have occurred over land (Mass and Schultz 1993) or over midocean regions (Reed and Albright 1986). These storms are often accompanied by hurricane force winds, extensive rain, and cloud shields and they have caused property damage and loss of life in nearshore and offshore regions (Sanders and Gyakum 1980; Bosart 1981; Kuo et al. 1992).

The important mechanisms contributing to rapid development in extratropical cyclones have been the focus of extensive research over the past decade. The importance of upper-level forcing in contributing to rapid cyclogenesis is well documented. The presence of an upper-level trough preceding the development of the surface cyclone was found in several observational studies (Sanders and Gyakum 1980; Sanders 1986; Rogers and Bosart 1986). Wash et al. (1992) compared rapidly deepening cases to non–rapidly deepening cases and found that strong upper-tropospheric features at the early stages of development produced stronger vertical motions and quicker development in the rapidly deepening cases. Several modeling and observational studies of individual cases of rapid cyclogenesis have demonstrated the presence of upper-level jet streaks, or upper-level potential vorticity anomalies, during the incipient and deepening phases (Uccellini et al. 1984, 1985; Reed and Albright 1986; Wash et al. 1988; Kuo et al. 1991; Davis and Emanuel 1991; Reed et al. 1992; Kuo et al. 1992; Reed et al. 1993; Neiman and Shapiro 1993).

Another important process acting in rapidly deepening cyclones is condensational heating. Several case studies have pointed to the presence of convection and extensive cloud shields associated with such storms (Bosart 1981; Gyakum 1983; Reed and Albright 1986; Neiman and Shapiro 1993). Modeling studies have shown that moist processes must be accurately included to successfully simulate the deepening rate of the sur-
face low, with deepening rates reduced from 30% to 70% when condensational heating is removed (Danard 1964; Chang et al. 1982; Chen and Dell’Osso 1987; Reed et al. 1988; Kuo and Low-Nam 1990; Kuo et al. 1991; Reed et al. 1993). The mechanisms of how latent heat contributes to cyclone deepening have been explored in several studies (Uccellini et al. 1987; Chang et al. 1984), including three recent cases of rapid cyclogenesis using model-derived fields (Kuo et al. 1991; Reed et al. 1992) and gridded National Centers for Environmental Prediction (NCEP) data (Davis 1992). Both Reed et al. (1992) and Davis (1992) used a potential vorticity approach in exploring this issue. One source of low-level potential positive potential vorticity is produced by condensation. Davis (1992) stated that the primary effect of condensational heating is to augment the growth phase of a cyclone. He found that this potential vorticity source contributed to approximately 20% of the total low-level circulation. In the case studied by Reed et al. (1992), the condensational potential vorticity anomaly formed rapidly as boundary layer air ascended the warm frontal surface, producing condensation, and lined up vertically with other sources of positive potential vorticity to contribute significantly to the overall circulation of the system. Kuo et al. (1991) used a quasigeostrophic vertical velocity approach to show that latent heating modified the frontal structure in such a way that the adiabatic secondary circulation was reinforced. The quasigeostrophic vertical motions were enhanced in a nonlinear way with the inclusion of latent heating. All of the above-mentioned studies are either model-based explorations of the issues or cases that occurred over, or sufficiently close to, land so that high-resolution data were available. Routine quantitative observational evidence of the role of moist processes in the majority of oceanic cyclones is lacking.

Unfortunately, since most rapidly deepening storms frequently occur over the data-sparse ocean regions, adequate in situ observations are unavailable. This has led forecasters and researchers to turn to remotely based platforms to observe rapid cyclogenesis. Forecasters often rely on infrared and visible satellite imagery to track their movement and rapid development (Böttger et al. 1975; Jager 1983; Evans et al. 1994). However, due to the limitations of these techniques, other satellite indicators of rapid development are being sought. For example, satellite-derived ozone maps and the 6.7-μm upper-level moisture images gave evidence of strong upper-tropospheric subsidence in two cases of rapid development (Uccellini et al. 1985; Reed and Albright 1986). In another study, Velden (1992) showed that upper-tropospheric thermal anomalies (signifying tropopause undulations), identified using the Microwave Sounding Unit (MSU), were stronger in storms that deepened rapidly compared to those that did not.

Observational evidence of the role of moist processes in cyclogenesis is available in the form of integrated water vapor and precipitation information retrieved from the Special Sensor Microwave Imager (SSM/I) over the open ocean regions. In this paper we explore the hypothesis that there are unique signatures in the water vapor and precipitation fields of rapid cyclogenesis. As explained above, modeling studies have demonstrated the importance of condensation in rapid cyclogenesis, so it is reasonable to expect to find observational evidence of this in the SSM/I precipitation fields. In a related study, Petty and Miller (1995) found that average rain rates within a small region northeast of the surface low was strongly correlated with deepening rate. In this paper, we examine a different set of cases, using different analysis areas and different precipitation indexes, and we explore what signatures of rapid deepening might be present in the integrated water vapor (IWV) fields. We expect that either the IWV or the difference between the observed IWV and the typical IWV for the region (IWV anomaly) would also show a relationship to rapid cyclogenesis for the following reasons. Rapidly deepening cyclones have been shown in airflow trajectory studies to have a large influx of warm, moist air from the south (e.g., Reed et al. 1992; Mass and Schultz 1993) oriented parallel and east of the cold front and rising up and over the warm front. This warm moist airstream would be manifested in the SSM/I IWV fields as a region of high IWV, or “higher than normal” IWV. In addition, rapidly deepening cyclones typically have large synoptic-scale vertical motions. The IWV content, or IWV anomaly, would be high in these regions due to low-level convergence of moisture. Since all midlatitude synoptic-scale cyclones possess an IWV pattern such that the IWV content is high along and ahead of the cold front extending up over the warm front (McMurdie and Katsaros 1985; McMurdie 1989; Katsaros et al. 1989; McMurdie and Katsaros 1991), we hypothesize that storms that deepen rapidly exhibit greater amounts of IWV, or IWV anomaly, than non–rapidly deepening cyclones. The ultimate goal of this work is to demonstrate ways in which the valuable information on atmospheric moisture fields available from microwave instruments such as the SSM/I-derived moisture fields can be used in an operational setting.

2. Methods

The SSM/I data used in this study was collected from the F-8 Defense Meteorological Satellite Program (DMSP) satellite launched in June 1987. The DMSP satellite is a polar-orbiting platform in a nearly synchronous orbit circling the earth 14 times a day. The SSM/I is a passive radiometer measuring the thermal emission of the earth and atmosphere at four frequencies, 19, 22.235, 37, and 85 GHz, in vertical and horizontal polarizations for each frequency except 22.235
**Fig. 1.** Monthly average integrated water vapor shaded every 4.5 kg m\(^{-2}\) in the North Atlantic for January 1988.

**Fig. 2.** Integrated water vapor from SSM/I shaded every 4.5 kg m\(^{-2}\) for 2046 UTC 16 February 1989 with 2100 UTC surface low and frontal zones superimposed. (a) Full SSM/I pass over storm. (b) Half-circle region within which all statistical calculations are done.
TABLE 1. List of SSM/I overpasses used in the study. The latitude and longitude given are for the location of the surface low pressure center at the time of the overpass.

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The integrated water vapor algorithm and the precipitation index are given by Petty (1994) and Petty and Katsaros (1990). These algorithms are valid over open ocean regions only. Land and ice surfaces have such high emissivities in the microwave portion of the spectrum compared to the ocean that it is difficult to use a space-based sensor to distinguish atmospheric constituents over land or ice regions. The water vapor algorithm is regression based using a linear combination of the brightness temperatures measured by the 19-, 22.235-, and 37-GHz channels:

\[
\text{IWV} = 174.1 + 4.638 \log (300 - T_{19H}) - 61.76 \log (300 - T_{22V}) + 19.58 \log (300 - T_{37H}),
\]

where IWV is integrated water vapor in kg m\(^{-2}\) and \(T_{19H}\) is the brightness temperature at 19 GHz in horizontal polarization (similar definitions hold for the other subscripted temperatures). IWV is flagged as contaminated by precipitation and discarded when \(T_{19H} - T_{19V}\) is greater than 15 K. In this study, 9 of the 39 passes had at least one pixel flagged as contaminated by rain. This pixel was removed from the field, and a value calculated as the average of the nine surrounding pixels replaced the contaminated value so that the IWV field did not contain holes. The vapor algorithm has been compared to independent radiosondes for validation, with an rms difference of 2.6 kg m\(^{-2}\) (Petty 1993).

In addition to integrated water vapor, fields of integrated water vapor anomaly are examined. Water vapor anomaly (WVA) is defined as the observed IWV minus the monthly average IWV at the location of the observation. The monthly average IWV fields were calculated in the following manner. All available SSM/I orbits over the North Atlantic ocean basin for each calendar month (e.g., January 1988) were composited. IWV was calculated at every pixel for each orbit, and the data were binned in 2.5° lat \(\times 2.5°\) long boxes. The IWV observations were averaged in each box to create the monthly average fields. The number of observations in each box varied from 1000 to 3000.

Water vapor anomaly is used in this study for the following reason. Over the ocean, IWV is strongly correlated with surface air temperature. In the Atlantic Ocean, due to the Gulf Stream, there is a significant decrease of IWV northward so that the monthly averages of IWV range from 30 kg m\(^{-2}\) at 30°N to 15 kg m\(^{-2}\) at 50°N (see Fig. 1). Rapidly deepening storms occur throughout the basin, and storms occurring northward exist in environments that are typically colder and drier than regions farther south. In order to group storms farther north together with storms farther south, we use water vapor anomaly to describe how much water vapor above or below normal exists in a particular storm.

The emission-based precipitation intensity index used in this study, P37, is defined as the observed difference in brightness temperature between the vertically and horizontally polarized 37-GHz channels divided by the expected difference for clear sky:

\[
P37 = \frac{(T_{37V} - T_{37H})_{\text{observed}}}{(T_{37V} - T_{37H})_{\text{clear sky}}}. \tag{2}
\]

Since the ocean surface is highly polarized and a raining cloud radiates uniformly in a nonpolarized manner, low values of P37 indicate rain and high values indicate...
either thin clouds or clear sky. From practical experience, a threshold of 0.8 is used here to indicate rain, with lower values indicating increasingly more intense rainfall (Petty and Katsaros 1990, 1992). Precipitation indexes can be defined in the same manner as above with the 19- or the 85-GHz channels. The 19-GHz channels are less sensitive to rain than the 37-GHz channels and may be more useful in situations of heavy rainfall since they do not saturate as readily. Unfortunately, we are unable to use the 85-GHz-channel information since the 85-GHz sensor was inoperative for over half of the time period used in this study.

This emission-based precipitation index, P37, has been compared to radar-derived estimates of rain rate in tropical regions by Petty and Katsaros (1990, 1992). They found that when the radar data were corrected for range-dependent errors and were averaged to be comparable to the satellite measurements, there was reasonable agreement between the radar and satellite estimates of rain occurrence and intensities. Other studies
Fig. 4. SSM/I-derived fields for 0905 UTC 7 February 1989 with 0900 UTC surface low and frontal zones superimposed. (a) Integrated water vapor shaded every 4.5 kg m⁻². (b) Water vapor anomaly shaded every 4 kg m⁻². (c) Normalized polarization difference P37. (d) Normalized polarization difference P19.

comparing precipitation estimates from SSM/I using a variety of different rain-rate algorithms to other rainfall measurements (radar, aircraft) over the ocean are discussed by Barrett et al. (1994). Despite these efforts, adequate and thorough validation of satellite-derived rainfall over the open ocean remains a difficult task.

Storms occurring in the North Atlantic, where the surface low centers occur between 25° and 60°N and between the east coast of the North American continent and 10°W, during the months of January, February, and March 1988 and January and February 1989 were included in this study. Six-hourly hemispheric surface charts produced by NCEP were used to determine the position and central pressure of the surface low. Only storms that developed and deepened over water were included.

The F-8 SSM/I typically sampled the North Atlantic region at approximately 0900 and 2100 UTC. Six- and 12-h deepening rates of the surface low were calculated from NCEP maps surrounding the time of the SSM/I overpass. The normalized deepening ratio (NDR) is defined as
Fig. 5. Scatterplot of maximum water vapor anomaly vs 6-h deepening rate for the full set of 39 passes. A deepening rate of 0.6 corresponds to 24 mb (24 h$^{-1}$), and 1.0 corresponds to 10 mb (6 h$^{-1}$). The correlation coefficient is 0.56, and it is 0.68 when 5% of the outlying data are trimmed. The horizontal long- and short-dashed lines delineate the rapidly deepening cases and the marginally rapidly deepening cases, respectively. The sloping solid line is the least squares regression line fitted to the full set of 39 passes.

\[
\text{NDR} = \frac{\text{DR}}{\text{THRES}},
\]

where

\[
\text{THRES} = 10 \text{ mb} \ 6 \text{ h}^{-1} \left( \sin f / \sin 60^\circ \right),
\]

\(\text{DR}\) is the deepening rate in millibars per 6 or 12 h, and \(f\) is latitude of the surface low pressure center. The threshold, \(\text{THRES}\), is the same as that used by Petty and Miller (1995) and takes into account the latitudinal dependence of planetary vorticity. Storms with NDRs greater than 1.0 correspond to storms that satisfy the Experiment on Rapidly Intensifying Cyclones in the Atlantic (ERICAN) criterion for rapid development [10 mb (6 h)$^{-1}$ or greater] and are classified as rapidly deepening cyclones in this study. Storms with NDRs less than 1.0 and greater than 0.6, which corresponds to Sanders and Gyakum’s (1980) criteria for rapid development [24 mb (24 h)$^{-1}$ at 60°N or greater], are classified as marginally rapidly deepening, and those with NDRs less than 0.6 are classified as nonrapidly deepening.

Of all the available SSM/I passes over the storms during the study period, only those up to 15 h before or 15 h after the time of maximum deepening were included. In addition, it was required that the pass fully sample a certain half-circle-shaped region near the storm center. The half circle is centered at the surface low pressure center, has a radius of 5° latitude (i.e., 550 km), and is oriented approximately parallel to the surface cold front with the half circle extending to the east of the low. This half-circle region was chosen because, as discussed earlier, we expect that the differences in IWV or WVA distribution between rapidly and non-rapidly deepening cyclones would be found in the region of high vapor content. This region is typically along and ahead of the cold front and extends northward up and over the warm front. The half-circle analysis region fully encloses this area. A comparison of a typical SSM/I pass and the size of this region is given in Fig. 2. The requirement that the SSM/I fully sample the half circle proved to be quite restrictive, and of 103 potential SSM/I passes, only 39 passes of 23 storms could be used for the study. These are listed in Table 1.

For the precipitation portion of the study, the calculations were performed within the above-described sector and within a 3/4 circle that includes the half-circle region and the quarter sector extending west and north of the low center. The 3/4 circle was chosen so that for cases where precipitation wraps around the low center, that is, storms exhibiting a so-called T-bone structure (Shapiro and Keyser 1990), the precipitation...
field would be fully enclosed. However, we did not require that the full analysis region to the west of the low be completely sampled by the SSM/I as the precipitation to the west is usually within 100–200 km of the low.

All calculations and correlations given in the results section were done within the above-described sectors. Several predictors quantifying the SSM/I fields and several different deepening rates were correlated. The predictors derived from the SSM/I IWV and WVA fields were chosen as different ways to quantify high water vapor content. These included the maximum value within the sector, the average value of the quantity in the sector, and the number of pixels within the sector greater than a certain threshold (as a measure of the areal extent of water vapor greater than that threshold). The predictors derived from the SSM/I precipitation indexes, P37 and P19, were chosen as different ways to quantify rainfall intensity. They included the minimum value within the sector, the average value within the sector, the average value of all pixels lower than the 0.8 threshold for rain, and the number of pixels less than a certain value (0.8 or less). Each predictor was correlated with concurrent 6- and 12-h deepening rates and 6- and 12-h deepening rates immediately after the SSM/I pass. The latter deepening rates were explored to see if the SSM/I predictors had forecasting potential.

3. Results

a. Typical cases of rapidly deepening and non-rapidly deepening cyclones

SSM/I-derived fields of IWV, WVA, P37, and P19 for orbit number 3873 at 0824 UTC 20 March 1988 of a rapidly deepening storm are shown in Fig. 3. The 6-h NDR for this time is 1.4 [the actual deepening rate was 12 mb (6 h⁻¹), and normalized to 60°N, it was 14 mb (6 h⁻¹)]. The IWV field (Fig. 3a) has a broad region of moderate to high water vapor south of the surface low in the vicinity of the cold front and in the warm sector. Just south of Newfoundland, the water vapor amount decreases sharply from about 30 kg m⁻² to 10 kg m⁻² over a distance of 150 km. Immediately north of the low, there is a sea-ice-covered region, which, as a result, falsely indicates high vapor content. Sea ice is easily identified in the IWV field as a region of high vapor content along the northern coastlines that does not change appreciably from day to day. This area is not used in the analysis. The WVA field (Fig. 3b and color version Fig. 13a) has a large region of vapor con-
tent that is much higher than the monthly average south and east of the surface low covering a large portion of the warm sector, the warm front, and the region north of the warm front. The maximum anomaly near the surface low is 21.4 kg m$^{-2}$. The rain area is quite extensive and intense, as indicated by the P37 and P19 fields (Figs. 3c and 3d). The rain area extends approximately 500–700 km east of the low and east of the cold front with the most intense rain areas in association with the frontal zones, as expected.

For comparison, the IWV, WVA, P37, and P19 fields for a non–rapidly deepening cyclone are shown in Fig. 4. The SSM/I pass occurred at 0905 UTC 7 February 1989 when the storm had an NDR of 0.38 [the actual deepening rate was 3 mb (6 h)$^{-1}$ or normalized to 60°N it was 4 mb (6 h)$^{-1}$]. In this case the maximum water vapor content is found along the cold front, with much lower water vapor content near the low center itself. There is a moderate vapor gradient toward the cold air north of the cold front. The WVA field (Fig. 4b and color version Fig. 13b) is clearly different from the WVA field of the rapidly deepening case. The maximum anomaly along the cold front is only 12 kg m$^{-2}$ and within the half-circle sector at the low the maximum anomaly is 8.5 kg m$^{-2}$. The P37 and P19 fields show that the precipitation is organized in the familiar comma shape. However, in comparison to the rapidly deepening case, the region of precipitation is far less extensive, and the maximum intensity is less.

b. Water vapor statistics

Maximum IWV within the sector and 6-h concurrent deepening rate for all 39 passes were correlated and found to have a correlation coefficient of 0.10. In addition, there is a lack of correlation between the other water vapor predictors and deepening rate. At first glance, this result may appear to be somewhat surprising. However, as described in the methods section, the monthly average IWV varies strongly with latitude (see Fig. 1). Both rapidly deepening and non–rapidly deepening storms occurring farther south will typically form in an environment with higher IWV content than storms farther north. Therefore, this result indicates that the absolute IWV content within a storm is not an important factor for cyclogenesis.

In contrast, the maximum water vapor anomaly shows a stronger correlation. A plot of maximum water vapor anomaly within the sector and 6-h concurrent deepening rate for all 39 passes is given in Fig. 5. The correlation coefficient between the two quantities is 0.56, and when 5% of the outliers are removed (two
cases), the correlation coefficient increases to 0.68. Although these correlations are not exceptionally high, they do indicate that in most cases the maximum WVA near the low center is higher during periods of rapid intensification. The rapidly deepening cases, with deepening rates greater than 1.0, all have maximum WVAs of at least 14 kg m$^{-2}$, and the non-rapidly deepening cases, with deepening rates less than 0.6, all have maximum WVAs less than 16 kg m$^{-2}$. The marginally rapidly deepening cases show the largest spread, from 10 to 20 kg m$^{-2}$. The other WVA predictors, such as average WVA within the sector and the number of pixels greater than a threshold of 8.0 kg m$^{-2}$, are also positively correlated with the concurrent 6-h deepening rate; however, the correlation coefficients were slightly lower at 0.5 and 0.48, respectively. The correlation coefficients were smaller for concurrent 12-h deepening rates and for deepening rates 6 and 12 h after the SSM/I overpass. When only the SSM/I overpasses that occurred before or at the time of maximum deepening (28 passes) were included, the correlation coefficient between maximum WVA and 6-h deepening rate was 0.57. These results indicate that the important quantity describing the IWV field within a storm is how much water vapor above normal a particular storm exhibits.

As an additional way to quantify the relationship between maximum WVA and deepening rate, the 39 SSM/I overpasses were placed in two categories: storms that deepened rapidly and storms that deepened modestly. Storms that deepened at least 24 mb in 24 h (regardless of latitude) were considered to be rapidly deepening. The average maximum WVA for the rapidly deepening storms was 15.3 kg m$^{-2}$, and the average maximum WVA for the other storms was 12.9 kg m$^{-2}$. This difference is significant at the 90% confidence level using a two-sided $t$ test.

c. Precipitation statistics

A plot of a precipitation index, defined as $1 - P_{37_{ave}}$, versus 6-h deepening rate is shown in Fig. 6, where
P37_{ave} is the average P37 value for all raining pixels within the half-circle region. The correlation coefficient is 0.47, and when the outliers are trimmed by 5% (two cases), the correlation coefficient increases to 0.55. The correlation coefficients for this quantity and the other predictors calculated over the \( \frac{3}{4} \)-circle region were essentially the same as for the half-circle region. The other predictors, such as minimum P37 (which is indicative of intense rain), average P37 within the entire sector, and the number of raining pixels with P37 values less than 0.4 (also indicative of large regions of intense rain) have correlation coefficients with 6-h deepening rates of 0.40–0.42. When two cases are excluded from the statistics, the correlation coefficients improve to 0.55 for these other quantities. However, the correlations of 1 – P37_{ave} with concurrent 12-h deepening rate and with deepening rates 6 and 12 h after the SSM/I pass were lower than those shown in Fig. 6. When only those cases that occurred before or at the time of maximum deepening (28 passes) are correlated with deepening rate, the correlation coefficient improves slightly to 0.51.

A plot of 1 – P19_{ave} calculated within the half-circle region versus the 6-h deepening rate is shown in Fig. 7. In this case, the correlation coefficient is 0.55, and when the outliers are trimmed by 5% (two cases), the correlation coefficient improves to 0.70. The correlations are the same when calculated within the \( \frac{3}{4} \)-circle region. The correlation coefficients for the other predictors (average P19 within the entire sector, the minimum P19, and the number of pixels with P19 less than 0.6) were slightly lower at about 0.45. The P19 indicator is a better predictor than the P37 indicator since P19 does not saturate at moderate rain rates.

Petty and Miller (1995) also correlated the deepening rate with rain rate for rapidly deepening cyclones. There are a number of differences between their study and ours. They used European Center for Medium-Range Weather Forecasts 12-h gridded datasets, from which the low center position and deepening rates were obtained. They used the Petty (1994) rain-rate algorithm, which requires brightness temperatures from all the SSM/I channels. Unfortunately, most of our cases occurred after the 85V-GHz channel failed on the F-8, and we were unable to use the Petty (1994) rain-rate algorithm. They also included storms that occurred in the North Pacific and did not place any requirements concerning the stage of the storm. They examined correlations for several sectors surrounding the low center. A copy of their Fig. 4 of the correlation between the 12-h deepening rate and rain rate is shown in Fig. 8. The region that had the maximum correlation in their study was the sector northeast of the low. They also show significant correlation in the small sectors in the immediate vicinity of the surface low and north of the low. Our correlation coefficients are lower than those of Petty and Miller since our averaging sector includes their northeast sector with the correlation coefficient of 0.75 and some sectors with very low correlations, -0.11 and 0.12.

d. Outliers

One obvious detractor from the moderate correlation between maximum WVA and deepening rate and between average raining P19 pixels and deepening rate is the existence of outliers. There are a few cases that deepen rapidly, yet do not have high maximum WVA, and there are cases that do not deepen rapidly, yet have high maximum WVA. Outlier A in Figs. 5 and 7 is a case that occurred 1 January 1989 where the storm is rapidly deepening, with an NDR of 1.5 [the actual deepening rate was 12 mb (6 h\(^{-1}\)], and normalized to 60°N, it was 15.5 mb (6 h\(^{-1}\)]. The WVA and P37 fields for this case are shown in Fig. 9 (the color version of WVA is given in Fig. 13c). The WVA distribution shows that the region of positive WVA is fairly large covering an area approximately 500–700 km east and south of the cold front and the surface low. However, the maximum WVA anomaly is only 14.2 kg m\(^{-2}\). The P37 field shows that the distribution of precipitation is in the typical comma-shaped pattern, with the heaviest precipitation north and east of the low. The 500-mb height and thermal fields (Fig. 10) show that this system is associated with an intense upper-level shortwave with very strong 500-mb level winds (47 m s\(^{-1}\) observed on the coast of Maine) and
moderate to strong baroclinicity. The configuration of the upper-level height pattern is very potent. There are two distinct shortwaves, one at 42°N and 44°W and one at 46°N and 55°W, appearing to merge and orient in a negatively tilted fashion. Studies have shown that this configuration is conducive to rapid surface development (Gaza and Bosart 1990; Lai and Bosart 1988; Hakim et al. 1995). In this case, the upper-level features appear to contribute significantly to the rapid development.

Figure 11 shows the WVA and P37 fields for outlier B (marked in Figs. 5–7). This case had an NDR of only 0.71 [an actual deepening rate of 5 mb (6 h)$^{-1}$ or normalized to 60°N of 7 mb (6 h)$^{-1}$] and occurred 16 February 1988. The WVA field shows an extensive area of positive WVA, with a significant region where the WVA is greater than 20 kg m$^{-2}$ (see Figs. 11a and 13d). The precipitation pattern indicates that this system has not yet developed into the typical comma shape; however, the precipitation intensity east and north of the low is quite strong. In contrast, the 500-mb height and thermal field (Fig. 12) is far less impressive than in the case of outlier A (Fig. 10). The 500-mb heights are higher, and the upper-level trough is less intense than for the previous case and not oriented in a negatively tilted fashion. The maximum observed winds at 500 mb in association with this trough are only in the 30–35 m s$^{-1}$ range, and there is little baroclinicity at this level. Thus, despite the ample supply of moisture and precipitation, the system did not deepen rapidly, probably due to the lack of strong upper-level dynamical support.

4. Discussion

Results presented in the previous section demonstrated that there is a moderate correlation between maximum WVA and the 6-h concurrent deepening rate and between rain intensity index P19 and the 6-h concurrent deepening rate. The maximum WVA and the average P19 in non–rapidly deepening storms are distinctly different than in rapidly deepening storms where rapidly deepening storms have high WVA and more intense precipitation (see Fig. 13 for WVA fields described in this paper). However, moderately deepening storms show considerable individual variance in these quantities, and the distinction between the moderate and very intense storms is not clear. This is largely due to the occasional outlier such as a case that does not deepen rapidly yet has high WVA and intense precipitation.

These results both verify and expand on those of Petty and Miller (1995). They found that there was a high correlation between 12-h deepening rate and average rain rate within a small sector northeast of the surface low pressure center. Our study found a positive correlation between rain index P19 (and to a lesser extent P37) within a broad region enclosing the warm sector, the area north and northeast of the warm front and extending west of the low center, and 6-h deepening rate. The rain indexes used in this study are less sophisticated and would be easy to implement in an operational setting compared to the rain-rate algorithm used by Petty and Miller (1995). In addition, unlike Petty and Miller (1995), we also examined the rela-
The relationship between IWV (and WVA) and deepening rate. The IWV and WVA computations are more robust than rain rates and rain indexes and have been verified to a reasonable accuracy against independent radiosonde measurements (Petty 1993). Our results indicate a positive correlation between WVA and deepening rate, and due to the accuracy of the IWV algorithm, these SSM/I-derived vapor quantities could be routinely used to monitor the development of oceanic cyclones.

Some of the deviation from the expected correlation evident in Figs. 5 and 7 may be due to the variance from case to case of the relative importance of moisture processes and upper-level processes. In some cases, the diabatic processes play a crucial role in the rapid development of a cyclone, such as in the Queen Elizabeth II (QEII) storm (Gyakum 1983; Kuo et al. 1991), the Presidents’ Day storm (Bosart 1981; Uccellini et al. 1984, 1985), and the ERICA IOP5 storm (Reed et al. 1993). These storms were more difficult to predict, and the inclusion of moist processes appear to be very important in explaining their deepening rates. In others, the diabatic processes are important, yet secondary to the dry baroclinic processes, as in the IOP4 storm of ERICA (Neiman and Shapiro 1993; Reed et al. 1994). In this case, the larger-scale processes strongly forced the deepening of the cyclone. It was shown that outliers A and B had very different upper-level structure, and it appears that dynamical processes contributed significantly to the development of case A, and the moisture processes were more important in case B. In future work, it would be good to explore the possibility of quantifying a two-predictor scheme for rapid cyclogenesis, where one predictor is based on atmospheric moist processes, such as the WVA or P19 used here, and the other predictor is based on upper-level baroclinic processes, such as the upper-level temperature anomaly observed in the MSU data by Velden (1992).

One uncertainty that may have affected our results is the potential underestimates of the central pressures in the NCEP analyses. Since these storms all occur over the ocean, in many cases there was little information available to make an accurate estimate of the central pressure of the surface low [see Fig. 2.2 of James (1994), showing typical coverage of the oceans by ships of opportunity]. It is possible that some of the storms classified as moderately intense were actually stronger than indicated by the NCEP maps.

One serious limitation in this study is the lack of vertical information in the IWV and P37 fields. Several modeling studies have demonstrated that the vertical and horizontal distribution of latent heat strongly affects the development of a cyclone. In a detailed modeling study of the QEII storm, Kuo et al. (1991) showed that the latent heating occurred in a narrow, sloping zone on the warm boundary of the warm front. This configuration enhanced the frontogenetic processes by directly heating the air on the warm side of the front and by creating a diabatically induced upward vertical motion in phase with the adiabatic secondary frontogenetic circulation. Without the synergistic horizontal and vertical location of the heating, the positive feedback of the latent heat to the frontogenetic processes and the adiabatic upward motions would not take place. Many different vertical distributions of water vapor can result in the same local maximum of integrated water vapor. For example, a high-IWV value can result from a warm and moist boundary layer with increasingly dry air aloft, or from cool air that is at or near saturation throughout a deep layer of the atmosphere. It is impossible to know from IWV values alone which layers, if any, of the atmosphere are saturated. In some of our outlier cases, the region of maximum WVA and precipitation may not have been optimally distributed in the vertical to create the positive feedback to the frontogenetic processes discussed by Kuo et al. (1991).

In the future, it may be possible to obtain some vertical information concerning the distribution of heating due to condensation. New algorithms are being developed and tested in a variety of situations for obtaining the vertical and horizontal distribution of precipitation using the brightness temperature information of the SSM/I (Kummerow and Giglio 1994a,b). If these al-

**Fig. 12.** Redrafted NCEP 500-mb chart for 12 UTC 16 February 1988. Solid lines are geopotential heights contoured every 60 dam, dashed lines are temperature every 5°C, and radiosonde observations are indicated using standard conventions. The surface low is indicated by a small L and is located at 38°N, 73°W.
algorithms prove accurate, they could be valuable for evaluating the contribution of latent heat to developing cyclones and to verify modeling studies. Vertical microwave sounders exist and are being improved for future operations, but the current horizontal and vertical resolutions are too coarse for the objectives pursued in this study.

Based on the results presented here and in earlier work (McMurdie 1989; Rabin et al. 1991), fields of IWV, WVA, P19, and P37 derived from the SSM/I have clear operational utility. Qualitatively, these fields provide indication of the precipitating regions and high water vapor content areas within individual storms. In addition, a quantitative comparison of the precipitation intensity or water vapor content of a storm to typical average values is easily obtained from these fields. Further work, such as examination of additional cases in the North Atlantic and in other ocean basins, would be required before the predictors proposed in this study could be routinely operational.

In summary, in this study we show a modest correlation between high maximum WVA or intense precipitation and deepening rate. Rapidly intensifying cyclones have stronger vertical motions and stronger hor-
izontal (ageostrophic) motions that enhance low-level moisture convergence. These enhanced motions can be manifested in the SSM/I vapor and precipitation intensity fields as high maximum WVA and large, intense rain areas. In many cases, the vapor, P19, or P37 fields can act as an indication of possible rapid and intense development, much like cold infrared and bright visible regions in satellite images indicate large regions of condensation and tight circulation centers in rapidly deepening cyclones (Evans et al. 1994). The SSM/I fields of WVA and precipitation indexes provide similarly useful qualitative information and additional quantitative data for analysis and forecasting of rapid development in cyclones over the ocean.

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