Atmospheric Water Distribution in a Midlatitude Cyclone Observed by the Seasat Scanning Multichannel Microwave Radiometer

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ABSTRACT

Patterns in the horizontal distribution of integrated water vapor, integrated liquid water and rainfall rate derived from the Seasat Scanning Multichannel Microwave Radiometer (SMMR) during a 10–12 September 1978 North Pacific cyclone are studied. These patterns are compared with surface analyses, ship reports, radiosonde data, and GOES-West infrared satellite imagery. The SMMR data give a unique view of the large mesoscale structure of a midlatitude cyclone. The water vapor distribution is found to have characteristic patterns related to the location of the surface fronts throughout the development of the cyclone. An example is given to illustrate that SMMR data could significantly improve frontal analysis over data-sparse oceanic regions. The distribution of integrated liquid water agrees qualitatively well with corresponding cloud patterns in satellite imagery and appears to provide a means to distinguish where liquid water clouds exist under a cirrus shield. Ship reports of rainfall intensity agree qualitatively very well with SMMR-derived rainrates. Areas of mesoscale rainfall, on the order of 50 km × 50 km or greater are detected using SMMR derived rainrates.

1. Introduction

Over data-sparse regions, such as the oceans, visible and infrared satellite imagery has aided forecasters and scientists in tracking storm movement and observing their development and decay. Over the past decade, instruments sensitive to the microwave portion of the electromagnetic spectrum have been placed on polar orbiting satellites (Njoku, 1982). The most recent is the Scanning Multichannel Microwave Radiometer (SMMR) aboard the Seasat and Nimbus 7 satellites. With SMMR, total integrated water vapor in a column (precipitable water), integrated liquid water and rainrate can be derived over oceanic regions on a spatial scale never before resolved by other microwave instruments. Because of the low emittance of the ocean compared to the land in the microwave region (Hollinger, 1970), the ocean is an excellent background for measuring variations of atmospheric water in gaseous or liquid form. In this paper, it will be shown that mesoscale features such as fronts and rain areas are easily mapped from SMMR data and that SMMR information adds a new dimension to the analysis and forecasting of extratropical cyclones over the ocean.

Several satellite-borne microwave instruments flown before SMMR have successfully monitored atmospheric water parameters. For example, the integrated water vapor calculations from the Nimbus-E Microwave Spectrometer (NEMS) and the Scanning Microwave Spectrometer (SCAMS) on Nimbus 5 and 6, respectively, were shown to be as accurate as the integrated water vapor derived from radiosonde profiles (Staelin et al., 1976; Chang and Wilheit, 1979; Grody et al., 1980). Integrated liquid water was also calculated from brightness temperatures measured by these instruments. However, there were no in situ measurements to validate the satellite derived values (Staelin et al., 1976; Chang and Wilheit, 1979). The Electrically Scanning Microwave Radiometer (ESMR) aboard the Nimbus 5 and 6 measured radiances at 37 GHz, and from these data rainrates were calculated over the ocean with reasonable success (Wilheit et al., 1977; Savage, 1976). Wilheit et al. (1977) compared satellite-derived rainrates to radar measurements and concluded that rainrates could be obtained via satellite to an accuracy within a factor of 2.

The SMMR has five frequency channels (6.6, 10.7, 18.0, 21.0 and 37.0 GHz), which is more than previous microwave instruments, and has improved spatial resolution (50 km × 50 km for the 18.0 and 21.0 GHz channels, 27 km × 27 km for the 37.0 GHz channel; Gloersen and Barath, 1977). These advantages allow for better discrimination between the effects of different atmospheric parameters and the effects of the earth’s surface. The satellite data are processed to correct for side lobe patterns, Faraday rotation and polarization coupling (Njoku et al., 1980), and then input into a retrieval algorithm limited to use over open, ice-free ocean areas to
obtain five geophysical parameters: sea surface temperature, surface wind speed, integrated water vapor, integrated liquid water and rain rate (see Wilheit and Chang, 1980 for details about the algorithm).

Extensive effort has been put forth to obtain accurate retrievals of these five geophysical parameters. The SMMR integrated water vapor retrieval has been shown to be as accurate as the radiosonde method of calculating integrated water vapor for the range of conditions experienced in the tropics and the midlatitudes (Lipes et al., 1979; Katsaros et al., 1981; Alishouse, 1983). However, verification of the other atmospheric water parameters, integrated liquid water and rain rate, has been difficult and only qualitative in nature. Nevertheless, Taylor et al. (1983) showed that estimates of integrated liquid water derived from SMMR agree reasonably well with radiosonde calculations, particularly for uniform marine stratocumulus. In general, the SMMR integrated liquid water amounts and rainrates agree qualitatively with satellite images of cloud cover and ship reports of present weather (Taylor et al., 1983).

The purpose of this paper is to demonstrate the potential of a SMMR-type instrument for studying the structure and evolution of midlatitude cyclones. A storm that crossed the Pacific between 10 and 12 September 1978 is used to illustrate how the SMMR information aids in locating fronts and rain areas and offers unique information about the distribution of water vapor and liquid water as the storm develops [additional case studies can be found in McMurtrie (1983)]. In the following sections, methods of analysis and the synoptic overview of the case study are reviewed followed by the SMMR results and discussion.

2. Methods of analysis

Marine analysis typically suffers from lack of data and accurate analysis can be difficult to make operationally. Therefore, in order to have the best estimate of the true location of the surface fronts, mean sea level pressure charts were reanalyzed, based on all available archived ship and buoy reports for the 10–12 September 1978 storm (McMurtrie, 1983). Because these reports are often sparsely distributed, satellite imagery taken at the synoptic times were crucial in the analysis (see Anderson et al., 1969 and Oliver and Bittner, 1970, for satellite image interpretation).

The weather ship P, at 50°N, 145°W, made two daily radiosonde ascents throughout the period of this study. From these data, a time–height cross section in mixing ratio was constructed to determine the vertical distribution of water vapor throughout the life history of the storm. Calculations of the integrated water vapor from these radiosonde profiles were made using the technique described by Alishouse (1983) to compare with SMMR.

Weather observations made from ships located within each SMMR overpass of this storm and other ones were compared statistically with SMMR-derived rainfall rates. Most ships made daily observations at 0000, 0600, 1200 and 1800 GMT. However, Seasat overpass numbers 1092 and 1106 occurred near 0900 GMT, three hours off the ship observing time. For those passes, the locations of ships reporting at 0600 and 1200 GMT were translated while preserving their relative position to the surface front. It was assumed that the storm did not develop appreciably for six hours and that the rain events reported were long-lived. Although this is often not the case, larger scale rainbands, such as wide warm and cold frontal rainbands, do exist on time scales of the order of 3–6 hours (Houze and Hobbs, 1982).

The SMMR data of integrated water vapor, integrated liquid water and rain rate were plotted separately on surface maps for each pass Seasat made of the storm. Independently analyzed surface low-pressure centers and fronts for the times of the satellite passes were then superimposed and the relationships between the horizontal distributions of SMMR atmospheric water parameters with respect to frontal locations and GOES-West infrared and visible satellite images were examined. Since the high emissivity of land surfaces contaminates SMMR data, satellite passes over land are not used.

Note that the SMMR swath width is only 600 km, and that each overpass is approximately 30° of longitude west of the previous overpass at 45°N. Consequently, a storm can easily fit between two consecutive satellite passes, or only be partially sampled by the satellite. Furthermore, the 600 km wide swath is too narrow to fully cover all sectors of a storm. For these reasons, several storms that occurred in the Gulf of Alaska region were studied (McMurtrie, 1983). The case study presented here was chosen because it was a particularly well sampled and well developed storm. Information from the other cases is also drawn upon in the conclusions.

3. Synoptic overview of the 10–12 September 1978 storm

Of the storms that crossed the North Pacific in September 1978, the 10–12 September storm maintained the highest wind speeds through the latter part of its development, 20 m s⁻¹, and the deepest surface low pressure center, 974 mb. However, the movement and development of this storm was typical of most storms that occur in this region. Figures 1, 2 and 3 are the meteorological maps and satellite pictures pertaining to this storm. Figures 1a, 2a and 3a are the surface analyses for 1800 GMT 10, 11 and 12 September, respectively. Figures 1b, 2b and 3b are the infrared satellite images for 1745 GMT 10, 11 and 12 September, and Figs. 1c, 2c and 3c are the NMC analyzed 500 mb charts for 1200 GMT 10, 11 and 12 September.
Fig. 1. (a) Surface analysis for 1800 GMT 10 September. Surface isobars contoured every 4 mb. Reports of wind direction and speed, in m s⁻¹, and current weather from ships are indicated. One pennant, full barb and half barb corresponds to 25, 5 and 2.5 m s⁻¹, respectively. The small crosses refer to locations of additional ships used in the analysis whose reports are not shown due to space limitation. (b) GOES-West infrared satellite photo for 1745 GMT 10 September. (c) Redrafted NMC 500 mb analysis for 1200 GMT 10 September. Heights (solid) contoured every 6 dam and temperature (dashed) every 5°C.
At 1800 GMT 10 September, the storm appeared as a broad, linear cloud feature near 160°W, oriented southwest–northeast on the GOES-W infrared satellite image (Fig. 1b). The surface low pressure embedded in the cloud band was located at 44°N, 159°W with a central pressure of approximately 1000 mb (Fig. 1a).

In the following 24 hours, the storm developed rapidly. The storm center traveled in the northeast direction at approximately 10 m s⁻¹ to 52°N, 152°W.
and deepened to 978 mb. At 1800 GMT 12 September several ships in the vicinity of the storm reported strong winds, 15–20 m s\(^{-1}\), and precipitation (Fig. 2a). An extensive cloud shield ahead of the warm and occluded fronts, a broad cloud band in the vicinity of the cold front, and a slot of drier air west
of the cold front were recorded from the GOES-W satellite at this time (Fig. 2b).

In the next 24 hours, the storm system matured and traveled north-northeastward to 57°N, 150°W. The surface fronts moved out ahead of the surface low and reached the British Columbia coast at approximately 0000 GMT 13 September and the Washington coast 0600 GMT 13 September. At 1800 GMT 12 September several ships reported wind speeds of 20 m s⁻¹, particularly in the vicinity of the surface low. The 1800 GMT 12 September infrared satellite image indicates that the frontal cloud bands and the cold drier air spiralled into the low center (Fig. 3b). The 1200 GMT 12 September 500 mb chart indicates that the upper-level low center associated with this storm was situated at 50°N, 150°W, nearly vertically aligned with the surface low pressure center (Figs. 3a, c).

4. Results

a. Integrated water vapor

Maps of integrated water vapor of four consecutive SMMR overpasses of the case study are given in Fig. 4. The surface fronts corresponding to each overpass are superimposed. In each map the surface fronts are located just west-northwest or within regions of maximum integrated water vapor. The strongest water vapor gradient lies just north or west of the maximum integrated water vapor in the cold air sector of the storm throughout its development. However, the water vapor distribution changes as the storm evolves.

Fig. 4. Horizontal distribution of integrated water vapor in kg m⁻² with frontal analysis superimposed. The data are contoured every 4 kg m⁻² and shaded every 8 kg m⁻² with darker shading indicating higher water vapor content. (a) Overpass number 1084, 1912 GMT 10 September 1978. (b) Overpass number 1092, 0900 GMT 11 September 1978. (c) Overpass number 1098, 1840 GMT 11 September 1978. (d) Overpass number 1106, 0830 GMT 12 September 1978.
In Fig. 4a, during the storm’s beginning stage, the water vapor amounts are generally about twice as large to the south of the maximum as to the north of it (38 versus 18 kg m\(^{-2}\)). Near the front, the change of water vapor occurs over a short distance toward the north. The front, as in the classical description, appears as a boundary between two air masses. In Figs. 4b, c, during the storm’s developing stage, a broad band of high integrated water vapor content about 200–300 km across lies parallel and just east of the cold front and extends 150–200 km north of the warm front. The gradient of water vapor is stronger toward the cold air than toward the warm air. This feature is remarkably similar to the distribution of air of high wet-bulb potential temperature within a midlatitude storm described by Browning (1974) and Harrold (1973). There is also evidence of a weak wave in the water vapor distribution along the cold front at 45°N, 153°W in Fig. 4b and at 48°N, 147°W in Fig. 4c (see also the infrared satellite picture, Fig. 2b). In Fig. 4d, during the storm’s mature stage, the maximum integrated water vapor lies in a narrow band along the slowly-moving cold front and the region ahead of the occluded and warm fronts. On either side of the cold front maximum, there is a sharp decrease in water vapor content, indicating that the air column is relatively dry on each side of the front, unlike the situation at the storm’s beginning and developing stages.

Figure 5 is a time–height cross section of mixing ratio constructed from ship P radiosonde data and the three-hourly surface observations. Times of frontal passages based on surface analyses are indicated by arrows and the numbers in boxes are the integrated water vapor amounts calculated for each radiosonde ascent. During this time period, Seasat made two passes over ship P, one at 0900 GMT 11 September and one at 0900 GMT 12 September (Figs. 4b, d). The 0900 GMT 11 September soundings sample the pre–warm front air mass. At this time the mixing ratios up to 400 mb are high compared to other soundings. In Fig. 4b, ship P is located in a region of
comparatively high integrated water vapor content. The SMMR derived integrated water vapor content at ship P is exactly the same as that calculated from radiosonde data, 34 kg m\(^{-2}\). In this case study, relatively high integrated water vapor content from SMMR corresponds to a vertical distribution of water vapor where the mixing ratio is relatively high throughout a deep layer of the troposphere. The 0900 GMT 12 September sounding samples the air mass following the cold front. At this time, most of the water vapor is limited to the layer below 700 mb, and the air is quite dry aloft. As before, the SMMR derived integrated water vapor at ship P agrees exactly with the radiosonde derived value, 17.3 kg m\(^{-2}\). Low SMMR water vapor amounts in this case corresponds to moisture confined to the lower layers of the atmosphere. The SMMR and radiosonde information together offer a three-dimensional picture of the moisture distribution in a midlatitude cyclone.

b. Integrated liquid water

The SMMR determined integrated liquid water amounts are overlayed on the corresponding infrared satellite image for overpass number 1106 at 0830 GMT 12 September in Fig. 6. North of 50°N, near the cold front and warm front, there are three distinct areas of liquid water content greater than 0.5 kg m\(^{-2}\) and as large as 1.0 kg m\(^{-2}\). The same region in the satellite image is white and obscured by high clouds, and it is difficult to determine that areas of higher liquid water content are present. The frontal band
**Fig. 4. (Continued)**

**Fig. 5.** Time-height cross section of mixing ratio in g kg\(^{-1}\) at ship P (50°N, 145°W). Frontal passes are indicated with arrows. Total atmospheric water content for each ascent are given in boxes at top of the figure in kg m\(^{-2}\); each vertical line represents the time of available radiosonde data from which the figure is drawn.

**Fig. 6.** Integrated liquid water in kg m\(^{-2}\) superimposed on the GOES-W infrared satellite image for the Seasat overpass 1106 that occurred at 0830 GMT 12 September 1978. The satellite image was taken at 0945 GMT.
south of 40°N is evident in the liquid water distribution as an area where amounts are between 0.1 and 1.0 kg m\(^{-2}\). In the infrared satellite picture, the clouds are a grayish shade in this region, indicating that they are warmer and hence lower clouds. Other small areas of 0.1–0.5 kg m\(^{-2}\) liquid water content are scattered within the swath between 40 and 50°N west of the cold front. Each cell determined by SMMR corresponds to regions of higher and probably deeper clouds in the satellite image.

c. Rainrate

Figure 7 gives examples of the rainfall patterns of a developing cyclone obtained from SMMR. Figure 7a corresponds to overpass number 1084 that occurred at 1912 GMT 10 September with the surface fronts and available 1800 GMT ship observations superimposed. Three cells of precipitation with rainrates greater than 3 mm h\(^{-1}\) are clearly distinguished in the vicinity of the warm and cold fronts. These untranslated ship reports agree qualitatively with the SMMR determined rainrates. For example, in the vicinity of 44°N, 156°W, there are two ships; the northern one reported steady moderate rain and the other reported rain within the last hour. The SMMR rainrates at the locations of the ships are 1.2 and 0.6 mm h\(^{-1}\), respectively.

Figure 7b gives the rainrates obtained from overpass number 1092 that occurred at 0900 GMT 11 September. Most of the ship locations shown in this figure have been translated using the methods described in Section 2, except the report marked “A.” This observation was made at 0900 GMT and steady heavy rain was reported in a region of SMMR rainrates greater than 4 mm h\(^{-1}\). The other observations plotted in this figure all agree well with SMMR rainrates in spite of the possibility of errors due to translation of the ship report; i.e., reports of light rain and drizzle occur in regions of rainrates less than 1.0 mm h\(^{-1}\) and the reports of moderate and heavy rain occur in regions of rainrates greater than 1.5 mm h\(^{-1}\).

Comparisons were made between the intensity of rainfall reported by the ship observers and the rainrates determined from SMMR. The results from this case study and two other storms in September 1978 are summarized in Table 1 (see McMurdie, 1983). The current weather observations of rainfall reported by the ship were placed in three categories: light, moderate, and heavy. The light category includes light and intermittent rain and drizzle, rainfall within sight of the ship and rain or drizzle within the last hour. The moderate category includes moderate continuous rainfall and drizzle, and the heavy category includes heavy continuous rainfall and heavy showers. Rainrates of 0.0–0.05 mm h\(^{-1}\) measured from SMMR corresponded to the “light” precipitation category of the current weather reports from the ships for 18 of 23 cases. Rainrates of 0.6–1.5 mm h\(^{-1}\) from SMMR corresponded to the moderate precipitation category for 16 of 23 cases. Rainrates greater than 2.0 mm h\(^{-1}\) from SMMR corresponded to the heavy precipitation category for three of three cases. During the three storms discussed above, the SMMR and ship reports simultaneously indicated either rain or no rain for 158 of 178 reports. Of the 20 reports that differed, the ship reported some kind of precipitation and SMMR did not 15 times. Of these, six are reports of shower activity and three are of intermittent precipitation. The remaining six include ships which had been translated whose reports were made three hours before or after the SMMR overpass time and ships reporting rainfall in convective type regions. Of the five occurrences where SMMR reported rain and ships did not, two of the ships reported fog and the remaining three were SMMR reports of rainrates of 0.1 mm h\(^{-1}\).

5. Discussion

a. Integrated water vapor

In order to establish a correlation between SMMR water vapor patterns and the location of surface fronts, the NMC mean sea level pressure charts were reanalyzed using all available ship and buoy reports and visible and infrared satellite imagery (see Section 2). This was to ensure our best estimate of the “true” location of the fronts. As is evident in Fig. 4, the distribution of integrated water vapor is correlated with the position of the surface fronts. In all of these maps, the cold, warm and occluded fronts are located either at the leading edge of the water vapor gradient or along the region of maximum integrated water vapor. The same pattern has been illustrated in other case studies (not shown here). These patterns are consistent with the classical Norwegian cyclone model. Bjerknes (1919) and Bjerknes and Solberg (1922) describe the vertical structure of midlatitude cyclones as warm, moist air forced to ascend sloping frontal surfaces. Since high integrated water vapor amounts result both from lifting the air, therefore moistening the upper levels, and from high amounts in the boundary layer, one would expect that the maximum integrated water vapor amounts occur in the vicinity of the surface fronts and in the warm sector. The integrated water vapor gradient is stronger behind the cold front than ahead of the warm front since the cold front has a steeper slope.

The horizontal distribution of water vapor differs at various stages of storm development. In this case, the cyclone’s beginning stage had at least twice as much moisture in the air south of the warm front as north of it. The front itself was located in the area of maximum water vapor content (Fig. 4a). As the storm developed, the maximum vapor content occurred in a broad band, about 200–300 km across, oriented
FIG. 7. Rainrate from SMMR in mm h$^{-1}$ and available ship reports of wind speed and direction and current weather. (a) Overpass number 1084, 1915 GMT 10 September and 1800 GMT ship reports. (b) Overpass number 1092, 0900 GMT 11 September and 0600, 0900 and 1200 GMT ship reports. The ship report labeled "A" is the only ship that reported at 0900 GMT. The others shown made observations at 0600 or 1200 GMT, and their positions have been shifted to preserve their relative positions to the fronts.
parallel to and just east of the cold front (Fig. 4b). At the mature stage, the maximum water vapor content was in a narrow band coincident with the cold front and strong water vapor gradients existed on both sides of the front (Fig. 4d).

The curvature in the contours of integrated water vapor at 45°N, 153°W in Fig. 4b and at 46°N in Fig. 4c possibly indicate a wave developing along the surface fronts. It is difficult to determine this from the infrared satellite pictures alone. In an operational situation, SMMR could provide a means for early detection of these waves.

There were 12 overpasses where the NMC surface analyses were redone using all the available surface and satellite information excluding SMMR (see Section 2). Four are presented in this paper. Of these 12, the SMMR information correlated with eight of the reanalyses much better than did the NMC operational analyses. An example of where the NMC analysis differed radically with the reanalysis is given in Fig. 8 along with the infrared satellite picture for 0900 GMT 27 September. The region of strong water vapor gradient in the SMMR map correlates best with the reanalysis of the fronts. Often there is very little information available over oceanic regions for the operational analyses of weather systems. This case study provides incentive for further study of how SMMR-type information can be used to aid marine frontal analysis.

b. Integrated liquid water

Distribution of integrated liquid water within storm systems over the ocean is difficult to obtain in situ. In the past, estimates of integrated liquid water have been derived from research aircraft measuring liquid water content (mg cm⁻³) while making several passes through a cloud at different levels (e.g., DeVault and Katsaros, 1983). Alternatively, by assuming adiabatic cooling of a parcel as it is lifted from cloud base to cloud top, liquid water estimates can be obtained from radiosonde data. However, these methods only provide a highly localized estimate whereas SMMR obtains spatially averaged measurements.

The horizontal distribution of integrated liquid water in the vicinity of midlatitude cyclones described by Liou and Duff (1979) using Nimbus 6 SCAMS data is similar to the distribution found in this case study, although their data were taken over land regions. Like this previous instrument, SMMR can sense areas of high liquid water hidden by overlying cirrus clouds. However, with SMMR's improved spatial resolution, areas of convection 50 km × 50 km are detectable. Thus, SMMR derived integrated liquid water provides a unique view of the structure of midlatitude cyclones that cannot readily be obtained any other way.

c. Rainrate

In the previous section, comparison of SMMR derived rainrate and ship reports of current weather were made. Although the comparison was only qualitative in nature, SMMR compared favorably. In addition to detecting rain or no rain, the relative intensity of rainfall agreed with ship reports. The discrepancies seem to result from the differences of scale: SMMR obtains a 50 km × 50 km areal average of rainfall; and ships make a point observation of rain.

Although the SMMR instrument has the finest resolution available of all the passive microwave instruments used to date, it is sufficiently coarse that problems in retrieving rainrate can result. The relationship between the measured brightness temperature and the computed rainrate is highly nonlinear (Wilheit and Chang, 1980). If the rainrate varies substantially within the field of view, the average brightness temperature measured will not represent the average rainrate, but will in general give an underestimate. This is of concern for studies requiring accurate rainrate estimates. However, in this investigation the relative magnitudes of rainrate is of as much interest as the absolute magnitudes. Even though the scale of rainrate variability within a midlatitude cyclone can be smaller than the field of view of the instrument (Houze and Hobbs, 1982), the information obtained from the satellite will still represent, even if coarsely, the rainrate variability within the cyclone.

Intense rainfall can cause the atmosphere to appear opaque at all frequencies and can mask the effects of other parameters. The problem is greater when there is intense rainfall over a small portion of the field of view of the instrument (Wilheit and Chang, 1980). For example, if a rainrate of 100 mm h⁻¹ occurs within only 1% of the field of view, that portion of the footprint would appear opaque and would affect the brightness temperatures measured by the instrument at all frequencies. When these brightness temperatures are processed through the algorithm, these will be erroneously interpreted as brightness temperatures resulting from the other geophysical parameters. However, in this case study, there is little evidence of
Fig. 8. (a) Integrated water vapor for Seasat overpass number 1321 at 0935 GMT 27 September 1978. The front position labeled “A” corresponds to the NMC analysis and the front position labeled “B” corresponds to analysis based on additional ship reports and satellite information. (b) Infrared satellite picture for 0945 GMT 27 September 1978.
intense convective-type rainfall. The authors are confident that rain did not affect the retrievals of the other parameters.

Figures 7a, b of SMMR derived rainrates show strikingly that heavy rainfall in midlatitude cyclones occurs in patches or bands within widespread light rain. In Fig. 7b the areas of maximum rainfall occur in bands oriented parallel to the warm and cold fronts. This rainfall pattern is very similar to that described as typical by Houze and Hobbs (1982) for midlatitude cyclones. However, the radar and aircraft measurements used in their experiments resolved the rainband structure on scales less than a kilometer. Some types of rainbands they describe are too small to be detected by SMMR. It is possible that the areas of maximum rainfall seen by SMMR are actually an average of several rainbands. Nevertheless, the large mesoscale distribution of rainfall within a midlatitude cyclone is particularly evident from these SMMR measurements.

6. Conclusions

Horizontal distribution of integrated water vapor, integrated liquid water and rainrate in a September 1978 storm in the North Pacific were examined. The water vapor distribution was found to be related to the location of the surface front throughout the development of the cyclone. Early in its history, the average water vapor content south of the warm front in the warm sector and in the subtropical regions was twice the average water vapor content north of the front. The front itself was in the vicinity of the maximum integrated water vapor amounts. As the storm developed, the front (cold, warm or occluded) was usually located between the maximum integrated water vapor and the sharp gradient of water vapor amounts. However, the slow-moving cold front during the cyclone's mature stage was located along the region of maximum integrated water vapor. The available radiosonde data from ship P agree qualitatively well with the integrated water vapor amounts obtained from SMMR. The radiosonde data and SMMR together produce a three-dimensional view of the distribution of water vapor in a developing cyclone.

The SMMR-derived integrated liquid-water content patterns agreed well with the cloud patterns evident in the GOES-W infrared satellite images; SMMR can detect areas of high liquid water content occurring below high-level ice clouds. This is an advantage over infrared satellite images or infrared sounders.

Areas of mesoscale rainfall, on the order of 50 km × 50 km or greater, within a midlatitude cyclone, can easily be distinguished using SMMR information and the resultant rainfall patterns are remarkably similar to those described by Houze and Hobbs (1982). In addition, ship reports of rainfall intensity qualitatively agree very well with SMMR derived rainrates.

The potential usefulness of a SMMR-type instrument has briefly been discussed herein. Studying a variety of storms in different oceans and in different seasons may shed light on the mesoscale evolution of a cyclone and provide a better understanding of the role atmospheric water vapor and liquid water has in midlatitude cyclone growth and decay. In addition, rainrates calculated from SMMR and then advected to the coast could provide a means for predicting coastal rainfall. The next generation of passive microwave sensors already planned for launch will have better resolution and wider swath width. These features will further enable microwave sensors to be useful in storm research by providing more accurate rainrate retrieval and sampling larger portions of storms.

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