Detection and Characterization of Mesoscale Cyclones in

RADARSAT Synthetic Aperture Radar Images of the Labrador Sea[1]

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ABSTRACT – *We consider RADARSAT synthetic aperture radar (SAR) ScanSAR wide mode images of several mesoscale cyclones that developed over the Labrador Sea during the winter of 1997/98. The three case studies demonstrate RADARSAT ScanSAR's capability to provide detailed information on the near surface wind field structure associated with these intense storms. The SAR images, along with accompanying meteorological conditions and thermal infrared images of the associated cloud patterns, show the spiral-form shear zones of the cyclones as well as nearby organized convection during various stages of cyclone development. In future, ocean wind fields retrieved from RADARSAT ScanSAR images could help to improve simulation models for polar and other mesoscale cyclones and could have a role in operational marine meterology.*

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1. Introduction

Since the launch of RADARSAT (see Raney *et al.*, 1991) in November, 1995, the Canadian Ice Service (CIS) has routinely used RADARSAT synthetic aperture radar (SAR) ScanSAR wide mode (500 km swath, 100 m resolution) image data in near real-time as a key input to its sea ice monitoring program (Ramsay *et al.*, 1993; 1998). The SAR images that are acquired for this application often include open ocean regions that frequently contain signatures related to the ocean surface imprint of atmospheric phenomena. Polar and synoptic scale mesoscale cyclones (MCs), meteorological fronts, areas of convective activity, boundary layer rolls associated with cold air outbreaks, lee waves, and freely propagating atmospheric gravity waves have all been identified in SAR images by their characteristic scales and modulations of the near surface wind speed. Meteorological data for high latitude ocean areas are rather scarce, so remote sensing techniques are relied upon. Optical and infrared sensors such as NOAA's Advanced Very High Resolution Radiometer (AVHRR) provide a cloud-top view of these atmospheric processes. On the other hand, the sea-surface view from the RADARSAT SAR can provide rather detailed information on the associated near-surface wind field structure.

In this paper, we discuss several MCs observed in RADARSAT ScanSAR wide mode images of the Labrador Sea that were acquired in December 1997 and January 1998. The images were obtained by CIS for routine sea ice surveillance. We first describe the characteristics and scales of polar MCs and we then review various atmospheric phenomena that may appear in SAR images of the ocean surface. Next we discuss the ocean surface signatures of three MCs that were noted in RADARSAT ScanSAR images, as well as the meteorological conditions that accompanied the MC development. Finally, we provide a few comments on the operational potential of RADARSAT ScanSAR images in the marine forecasting application.

1.1 General Characteristics of Polar MCs

Atmospheric mesoscale cyclonic vortices that develop at high latitudes during cold air outbreaks are significant and of increasing interest (Twitchell *et al.*, 1989; Heinemann, 1995;

Mitnik *et al*., 1996). Often called polar lows, these intense MCs form poleward of major jet streams in cold air masses or frontal zones; their cloud mass is mainly convective in origin (Businger and Reed, 1989). The small spatial scales (< 1000 km) and short life times (24 to 48 hours) inherent to polar MCs require high-resolution numerical weather prediction models to simulate their initiation, temporal evolution, and spatial structure; it is difficult to validate these models due to an absence of high spatial resolution, near surface wind field measurements. Polar MCs may be a source of sudden atmospheric forcing or cooling of Labrador Sea water that significantly impacts the Labrador Sea climate (Moore *et al*., 1996).

The airflows in which polar MCs form are characterized by cyclonic flow or shear, by near neutral or unstable lapse rates in a marine boundary layer that may extend up to height of a few kilometres, and by large heat and moisture fluxes from the ocean surface. It has been proposed that arctic fronts play a significant role in the formation of arctic-front type polar MCs (Shapiro and Fedor, 1989; Twitchell *et al.*, 1989). The favoured region of formation for arctic fronts is along the ice margin where relatively warm open water lies adjacent to sea ice or cold continents. In these regions, strong low-level baroclinicity (*e.g.*, Gill, 1982) exists due to differential heating of the atmospheric boundary layer above the open water and ice-covered surfaces. Low-level baroclinicity also plays an important role in the formation of polar MCs that occur in conjunction with outflows of surface air from ice or snow covered regions to open water (Twitchell *et al.*, 1989; Moore *et al*., 1996; Mailhot *et al*., 1996). Such outflows are often characterized by the presence of cloud streets associated with atmospheric boundary layer rolls.

Arctic front type polar MCs develop in conditions of “reversed shear” flow, in which the storm motion or low-level wind is opposite in direction to the thermal wind. The baroclinicity is a necessary but not a sufficient condition for the development of polar lows. Most of the lows observed in the Barents and Norwegian Seas (Okland, 1989; Twitchell *et al*. 1989; Nordeng and Rasmussen, 1992; Heinemann, 1995; Heinemann and Claud, 1997) and the Labrador Sea (Mailhot *et al*., 1996; Moore *et al*., 1996) were triggered by an upper-level disturbance noted in the form of a cold 500 hPa trough or, equivalently, by an upper-level potential vorticity (PV) anomaly. Thus, baroclinic instability coupled with upper-level PV forcing was suggested as the triggering mechanism, with convection contributing at a later stage in the form of conditional instability of the second kind (CISK) or air-sea interaction instability (Businger and Reed, 1989; Mailhot *et al.*, 1996). The CISK process occurs if the convection becomes sufficiently well organized that a positive feedback develops between the cloud scale and the developing vortex scale. At this stage of formation, the vortex motion provides moisture convergence for the convective process and the cumulus scale provides latent heating that intensifies the large-scale disturbance. The release of latent heat may be a sufficient energy source to account for spin-up (Okland, 1989; Businger and Reed, 1989). The importance of instabilities (baroclinic, CISK, and air-sea interaction) in development and maintenance of MCs is still debated in the literature (Heinemann and Claud, 1997; Businger and Reed, 1989; Moore and Peltier, 1989; Harrold and Browning, 1969; Nordeng and Rasmussen, 1992). Numerical simulation and forecasting of polar MCs is still a problem (Businger and Reed, 1989; Heinemann and Claud, 1997).

Polar MCs usually occur in data sparse regions. Therefore, satellite images have been an important tool for the detection and study of these phenomena. A constructive way to remotely study polar MCs is to combine various available satellite measurements that are nearly coincident in time (Heinemann and Claud, 1997; Mitnik *et al*., 1996). RADARSAT SAR observations of polar MCs could contribute to these multisensor studies. The RADARSAT ScanSAR wide mode has a swath of 500 km with a spatial resolution of about 100 m, permitting observations of both mesoscale and small-scale variations of the near-surface wind field within polar MCs. The fine structure of the wind fields within the cores of MCs observed in RADARSAT ScanSAR images is the focus of this paper. The images display the detailed shape of the wind shear boundaries within the MC vortex as well as the small scale wind variations caused by atmospheric organized structures such as boundary layer rolls, convective cells, and atmospheric gravity waves. In general, MC development is affected by the interaction between the organized structures and the vortex (Twitchell *et al.*, 1989).

1.2 Ocean Surface Imprints of Atmospheric Phenomena in SAR Images

We describe now the properties, characteristic scales, and ocean surface imprints of atmospheric processes in SAR ocean images. SAR images of such processes have previously been validated with *in situ* measurements and atmospheric models (*e.g.*, Brown, 1986; Gerling, 1986; Atlas, 1994; Johannessen *et al.*, 1991; Johannessen *et al.*, 1994; Alpers and Brümmer, 1994; Sikora *et al*., 1995; Mourad and Walter, 1996; Mitnik *et al*., 1996; Kravtsov *et al*., 1996; Vachon and Dobson, 1996; Jameson *et al*., 1997; Alpers *et al*., 1998).

Meteorological fronts and organized atmospheric structures, such as convective cells, boundary layer rolls, and atmospheric gravity waves, modulate the wind stress on the ocean surface, thereby modulating the small-scale sea-surface roughness and the radar backscatter cross-section (*e.g.*, Brown, 1986; Gerling, 1986; Johannessen *et al*., 1994; Atlas, 1994; Mourad, 1996; Mitnik *et al*., 1996). The higher the local surface wind speed, the brighter the SAR image appears. The relationship between wind speed and radar cross section forms the basis of wind scatterometry, and may be used with radiometrically calibrated SAR images in SAR's role as an imaging wind scatterometer (Vachon and Dobson, 1996).

Convective cells are observed in an unstable atmospheric boundary layer when the ocean surface temperature is higher than the air temperature and when the wind speed is low enough (Agee *et al*. 1973; Albrecht *et al*. 1995; Atkinson and Zhang, 1996, Hartmann *et al*., 1997). The mottled patterns in SAR images are the surface counterpart to the well-known cloud patterns resulting from convective airflow in an unstable boundary layer (Alpers and Brümmer ,1994; Johannessen *et al*., 1994; Kravtsov *et al*., 1996; Sikora *et al*., 1995; Mourad and Walter, 1996; Mourad, 1996; Atkinson and Zhang, 1996). Typical cells are nearly circular, 1 to 3 km in diameter, and often become organized downwind into larger scale atmospheric boundary layer rolls. (*e.g.*,; Mourad and Walter, 1996; Atkinson and Zhang, 1996).

Numerous convective boundary layer studies using aircraft wind velocity and temperature measurements (*e.g.*, Young, 1987; Schumann and Moeng, 1991; Miura, 1986; Muller and Chlond, 1996; Hartmann *et al*., 1997) have shown that the peak wavelength ? of horizontal wind velocity spectra for cellular convection depends on the depth z_i of the mixed atmospheric boundary layer. Kaimal *et al*. (1976) found that the peak wavelength increases as $1.5z_i$. Recent satellite observations of convective processes over the open ocean during cold air outbreaks have shown convective cells with characteristic diameters from 10 to 40 km that existed in a convective layer with a depth of 1 to 3 km (Atkinson and Zhang, 1996).

When cold air leaves the land surface, it is modified by vertical fluxes of heat and moisture from the underlying relatively warm water surface. This modification of the airflow causes the formation of boundary layer rolls. If the moisture conditions are favourable, cloud streets may be formed in the upward rising branches of the roll circulation. Farther downwind in the outbreak, roll convection transforms into three-dimensional cells. The axes of the boundary layer rolls are usually oriented to within –20º to +30º of the mean surface wind vector (Etling and Brown, 1993). The ratio of the horizontal spacing of the roll pattern to the roll height (which approximately coincides with the depth of the unstable marine boundary layer), referred to as the aspect ratio, ranges from 2 to 15. There is a wide range of parameters that control the wavelength and the aspect ratio.

The large aspect ratios (>10) observed during cold air outbreaks cannot be explained by linear instability theory (Etling and Brown, 1993). Several different mechanisms have been proposed including latent heat release (Sykes *et al.*, 1988), nonlinear scale interactions within the original small-scale convective region (Mourad and Brown, 1990), coupling between boundary layer convection and atmospheric gravity waves within the stably stratified layer aloft (Clark *et al*., 1986; Sang, 1991; Balaji *et al*., 1993), and others (see Etling and Brown, 1993).

The regimes of organized convection are often classified with respect to the boundary layer stability parameter z_i/L, where $L = -u*^3/\beta Q$ is the Obukhov length, which is a characteristic surface-layer length scale, u* is the friction velocity, which is related to the surface wind stress via $u^* = (-< w'u'>)^{1/2}$, where w' and u' are vertical and horizontal components of the wind velocity fluctuations, respectively, Q is the surface mean heat flux, $\beta = g/T_s$ is the buoyancy parameter, T_s is the surface temperature, and g is the acceleration of gravity. Evaluation of z_i/L for some boundary layer roll vortex observations gave values from –6 to –15 (Deardorff, 1972; Grossmann, 1982), whereas three-dimensional convective cells usually exist for $z_i/L < -25$. However, the scatter in the measured stability parameter values is rather large (Etling and Brown, 1993; Hartmann *et al.*, 1997).

Contrary to organized convection, atmospheric gravity waves (also referred to as internal waves, not to be confused with oceanic internal waves that are also seen in SAR images) exist in stably stratified layers of the atmosphere. Atmospheric gravity waves are very common in SAR images where they manifest themselves as wave packets with typical wavelengths ranging from a few to tens of kilometres (Thomson *et al.*, 1992; Vachon *et al.*, 1994; Vachon *et al.*, 1995; Alpers and Stilke, 1996; Zheng *et al.*, 1998; Chunchuzov *et al.*, 2000). There are many generation mechanisms. Lee waves are generated by wind blowing over a mountain ridge. Other lower atmosphere sources include meteorological fronts, turbulent jet streams, and convective storms (Gossard and Hooke, 1975). Based upon atmospheric pressure and wind speed measurements, the wave-induced wind field in the lower troposphere usually oscillates with periods from a few minutes to a few hours (*i.e.*, up to the inertial period) and with amplitudes of up to 3 m/s (Gossard and Hooke, 1975).

SAR imagery can show the ocean surface imprints of both the atmospheric gravity wave source, such as a meteorological front, and the waves themselves, thus demonstrating SAR's capability to study generation mechanisms for atmospheric gravity waves and their interaction with mesoscale atmospheric motion (Chunchuzov *et al.*, 2000). In polar MCs, the strong vertical shears existing in the MC's horizontal wind field may also act as an atmospheric gravity wave source (Rasmussen and Aakjaar, 1989). A cloud pattern attributed to atmospheric gravity waves was observed in AVHRR thermal infrared (IR) images west of the eye of a polar MC in the Labrador Sea (Moore *et al*., 1996).

As was noted, the interaction between a mesoscale vortex and smaller scale organized convection can contribute significantly to the intensification of MCs. A joint analysis of real aperture radar and AVHRR IR images of polar MCs conducted by Mitnik *et al.* (1996), showed a strong correlation between the surface wind and cloudiness fields. X-band RAR images showed sharp wind gradients as well as the detailed structure of the horizontal wind speed in the MCs due to the 2 to 3 km spatial resolutions that were available across a very wide image swath. As a result, the positions of the centre and wind shear boundaries within a polar MC were better determined with imaging radar than with more conventional passive microwave data with their much coarser spatial resolution (~25 km).

2. RADARSAT ScanSAR Images of Labrador Sea MCs

We now consider three case studies of MCs that occurred over the Labrador Sea (Fig. 1) during winter 1997/98 and were identified in RADARSAT ScanSAR images that were acquired for routine sea ice surveillance (Bradley *et al*., 1998). The ice edge is visible in each RADARSAT image that we consider.

2.1 Case 1: 28 and 29 December 1997

The meteorological conditions and remote sensing data for 28 December 1997 are shown in Fig. 2. The meteorological conditions were taken from synoptic charts of the 1000 mb and 500 hPa height fields, and from uncalibrated NOAA 12 AVHRR Channel 4 (thermal IR) images of the cloud patterns. The 1000 mb height field of 28 December 1997 at 18:00 UTC shows that there was a synoptic-scale cyclone over the Labrador Sea, together with a ridge of high-pressure over the Greenland ice cap (Fig. 2a). This cyclone, with a central sea-level pressure of 977 mb, was a precursor of what was likely a polar MC that was imaged the next day by the RADARSAT SAR.

RADARSAT ScanSAR images of the Labrador Sea acquired in the morning and evening of 28 December are shown in Figs. 2c and 2e. The image of Fig. 2c shows the distribution of radar brightness over the ocean area adjacent to the Labrador and Baffin Island coastlines including Davis Strait. We see that there was a strong cold airflow (the bright pattern) from the land to the open water. The ice edge is visible as the brighter filaments adjacent to the coast. According to the coastal weather station at Nain, the mean daily data for 28 December 1997 indicated a strong westerly wind with a near surface temperature of –22ºC. A sharp wind shear boundary (the sharp brightness discontinuity) is also visible in Fig. 2c, separating the strong cold airflow crossing the coastal margin (the brighter area) and the calmer, warmer air above the open water (the darker area). The strong thermal gradient, existing due to differential heating of the atmospheric boundary layer over the cold land and the much warmer ocean, would have provided favourable conditions for polar MC development.

The weak, kilometer-scale, periodic variations of the backscatter signal across the bright area of the image of Fig. 2c are likely the signatures of boundary layer roll vortices that developed in the shallow boundary layer during the cold air outbreak. The presence of boundary layer roll vortices shows that the cold air leaving the land surface was modified, most likely by strong heat and moisture fluxes from the underlying relatively warm ocean surface. The horizontal spacing between the roll vortices grew with distance downwind from the coast and reached values as high as 10 km at 300 km downwind. There is no indication that convective cells existed within the area covered by the SAR image. The strong airflow visible in the lower part of the image was likely caused by the cold air advection associated with the upper-level closed low approaching the coast (Fig. 2b).

We suggest that upper level vorticity advection played a role in the initial development of the MC imaged by RADARSAT on 29 December, and that the image of Fig. 2c shows the destabilized cold air flow over the warmer water at the initial stage of development. This early stage of development is also evident from the cloud signature in the IR image of 28 December

1997 at 11:34 UTC (Fig. 2d). The cloud lines that originated over Greenland turned southeastward through Hudson Strait. The RADARSAT ScanSAR image of Fig. 2e shows essentially the same area as that in Fig. 2c, but obtained during the evening of December 28. The cold airflow along Hudson Strait was still organized into boundary layer roll vortices, but the mean surface wind had become weaker than in the morning and the separation between cloud streets had become larger and better defined. The IR image of Fig. 2f, acquired about 30 minutes prior to the RADARSAT image of Fig. 2e, also shows the spatial evolution of the organized convective structures (cloud streets and convective cells) in the developing MC, but with coarser resolution. At the same time, the IR image overlaps a much larger ocean area than that covered by the RADARSAT image and reveals a curved cloud band (adjacent to the cloud streets) with a cloud free zone northeast of the region of organized convection.

The meteorological conditions and remote sensing data for 29 December 1997 are shown in Fig. 3. Figs. 3b and 3c show the evolution of the upper-level synoptic low and the relative vorticity advection through the coastal zone during the period between 00:00 UTC of December 29 and 00:00 UTC of December 30. The RADARSAT ScanSAR image of Fig. 3e shows that, by the morning of 29 December, the convection near the southern region of the Labrador coast had evolved such that the boundary layer rolls with increasing downwind spacing from the coast had become convective cells with 5 to 10 km diameters. As was noted, convective cells have larger absolute values of the stability parameter than roll vortices. The increase in roll wavelength and aspect ratio downwind from the coast could arise from an increase in the mixed boundary layer height z_i, coinciding with an increase in latent heat release in the cloud layer.

Since the length scale of the convective cells grows with z_i, the large cell sizes visible in Fig. 3e may be a consequence of a deep convective regime that existed during December 28 and 29 in the developing MC. Lee waves are visible close to the coast in the southwest portion of Fig. 3e. They were likely generated in the stably-stratified airflow by the coastal topography, whereas further from the coast, organized convection occurred in the form of boundary layer rolls and convective cells (towards the northeast of Fig.3e). Comparison of the IR image acquired in the evening of 28 December at 21:15 UTC (Fig. 3f) with that of the morning of 29 December at 11:11 UTC (Fig. 3h) shows that during the period between the two IR images, the spacing between the boundary layer rolls increased as they evolved into large-scale convective cells far from the coast. The IR image also reveals a curved cloud band over Hudson Strait (north of the area imaged by RADARSAT) that took the form of a spiral. When comparing the 1000 mb charts for 28 December (Fig. 2a) and 29 December (Fig. 3a) we note that two closed lows with cores east and west of Greenland had formed by 29 December at 18:00 UTC from one larger-scale synoptic low that existed in the Labrador Sea on December 28. Both of the lows had deeper depressions than the pre-existing larger-scale cyclone.

The most intense low was located over Davis Strait, and reached a maximum depression of about 964 mb. Three hours later, RADARSAT acquired a ScanSAR wide image of the same region of the Labrador Sea, showing the core of the well-developed MC (Fig. 3g) close to the ice edge off Baffin Island. The centre of the intense closed low in the 1000 mb chart of December 29 (Fig. 3a) lies within the RADARSAT coverage. The 500 hPa chart of 30 December at 00:00 UTC (Fig. 3c), about 2.5 hours after the RADARSAT image of Fig. 3g, also shows a deep closed low over Davis Strait with centre within the RADARSAT coverage. The interaction between the upper-level trough and the low-level baroclinicity near the ice-edge appears to have triggered the MC visible in the RADARSAT image (Fig. 3g). A drop in pressure over Davis Strait that took place between December 28 at 18:00 UTC and December 29 at 18:00 UTC (as judged from the 1000 mb charts in Figs. 1a and 3a) was likely associated with the deepening of the developing MC. The rapid deepening stage of a polar MC has been ascribed to the effect of organized deep convection (Rasmussen, 1985). We suggest that organized deep convection contributed to the development and intensification of the observed MC, in agreement with numerical case studies of the development of polar MCs in the Labrador Sea (Mailhot *et al.*, 1996).

During the period from December 28 at 00:00 UTC to 30 December at 00:00 UTC, the upper-level trough, as observed from 500 hPa charts of Figs. 2b, 3b, and 3c, moved east towards the Labrador Sea, crossing the coastal zone with its enhanced low-level baroclinicity. The trough could have been the triggering disturbance for the observed MC. Fig. 3g shows, in detail, the spiral-form structure of the surface wind field around the eye (dark ellipsoid-shaped pattern) of the MC. The convergence zone of the surface winds in the core of the MC is characterized by the sharp wind field gradients that are revealed by the relatively high spatial resolution of the RADARSAT ScanSAR image.

As on December 28, the Nain station indicated that on December 29 a strong, cold westerly wind was blowing over the coast, but with a lower mean wind speed and a near surface temperature of −23ºC. The 500 hPa height and vorticity charts (Fig. 3c) indicate that strong vorticity advection occurred along Hudson Strait. The sounding data from Goose Bay on December 29 at 12:00 UTC (Fig. 3d) show that the air mass leaving the land had stable stratification (note the Brunt-Väisälä frequency and potential temperature profiles) with a local stability maximum about 0.5 km above the land surface. The cold air that was advected from Baffin Island to the warmer open water corresponds to the bright area visible in Fig. 3g. Downwind from the coast, the strong airflow became organized into spiral-form boundary layer rolls with increasing aspect ratio. The horizontal roll spacing reached 20 km at 300 km downwind, which was larger than the roll spacing of 28 December at the same downwind distance. Cellular convection is evident to the north of the eye. At the same time, the strong airflow that left the coast appeared to be stable (the bright area southwest of the eye), but quickly destabilized with downwind distance from the coast, probably due to strong heat fluxes from the warmer ocean. An IR image of the MC that was acquired on 29 December 1997 at 21:11 UTC (Fig. 3h) shows that the cloud pattern included the spiral-form cloud streets around the vortex as well as a well-defined white (*i.e.*, cloud-covered) eye.

2.2 Case 2: 1 January 1998

The day after the MC of Case 1, the 1000 mb chart of 30 December at 18:00 UTC showed that the strong depression that existed on 29 December in the Labrador Sea between Greenland and Baffin Island had weakened and moved to the east toward Greenland. This seems to be associated with the decay of the depression and the eventual disappearance of the MC. According to subsequent 1000 mb charts (not shown here) a new closed synoptic low formed on December 31 close to the Labrador coast. This low had disappeared from the 1000 mb and 500 hPa charts by the time the two mesoscale vortices of Fig. 4a were imaged by the RADARSAT ScanSAR on 1 January at 21:30 UTC. One of the vortices is visible in the northeast corner of the image (labelled "1" in the corresponding IR image of Fig. 4b), whereas the second is visible near the bright area in the southern portion of the image (labelled "2" in Fig. 4b). A wind shear boundary around the dark eye of the lower MC is visible between the cold air (–20ºC near surface temperature measured at Cartwright) blowing strongly across the ice edge (bright area) and the warmer air above the sea surface (darker area).

There is no indication in Fig. 4a of cellular convection close to the cores of the noted vortices, although boundary layer rolls and small-scale convective cells are visible (in RADARSAT images not shown here) to the south of the imaged area. The 1000 mb charts for both January 1 at 18:00 UTC and January 2 at 18:00 UTC do not show any mesoscale lows in this region. The IR image of 1 January 1998 at 21:28 UTC (Fig. 4b) shows that the vortices visible in Fig. 4a are obscured by an upper cloud layer, although boundary layer rolls associated with the cold air outflow are visible near the Labrador coast. Whereas the MC of Case 1 could have been a well-developed polar MC, this case could be a polar MC at an earlier stage of development.

2.3 Case 3: 15 January 1998

Fig. 5a shows a RADARSAT ScanSAR image of an occluded synoptic low acquired on 15 January 1998 at 21:18 UTC to the north of the Island of Newfoundland. The 1000 mb charts for the time period between 14 January at 18:00 UTC and 15 January at 18:00 UTC (not shown here) showed a closed synoptic low located north of the Island of Newfoundland that intensified during this period. The next day, the 1000 mb charts (16 January 1998 at 18:00 UTC) show that this low had decayed and moved to the east. Similar to the possible polar MC of Case 1, several distinct regions are clearly visible in the ScanSAR image of Fig. 5a. We see cellular convection (north of the eye) and a spiral-form shear boundary converging towards the calm eye (the sharp brightness discontinuity around the eye between the bright and dark areas). In this case, the air moves westward to the north of the eye so that the wind shear boundary curves across the Labrador landmass. The horizontal extent of the convective region within the MC is well defined and is also visible as a mottled cloud pattern in the IR image of 15 January at 21:19 UTC (Fig. 5b). However, clouds mask the eye (which is indicated by the arrows). The associated cloud pattern in the IR image clearly shows the full extent of the vortex.

3. Operational Significance for Marine Meteorology

The RADARSAT ScanSAR images presented here represent a potential new source of marine boundary layer information for operational marine meteorology. The local changes in radar backscatter caused by the modulation of wind stress on the ocean surface enable the identification of MCs and other atmospheric phenomena at near synoptic scales within the 500 km ScanSAR wide mode swath. On the other hand, the convective cells, boundary layer rolls, atmospheric gravity waves, and shear zones that are detectable at a resolution of about 100 m in these images, are of much finer scale than is available from conventional marine meteorological networks.

RADARSAT image files include geographic location data that allow the positions of the meteorological phenomena of interest to be extracted and integrated with data from other satellite and surface observations. Furthermore, ScanSAR wide mode with its 500 km swath offers frequent repeat coverage at high latitudes (*e.g.*, at least daily coverage of any point north of N70º).

It is worthwhile to note that RADARSAT SAR data can be made available within an operational schedule. As an example, RADARSAT images are a significant operational input to the Canadian Ice Service (CIS) program (Ramsay *et al*., 1998). SAR signal data acquired at Canadian reception stations in Prince Albert, Saskatchewan and Gatineau, Quebec are processed into image products at the Gatineau station. CIS receives the images via a dedicated fibre optic link within 2 hours of satellite acquisition.

4. Conclusions

Three case studies of RADARSAT ScanSAR images of mesoscale cyclones (MCs) that developed over the Labrador Sea illustrate RADARSAT's capability to provide unique information on mesoscale and small-scale variations of the near-surface wind field inherent to MCs during various stages of development. Spiral-form wind shear boundaries that converge towards the eye of the MC are visible in all three cases (Figs. 3g, 4a, and 5a). The images also indicate strong cold air advection through the coastal zone, sharp wind speed gradients, and the initially stable flow forming a cyclonic rotation around a calmer and warmer air mass in the eye. Also visible are boundary layer rolls, convective cells, and atmospheric gravity waves that are all evidence of varying degrees of atmospheric instability.

Case 1 considered a possible well-developed polar MC that was in Davis Strait from 28 to 29 December 1997 (Fig. 3g). The 1000 mb and 500 hPa charts showed a deepening closed low over Davis Strait from 28 to 29 December 1997. An upper-level trough passing over the coastal front with a strong thermal anomaly that was the likely trigger mechanism. The ScanSAR images reveal the sharp wind field variations close to the coastal zone as well as the evolution of fine wind field structures in the regions of organized convection in the developing MC. Case 2 considered a pair of vortices off the Labrador coast (Fig. 4a), possibly a polar MC at an early stage of development. Case 3 considered an occluded synoptic low off the north coast of the Island of Newfoundland (Fig. 5a) that had several characteristics in common with the possible polar MC of Case 1.

In each case study, the MCs were at least partially obscured by cloud and the accompanying IR image of the cloud pattern did not reveal the detailed structure or the organized convection around the eye. On the other hand, the IR images captured more of the ocean area occupied by the MC. Therefore, the narrow but detailed sea-surface view of RADARSAT ScanSAR images, would appear to complement the wide field but lower resolution cloud-top view of the IR images. Note that wind vector retrieval has already been validated for RADARSAT single beam mode SAR images (Vachon and Dobson, 2000).

According to numerical simulations of polar MC development (Nordeng and Rasmussen, 1992; Okland, 1989; Heinemann and Claud, 1997), the region with shallow convection that is confined to low levels by a capping inversion, and the region with deeper convection that results in latent heat release in ascending regions, may be important for the development of polar MCs. The ability of RADARSAT to detect and distinguish the fine wind structure within various convective regions may be useful for improving these numerical simulations and for studying driving mechanisms of initiation, development, and maintenance of polar MCs. In particular, near-surface, small-scale wind fields extracted from RADARSAT ScanSAR images combined with existing remote sensing measurements of temperature, humidity, cloud cover, *etc.* could be used to parameterize the influence of the organized convection on MC development. Furthermore, RADARSAT ScanSAR images, such as those currently being obtained for operational sea ice surveillance, contain unique meteorological information that could have a role in marine meteorology within an operational schedule.

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Figure Captions

Fig. 1. The region of RADARSAT ScanSAR observations during winter 1997/98.

Fig. 2. Case 1: 28 December 1997:

a. 1000 mb height (solid lines in meters) of 28 December 1997 at 18:00 UTC. The coverage of the RADARSAT images of Figs. 2c and 2e is indicated.
b. 500 hPa height (solid lines) and relative vorticity (dotted lines in 1.E-5/s) for 28 December 1997 at 00:00 UTC.
c. RADARSAT ScanSAR Wide at 10:18 UTC (500 km by 1200 km) (© CSA 1997).
d. NOAA 12 AVHRR channel 4 at 11:34 UTC. The coverage of the RADARSAT image of Fig. 2c, also shown as a low resolution insert for reference, is indicated.
e. RADARSAT ScanSAR Wide at 21:46 UTC (500 km by 1500 km) (© CSA 1997).
f. NOAA 12 AVHRR channel 4 at 21:15 UTC. The coverage of the RADARSAT image of Fig. 2e is indicated.

Fig. 3. Case 1: 29 December 1997:

a. 1000 mb height of 29 December 1997 at 18:00 UTC. The coverage of the RADARSAT images of Figs. 3e and 3g is indicated.
b. 500 hPa height and relative vorticity of 29 December 1997 at 00:00 UTC.
c. 500 hPa height and relative vorticity of 30 December 1997 at 00:00 UTC.
d. Profiles of Potential Temperature [K], Brunt-Väisälä Frequency [rad/s], Relative Humidity [%], Wind Direction (from) [deg], and Wind Speed [m/s] obtained from sounding data acquired at Goose Bay.
e. RADARSAT ScanSAR Wide at 09:50 UTC (500km by 1000km) (© CSA 1997).
f. NOAA 12 AVHRR channel 4 at 11:11 UTC. The coverage of the RADARSAT image of Fig. 3e is indicated.
g. RADARSAT ScanSAR Wide at 21:19 UTC (500km by 1000km) (© CSA 1997).
h. NOAA 12 AVHRR channel 4 at 21:08 UTC. The coverage of the RADARSAT image of Fig. 3g is indicated.

Fig. 4. Case 2: 1 January 1998:

a. RADARSAT ScanSAR Wide at 21:30 UTC (500 km by 1000 km) (© CSA 1998).
b. NOAA 12 AVHRR channel 4 at 21:28 UTC. The coverage of the RADARSAT image of Fig. 4a is indicated.

Fig. 5. Case 3: 15 January 1998:

a. RADARSAT ScanSAR Wide at 21:18 UTC (500 km by 1450km) (© CSA 1998).
b. NOAA 12 AVHRR channel 4 at 21:19 UTC. The coverage of the RADARSAT image of Fig. 5a is indicated.