Canadian Atlantic Storms Program: Progress and Plans of the Meteorological Component

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Abstract

The Canadian Atlantic Storms Program (CASP) field project was conducted from 15 January to 15 March 1986 over Atlantic Canada in conjunction with the American Genesis of Atlantic Lows Experiment (GALE). The goals of CASP were to begin the process of understanding and eventually better predicting the mesoscale structure of East Coast storms as well as the storms themselves. Conceptual models of the storms have been formulated, the nature of cyclogenesis and the structure of frontal surfaces have been investigated, and precipitation regions and precipitation type transitions have been studied. Numerical weather simulations have been used to better understand critical parameters affecting storm behavior and improvements in instrumentation have been made. Future research activities are needed to better understand the interaction of the storms with surface features such as coastlines and sea ice.

1. Introduction

The Canadian Atlantic Storms Program (CASP) field project was conducted from 15 January to 15 March 1986. This field project represents the first step towards reaching the long-term goal of the meteorological component of CASP which is to improve the prediction of the mesoscale structure of Canadian East Coast winter storms as well as the storms themselves. A detailed overview of the field project operations and objectives is contained in Stewart et al. (1987).

The field project area is illustrated in Fig. 1. Enhanced rawinsondes were released into the storms from a number of operational and portable sites, radar coverage was expanded at the indicated locations, surface mesonets were operated on Nova Scotia and Sable Island, and a multi-channel radiometer and special precipitation measurements were made at Shearwater, Nova Scotia. In addition, two instrumented aircraft penetrated a number of storm features. In a companion oceanographic program, sea state and other oceanographic parameters were measured along the southern coast of Nova Scotia (Anderson et al. 1989).

During the field project, 16 storms were sampled. A number of the storms underwent rapid deepening, some produced heavy snowfall, and all produced freezing precipitation. As described by Dirks et al. (1988), many of these storms had also been previously sampled over the United States as part of the Genesis of Atlantic Lows Experiment (GALE).

The purpose of this article is to summarize the progress that has been made towards the long-term goals of the meteorological component of CASP. Plans for future activities will also be discussed.

2. The nature of Canadian east coast winter storms

CASP represented the first major Canadian effort designed specifically to improve the prediction of storm and mesoscale features. Because of the pioneering nature of the project, a number of studies were conducted in order to characterize the basic nature of the storms.

Conceptual models of typical East Coast storms have been developed (Fig. 2). As illustrated in the study by Stewart and Macpherson (1989), a typical storm can be described as being a split-frontal system with the upper cold front oriented parallel to but generally moving faster than the surface cold front. This conceptual model of the overall features of the storms is similar to that found by, for example, Carlson (1980) and Browning and Monk (1982) and it is similar to the structure of some GALE storms, as observed by, for example, Martin et al. (1990). This organization is also similar to that proposed some time ago for storms over Canada, as discussed by, for example, Crocker et al. (1947) and Godson (1950). They had proposed a 3-front model of storms in which warm air was aloft ahead of the surface cold front, as has been confirmed in the CASP observations. One difference between the CASP conceptual model and some of the other work was that there can be two cold conveyor belts. The most distinct one is associated with the warm front as in the other studies but a weaker one may occur in the warm sector as well. This latter conveyor belt can undercut the ascending warm air and can give rise to strong temperature inversions in that region.

The nature of surface fronts has been found to vary substantially. In most storms, the cold and warm fronts are distinct (an example is shown in Fig. 3). In other storms, the surface cold front can essentially be ab-

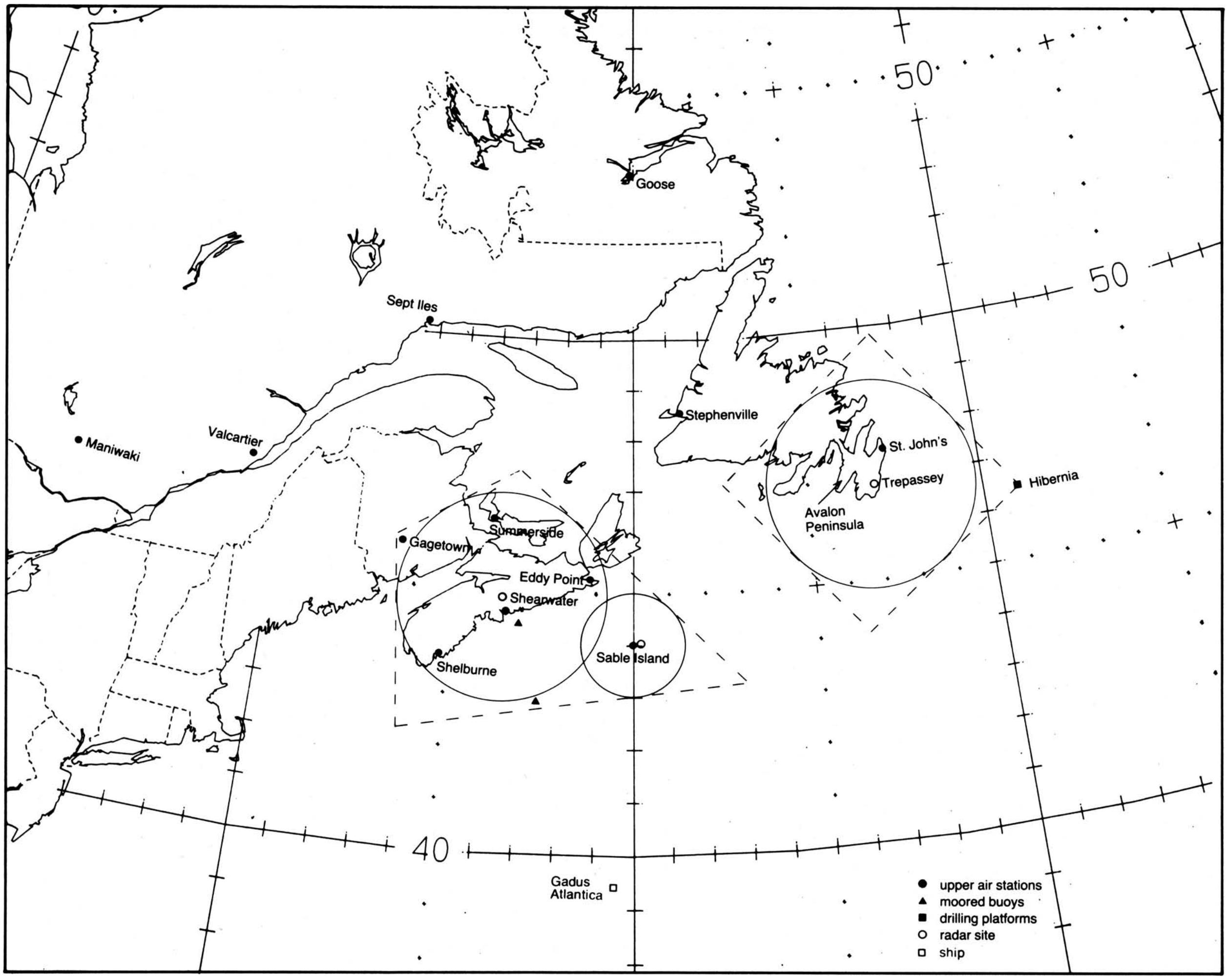

FIG. 1. The CASP project area.

sent (Donaldson and Stewart 1989). Martin et al. (1990) also found that some of the storms sampled during GALE had no apparent cold front. When distinct, the temperature variations across either the warm or cold front are typically only about 2-3°C and the distance over which these temperature changes occur varies from about 30 km to over 100 km (Taylor et al. 1991). Such fronts are much weaker than some cases observed elsewhere (see, for example, Shapiro 1984). The typical presence of distinct warm fronts is also in contrast to the nature of some storms observed elsewhere in which the warm front is very diffuse (see, for example, Browning and Monk 1982).

Precipitation associated with the systems was normally organized into precipitation bands. As discussed by Donaldson and Stewart (1989), precipitation on the north side of the storm systems was generally characterized by fairly narrow bands of the order of 40 km wide (Fig. 4). Only one such band can occur or several can exist. It is not uncommon for such bands to dissipate once they strike the coastline although this is not always the situation.

As observed elsewhere (see, for example, Hobbs 1978), precipitation associated with the warm front is also normally characterized by banded structures (Fig. 4). Such bands are normally of the order of 100 km across and are oriented parallel to and less than 200 km ahead of the surface front. These bands are relatively steady state in appearance as they move over the region.

Precipitation linked to the upper level front is also typically associated with banded features. In contrast to the other forms of bands, these show considerable variation. In particular, the western flank of these bands is believed to be characterized by convection and consequently by changing patterns of precipitation, whereas the eastern side is more characteristic of steady state conditions. Such observations are again quite similar to that reported elsewhere by, for example, Hobbs (1978).

In contrast to the banded structure associated with the warm and upper cold fronts, the passage of the surface cold front is seldom linked with substantial precipitation. There were no clear-cut cases in which

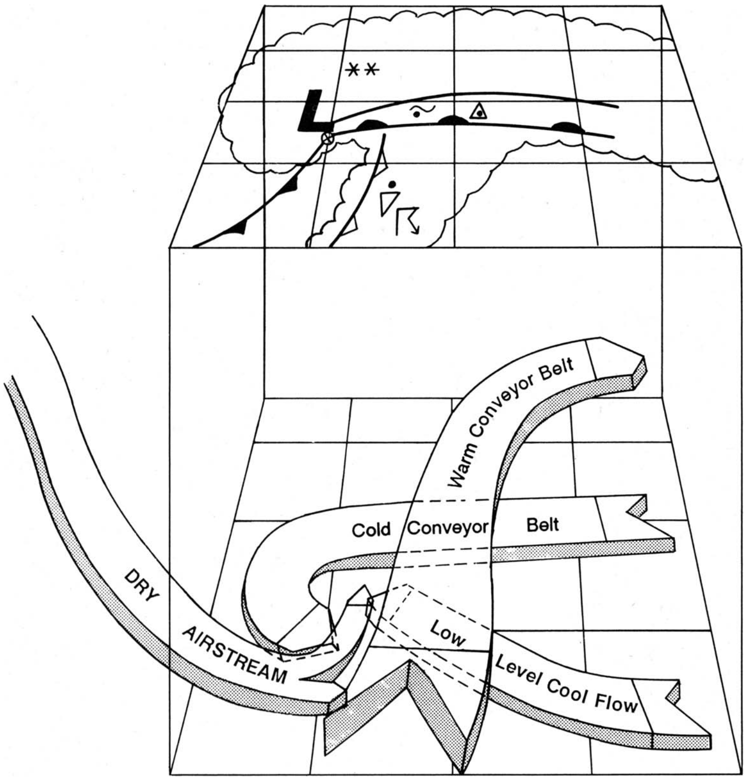

FIG. 2. Schematic of the flow field within a storm at 1200 UTC on 11 March 1986. The standard symbols are used for denoting precipitation types (adapted from Stewart and Macpherson 1989).

either a narrow or a wide band was linked directly with the surface cold front. In contrast, such bands are quite common over the Pacific west coast (Hobbs 1978).

The nature of the precipitation itself varies considerably within these storms. Within each storm, the precipitation typically varies between snow, freezing rain, ice pellets, and rain. No hail or graupel was ever reported although snow pellets, heavily rimed snowflakes, sometimes occur. The snow is typically located ahead of and north of the low pressure center and warm front. The bands associated with the warm front normally represent the region of heavy snow, and the eastern or southern flank of these bands coincides with the location of freezing precipitation (Stewart and Patenaude 1988). Within the warm sector, precipitation is in the form of rain.

3. Processes occurring within the storms

Considerable progress has been made in modeling storm evolution and storm features. Numerical simulations of rapidly deepening storms in the vicinity of Atlantic Canada have revealed that the fluxes from the Gulf Stream typically play a crucial role in the deepening process by providing the needed moisture for the system to evolve (Mailhot et al. 1989; Mailhot and Chouinard 1989). The development and maintenance of a warm low level jet just ahead of the surface cold front furthermore appears to be critical for explaining the deepening behaviour of the storms. It is critical therefore to properly account for the low level air-sea interactions within operational prediction models. Grossman and Betts (1990) discussed some aspects of these interactions using GALE observations. Critical attention in general needs to be paid to the role of subsynoptic scale features on storm evolution, a point also recently mentioned by Wash et al. (1990).

Yau and Jean (1989) estimated that about half the deepening rates of storms could be explained on the basis of quasi-geostrophic forcing. For their estimates, they used a version of the Sanders (1971) analytic model. They also showed that forced baroclinicity near the Atlantic coastline can play an important role in storm evolution. Although few specialized measurements were made of coastal baroclinic zones in CASP, this was an area of considerable interest to GALE, as reported by, for example, Riordan (1990) and Doyle and Warner (1990).

Ford and Moore (1990) examined one small-scale CASP storm which occurred on February 5-6, 1986. They found that this storm possessed a horizontal length scale of 1200 km, a vertical scale of 4 km, and a rapid growth rate. Traditional theories of baroclinic instability which use some approximation to the primitive equations cannot adequately describe such storms. However, a linear stability analysis employing the hydrostatic primitive equations with a realistic 2-dimensional frontal zone as the basic state has recently been developed (Moore and Peltier 1987). The structure and evolution of a particular mode of instability revealed by this analysis, the cyclonic-scale mode, closely resembles that of this particular storm.

Until CASP, little work had been conducted on slantwise convective instability within Canadian storms. In contrast, a great deal of work has been conducted elsewhere on the importance of this instability on the nature of storms and precipitation bands (see, for example, Bennetts and Hoskins 1979; Emanuel 1983; Emanuel 1985; Seltzer et al. 1985; Knight and Hobbs 1989). As indicated in the studies by Donaldson and

Stewart (1989) and Reuter and Yau (1990), it appears that the atmosphere in Atlantic Canada winter storms is often in a state of near-neutrality or slight instability with respect to slantwise convective instability. In the lower, normally saturated, levels of the atmosphere, it would be expected that this instability would normally be realized. Consequently, this instability may be responsible for the formation of some of the precipitation regions observed within Atlantic Canada storms.

Studies have also pointed out that the phase changes of the precipitation affect the structure of the storms. As proposed by Lin and Stewart (1986) and Szeto et al. (1988a,b), the variation in the gradient of melting snow will lead to a mesoscale circulation characterized by ascent over the snow region. Although a complete understanding of the influence of phase changes must incorporate all phase changes such as evaporation and sublimation, some of the observations are quite consistent with these melting-induced circulation concepts (Stewart and Patenaude 1988; Stewart and Macpherson 1989; Stewart et al. 1990a). Within precipitation type transition regions, phase changes of precipitation have furthermore contributed to the production of layers sometimes over 1 km deep with temperatures near-0°C (see, for example, Stewart and Patenaude 1988; Stewart et al. 1990a). The consequent strong stability of the atmosphere in these regions may provide an ideal environment for gravity waves (Robichaud and Lin 1989). Although the theoretical development of dynamics associated with precipitation phase changes has so far only considered a 2-dimensional situation, the extrapolation of these results to 3-dimensions was proposed as being important in defining stormscale features (Stewart and Macpherson 1989; Stewart and Donaldson 1989; Stewart 1991). The vertical separation between the warm and cold conveyor belts exactly at 0°C as observed in CASP and by Carlson (1980) and low centers close to 0°C as observed in CASP and by Eagleman (1983) are consistent with these suggestions.

Some storm features were linked to the coastline. A particular example of this is the production of heavy snow and freezing precipitation close to the coastline (Stewart et al. 1990a). The aircraft observations in one storm producing record snowfalls were quite consistent with the concept that the imposed surface temperature gradient across the (warm) ocean- (cold) land interface works in combination with surface roughness changes to maintain precipitation near the coastline. The precipitation types vary in such a situation with snow and freezing precipitation occurring over the land and rain occurring over the ocean. The net effect of the couplings at the coastline also may lead

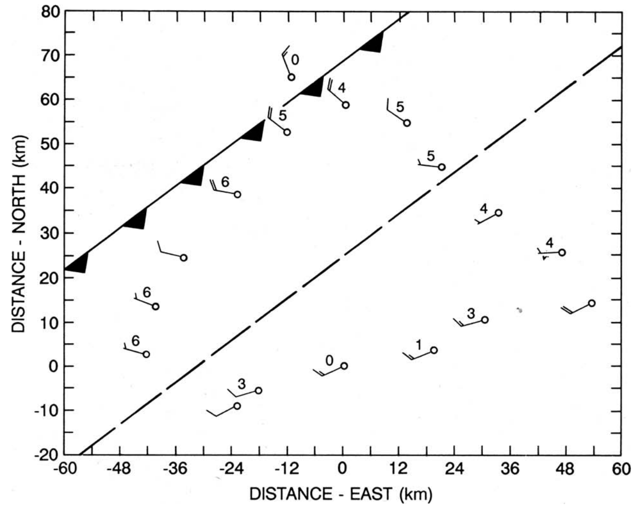

FIG. 3. Surface mesonet observations over Nova Scotia of a cold front at 0030 UTC on 12 February 1986. The approaching cold front and the major wind shift line (dashed) are shown. Long wind barbs correspond to 10 m s^{-1} and short ones to 5m s^{-1}. Temperatures (°C) are also shown if available. The southern line of stations lies along the Atlantic coastline.

to the production of convergence at the coastline from both the land and ocean.

Although the studies on symmetric instability pointed out that it may often be present, it must be remembered that precipitation bands are often detected by radar. Radar information consists of the backscattering of electromagnetic information from precipitation. In the vicinity of the precipitation type transition region, the complex nature of the precipitation may lead to the detection of enhanced reflectivities. It is well-known that in stratiform clouds there is often a radar bright band (see, for example, Battan 1973). Observational studies have confirmed that much of this enhanced reflectivity results from the presence of large wet snowflakes (see, for example, Stewart et al. 1984; Willis and Heymsfield 1989). In the precipitation type transition region, such snowflakes have been observed aloft and at the surface (Stewart et al. 1990b; Raga et al. 1991). Viewed on a horizontal radar scan, the region of these particles reaching the surface would appear as a precipitation band (Stewart et al. 1990a; Stewart and King 1990).

The transition region between snow and rain represents a major feature of the storms. This feature, often including freezing precipitation, is normally of the order of 100 km across and it extends laterally for hundreds of kilometers. Within the transition region, the precipitation sometimes follows a 5-step pattern of precipitation type combinations involving snow, freezing rain and ice pellets (Stewart and King 1987; Stewart and Patenaude 1988). Precipitation rates can be high in this region as well. This is due in part to the variation of particle terminal velocity (Stewart et al.

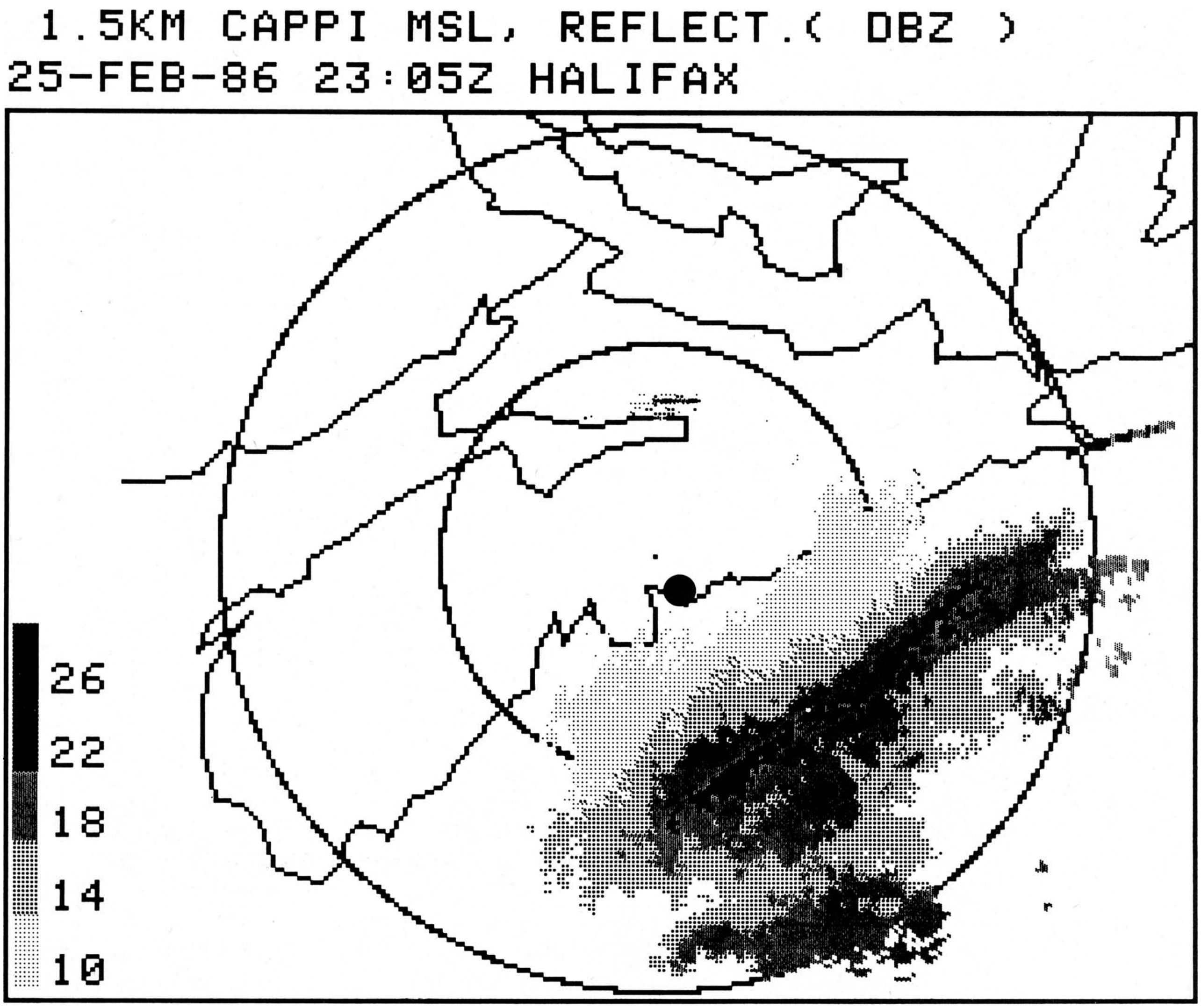

FIG. 4. Radar picture showing a precipitation band about 200 km north of a low pressure center at 2305 UTC on 25 February 1986. The range rings are at 100 and 200 km. Reflectivities are in units of dB(Z_e) and the dot shows the location of Shearwater where a number of enhanced observations were made (adapted from Donaldson and Stewart, 1989).

1990a). Partially melted particles falling slower than raindrops would be carried toward this region from upwind warmer areas, whereas large snowflakes falling faster than smaller ones (Auer 1971) would fall into this region rather than being carried further downwind towards colder areas.

4. Impacts of the storms

Studies of the interaction of the storms with the underlying sea ice and ocean have been conducted. Such studies have been very limited in the case of sea ice however. In the often ice-covered Gulf of St. Lawrence, no crucial current measurements could be taken and so modeling studies could only use climatological values (Nerella 1990). Model calculations showed little dependence on whether these climatological currents were used or not. For short-term prediction, much better current information is need (Hibler and Bryan 1984). In contrast to the lack of appropriate data for sea ice studies, a major effort was mounted to examine the oceanographic response to the storms. A summary of the research conducted within the oceanographic component of the project was reported by Anderson et al. (1989). In addition, a test of several operational wave forecasting models was carried out (Khandekar 1989). Where wave measurements were available for comparison, the model results provided a reasonable degree of confidence. There was nevertheless a lack of appropriate validating observations away from coastal areas.

Hazardous aircraft flying conditions have also been studied (Macpherson and Isaac 1989). Hazardous conditions included heavy snow limiting alternate airport landing sites, airframe icing, and strong low level wind shears on landing. Heavy icing situations within some precipitation bands were generally characterized by large cloud droplet sizes and sometimes also by the presence of snow. Strong low level wind shears were generally linked to frontal passages. However, the degree of this shear was sometimes very dependent upon the aircraft's location with respect to the coastline, with the highest shears along the coast and less inland.

Ice and snow accretion can cause a large amount of damage in these storms. Using an accretion measuring instrument, it was shown that accretion was attributable to a number of types and combinations of precipitation (Stewart et al. 1990c). To acceptably understand accretion, careful attention must be placed on the environmental temperatures and winds as well as the nature of the precipitation. Particles comprised of both liquid and solid, such as wet snow, are believed to sometimes contribute to rapid accretion.

5. Observational improvements

Improvements in the use of instruments have also been achieved. Information from satellite, radiometer, mesonet towers, and surface precipitation instruments has been examined in particular.

GOES satellite information has been examined in order to infer features of the cloud and environment over the ocean. Garand (1989) found that similar detection of precipitation probabilities were obtained if one used either a cloud type classification or if one used a cloud top and cloud albedo method. Garand (1988) and Garand et al. (1989) furthermore showed that the use of a cloud classification scheme led to a method of inferring air temperature and humidity anomalies over the ocean.

Progress in using use polar-orbiting satellite information has also been made. The data sets available from CASP have been used for assimilating microwave TOVS radiances into the Canadian regional analysis system (Steenbergen et al. 1989). The technique follows the nonlinear optimal estimation approach of Eyre (1989). Alteration to the conventional temperature analysis was most pronounced below 70 kPa. In contrast, alteration to the water vapor analysis was most pronounced above this level.

It has been demonstrated that a multi-channel radiometer can provide extremely useful information on the nature of the storms. The temperature information obtained with this instrument corresponded well with colocated rawinsonde information (Blaskovic et al. 1989). Furthermore, the instrument quite accurately detects the presence and amount of liquid water within the clouds as revealed through intercomparisons with instrumented aircraft. Within the two storms studied in detail, the highest integrated liquid water contents were either associated with the surface fronts or were within the warm sector.

An understanding of the boundary layer has been used to develop a method of deducing wind field information over the open ocean from, for example, beach-based or drilling rig wind measurements (Walmsley 1988). The technique has been successfully applied to data over Sable Island.

A remote-sensing device for the automatic detection of precipitation and its type has been found to be extremely valuable (Sheppard 1990). It was shown that it could reasonably-well detect the transition in precipitation types at the surface (Stewart et al. 1990c). The ongoing development of this relatively-low cost instrument is crucial to the automated detection of precipitation types in winter storms.

6. Operational experience

During the field phase of CASP, a special forecasting center was operated (Macdonald et al. 1988). In addition to the regular forecast tools, this office was equipped with graphical displays to present a number of products including special numerical guidance information. This office also had real-time access to 3-h rawinsondes, mesonet data, radiometer data and special observer reports.

As a result of operating this office, the forecasters developed a great appreciation for the requirements of future mesoscale forecasting. They felt that a single powerful workstation capable of assimilating and displaying products from a number of sources is essential. This must be coupled with the necessary communications links. They also pointed out that the types of observations must be appropriate to the nature of the phenomena and that sites for such observations must be well-chosen to maximize the usefulness of the data to the forecaster.

7. Concluding remarks

As part of a long term commitment to improve the prediction of storms and mesoscale features in Atlantic Canada, a field project was mounted during the winter of 1986. Analysis of information obtained from this project has proceeded since that time and substantial progress has been made towards achieving the long term goals. The analysis has, for example, shown that the storms exhibit an organization similar to that seen elsewhere, although the occurrence of a variety of precipitation types has not been studied extensively before. The geographical setting of the warm Gulf Stream to the south and the cold, often snow-covered, land represents a unique situation which can sometimes assist in rapid storm evolution and it can also result in the establishment of heavy-precipitation producing regions along coastlines.

Although CASP was very successful, it has also become apparent that another field project is needed. This time the focus will be on the weather affecting the Avalon Peninsula/Hibernia region (See Fig. 1). Consequently, the CASP II field experiment will be conducted over this region from 15 January to 15 March 1992.

A major concern of CASP II is sea ice. In late winter and spring in particular, the southern advance of sea ice moves into the area. Both pack ice and icebergs can occur there. The behaviour of this ice is of grave concern to offshore interests. The storms of course play a major role in determining the behaviour of this ice.

In addition, studies from CASP have indicated the importance of the coastline in determining the nature of storm features. Although it is believed that the basic processes through which the interaction occurs will be the same, the jagged Avalon Peninsula coastline will undoubtedly have a much more complicated effect on the storms than the almost linear southern Nova Scotia coastline.

CASP II will be able to utilize improved observational capabilities. To properly monitor the 3-dimensional kinematic and thermodynamic fields over the ocean and ice fields, a dropsonde capability utilizing a cross-chain Loran system will be used. This dropsonde facility was developed at the National Center for Atmospheric Research. The National Aeronautical Establishment Convair aircraft will be the principal platform for the project. It will be used for dropsonde missions, as well as for in-situ observations. To properly measure the low level winds associated with very strong shears in the lowest few hundred meters, a portable Doppler radar will also be available. These instruments will be augmented by enhanced rawinsonde observations, a small network of surface weather stations, and special precipitation observations. The oceanographic component of the project will operate a ship in the Hibernia area and will deploy a number of instruments to observe the oceanographic and sea ice response to the storms.

Although not specifically directed towards the better short term prediction of weather, it should be pointed out that the result of the increasing understanding of these storms, their mesoscale structure, and their precipitation production will also affect other fields. Climate studies in particular will be a major beneficiary of the ongoing progress being made from projects such as CASP. For example, CASP II promises to lead to a better understanding of the interaction between the atmosphere, sea ice and the ocean. This interaction is a major concern of those modelling the climate (see, for example, Mysak and Manak 1989).

In summary, the field phase of CASP was a resounding success, the analysis phase has proceeded well, forecasting applications are being developed, and a future project based upon the experiences of CASP is being planned.

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