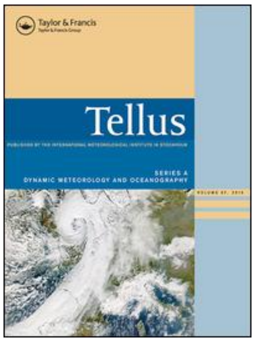

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The synoptic climatology of polar low outbreaks

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The synoptic climatology of polar low outbreaks

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ABSTRACT

The evolution of the 500 mb height field has been analysed during outbreaks of well-developed polar lows over the Norwegian and Barents Seas using a "superposed epoch method" to composite the data. 42 cases were selected on the basis of synoptic and surface data. In addition, 10 independent cases were chosen on the basis of infrared satellite imagery. To further describe the synoptic climatology of polar low outbreaks, 500 mb temperature, 1000–500 mb thickness, and surface pressure data were each composited for the combined 52 cases of the superposed epoch studies. In order to provide a background from which to evaluate the results of the composite studies, a brief case study of a typical polar low development over the Barents Sea is given.

The results of the composite studies reveal the presence of significant negative anomalies in both the temperature and height fields at the 500 mb level over the Norwegian and Barents Seas, indicating strong positive vorticity and very low static stability over the area on the days when mature polar lows were present. The evolution of the height anomaly pattern shows ridging along the west coast of Greenland, and the development of a trough north of Norway, resulting in a northerly component of the flow aloft and at the surface over the Norwegian Sea, as much as 3 days prior to the outbreak of polar lows. The northerly surface flow results in the development of low-level baroclinicity. Evidence suggests that a rapid deepening, characteristic of polar lows, occurs coincident with the outbreak of deep convection. It is suggested that the outbreak of convection is organized by the baroclinicity.

The evolution of the negative height anomaly just prior to polar low outbreaks is suggestive of forcing by a migratory short wave aloft. The 1000–500 mb thickness composite supports this view, with the presence of some deeper baroclinicity across the Norwegian Sea. However, comparison of the surface and thickness composites reveals only slight asymmetries in the respective contours, indicating that the atmosphere was nearly equivalent barotropic on the days when strong polar lows were present over the region. The *in-situ* evolution, and wavelength of the height anomaly pattern suggest that topographical forcing by the high Greenland Plateau, juxtaposed with the warm water of the Norwegian Sea, may enhance the development of polar low outbreaks off the Norwegian coast.

1. Introduction

Fishermen off the Norwegian coast, not to mention Norwegian meteorologists, have long been aware of subsynoptic-scale storms that develop rapidly over the Norwegian Sea and can unexpectedly strike the Norwegian coast with sharp falls in pressure, high winds and dangerous seas (Rabbe, 1975). In recent years, satellite photography has revealed a multitude of mesoscale and small synoptic-scale vortices in cold air masses poleward of the polar front (Forbes and Lottes, 1982). Although interest in these disturbances is increasing, classification of well-developed vortices on the basis of their underlying physical mechanisms remains a challenge. However, inspection of photographs taken by polar-orbiting satellites over high-latitude oceans, and the scientific literature in recent years, support the view that mature "polar" vortices can be divided into two broad categories: "comma clouds", which are large mesoscale to small synoptic-scale, comma-shaped cloud patterns that develop in regions of enhanced positive vorticity advection at mid-tropospheric levels (Reed, 1979; Locatelli et al., 1982), and "polar lows" (sometimes referred to as "arctic instability" lows), which are smaller, spiral-shaped cloud patterns that form well into the cold air away from deep baroclinicity associated with the polar front (Rasmussen, 1979, 1981, 1983, 1985; Wilhelmsen, 1981). It is not the intent of this paper to argue the validity of this division; utility in the subsequent analysis is considered sufficient reason to use it here. For a further discussion of the characteristics of comma clouds, the reader is referred to Mullen (1979, 1983) and Locatelli et al. (1982). The remainder of this paper is concerned with the characteristics and climatology of polar lows.

2. Characteristics of polar lows

The following is a summary of the characteristics of polar lows and the environments in which they form as deduced from satellite photographs, standard synoptic data, the Arctic Cyclone Experiment (ACE) (Fedor, 1984), and the results of the work described in the following sections.

—Tight spiral cloud pattern, generally asymmetrical, indicative of rotational motion superimposed on slow translational velocity (Fig. 1).

—Generally limited to the winter half-year (October through April in this study).

—Dimensions: 200–500 km in diameter.

—Conditionally unstable through a substantial depth, with below average temperatures at the 500 mb level (Figs. 2 and 8a).

—Form beneath regions of low geopotential heights, poleward of strong middle and upper tropospheric jet streams (Fig. 2).

—Form over open water, where strong surface heat and moisture fluxes result in rapid destabilization of the boundary layer air; polar lows tend to fill as they pass over land (Fig. 4). (K. Wilhemsen, personal communication).

—Typically accompanied by convective showers or thunderstorms (Rabbe, 1975).

—Strongest cyclonic circulation occurs near the surface and weakens upward, consistent with the hypothesis that polar lows may have a warm core at lower levels; satellite photographs reveal a "clear eye" in some cases (Rasmussen, 1983).

—Form in regions where a secondary, low-level baroclinic zone exists most of the time, associated with the close proximity of ice or snow covered surfaces and warm open water (Fig. 5).

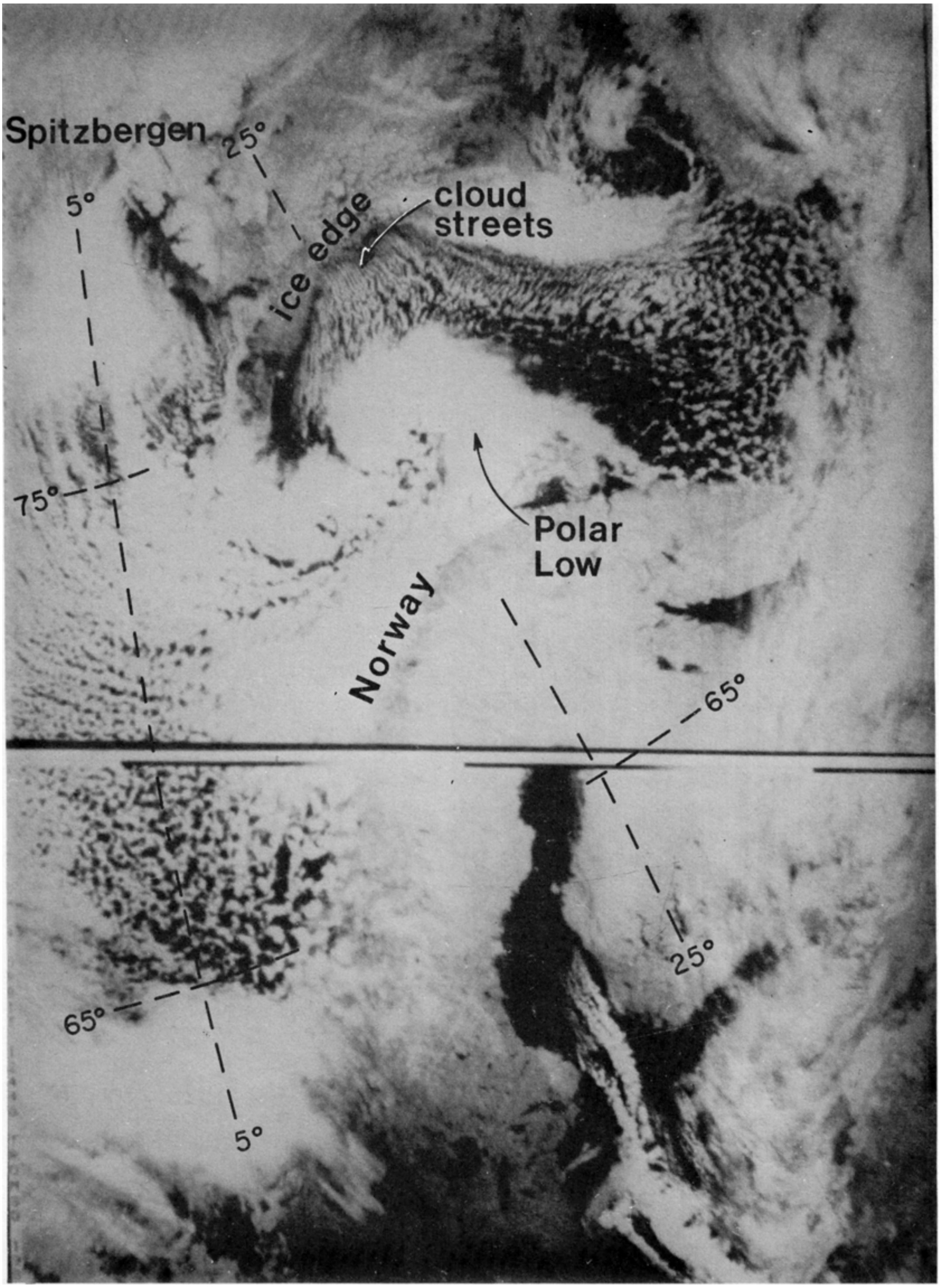
Along the ice margin off the east coast of Greenland, and in the Barents and Norwegian Seas, strong low-level baroclinicity exists due to contrasts in the boundary layer over open water and over ice covered surfaces (note the surface temperature gradient between Bear Island (−17 °C) in the Barents Sea, and the northern coast of Norway (−4 °C) in Fig. 3c). This low level baroclinicity may play an important role in the formation of polar lows, which usually occur in conjunction with outflows of surface air from ice and snow covered regions over open water. These outflows are characterized by the presence of cloud streets in the boundary layer (Brown, 1980). In more than two thirds of the cases studied here, satellite photographs revealed cloud streets in the vicinity of mature polar lows (Fig. 1).

3. A case study of a polar low

In order to document some of the characteristics of polar lows discussed in Section 2, and to provide a broader background from which to evaluate the results of the composite studies given in the following section, a brief presentation of a case study of a polar low development over the Barents Sea will be given in this section. This case is typical of the polar low developments over the northern Norwegian Sea and Barents Sea used in the composite studies.

Following the passage over Scandinavia of a strong, occluded frontal system, a deep, upper-level low dominated the middle troposphere to the north of Norway on November 20, 1983. This closed low, centered over the Barents Sea, remained nearly stationary for several days. Fig. 2a shows the 500 mb heights and temperatures for 12 GMT November 21, 1983. At this time, a small synoptic-scale vortex and very cold temperatures were present at 500 mb in the vicinity of Spitzbergen. Inspection of

Fig. 1. Polar low and cloud streets over the Barents Sea; 0320 GMT November 22, 1983. NOAA-7 infrared satellite photograph.


Spitzbergen
25°
5°
cloud
streets
ice edge
75°
Polar
Low
Norway
65°
25°
65°
5°

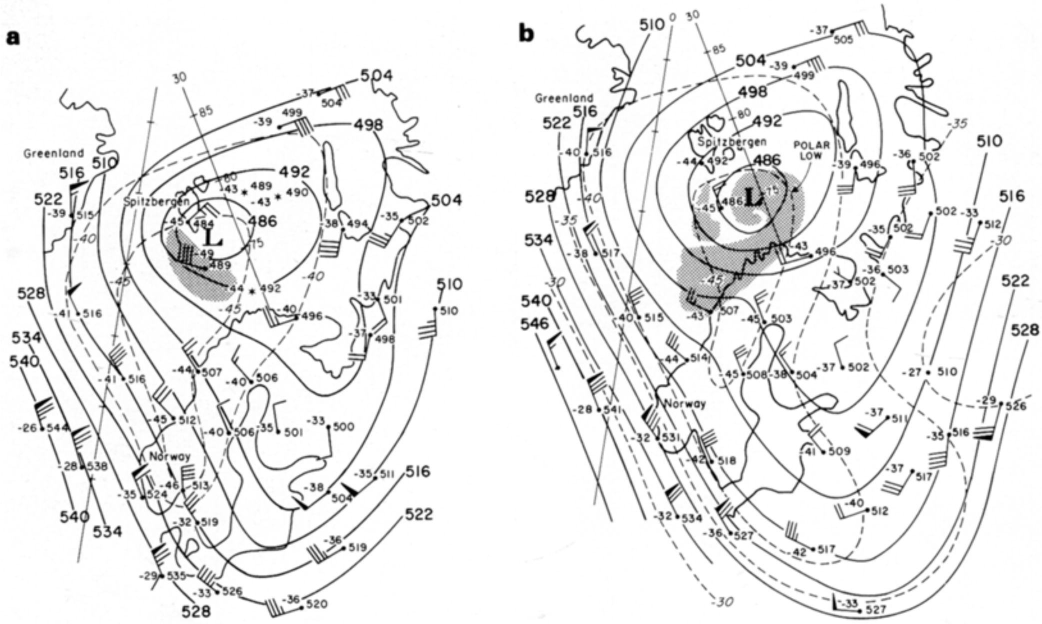


Fig. 2. 500 mb heights (solid contours, interval: 60 m) and temperatures (dashed contours, interval: 5 °C), shaded regions indicate the approximate extent of the cloud cover derived from satellite photographs: (a) 12 GMT November 21, 1983, (b) 00 GMT November 22, 1983.

500 mb data shows that this small vortex can be traced back to a region north of Novaya Zemlya on the previous day.

The infrared satellite image at 10 GMT November 21 (not shown), reveals the presence of cloud streets indicating a northerly flow direction at low levels west of Spitzbergen, and a cloud shield associated with an incipient polar low. The extent of this cloud cover is given in Fig. 2a. The corresponding surface pressure field for 12 GMT November 21 (Fig. 3a) indicates the presence of a trough extending south along the west coast of Spitzbergen curving eastward over the Barents Sea to the south of Bear Island. Although details of the mesoscale temperature and moisture distribution in the boundary layer are not available from the data, it is likely that low level baroclinicity and positive vorticity are a maximum in the boundary layer in the vicinity of the surface pressure trough at this time. The northerly flow direction to the west of Spitzbergen results in a rapid modification, and reduced static stability of the boundary layer over the open water, with cold unmodified air further east; a configuration which is favorable for the formation of strong baroclinicity in the boundary layer, and a resulting low-level jet along the west coast of Spitzbergen (Fedor, 1984; M. Shapiro, personal communication).

As the 500 mb level vortex slowly tracked southward over the Barents Sea during the following 12 hours (Fig. 2b), rapid deepening occurred at the surface along the northern coast of Norway. The most rapid pressure falls (12 mb in 6 hours) occurred just north of Norway over the region of maximum sea surface temperature over the Barents Sea (Fig. 5) during the 6 hours between 12 GMT and 18 GMT November 21. Evidence from satellite imagery indicates that an outbreak of strong convection along the axis of the surface trough was coincident with the rapid deepening at the surface. Fig. 3b gives the surface pressure field for 18 GMT. Fig. 3c gives the surface pressure field for 12 GMT November 22, at the time the polar low was most well developed. The shaded region shows the approximate extent of the cloud shield associated with the polar low and was taken from the satellite photograph shown in Fig. 1.

Radiosonde data from Bear Island, Bodø (Norway) and, Murmansk (USSR) were inspected preceding and following the polar low development

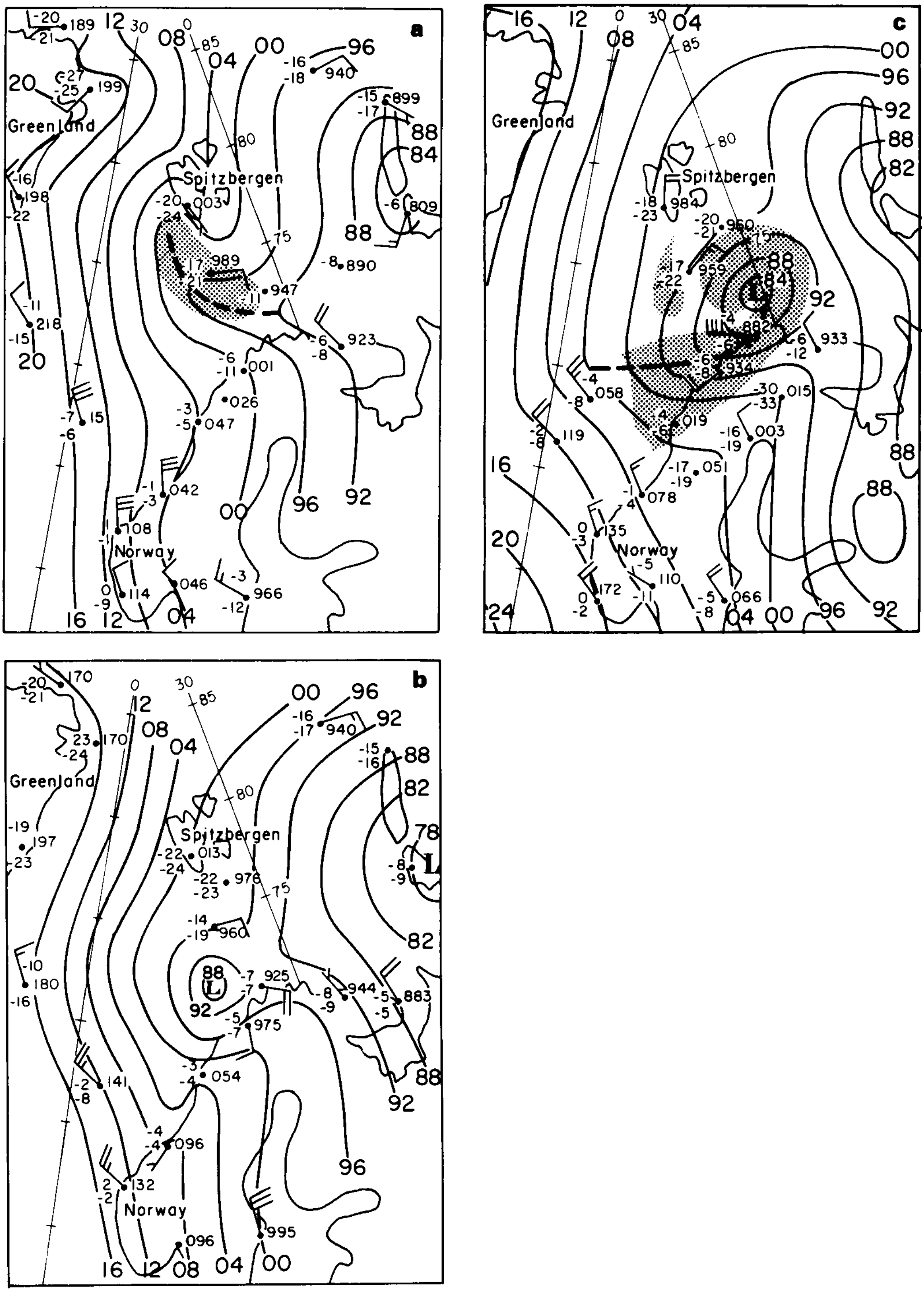


Fig. 3. Surface maps showing polar low development: (a) 12 GMT November 21, 1983, (b) 18 GMT November 21, 1983, (c) 00 GMT November 22, 1983.

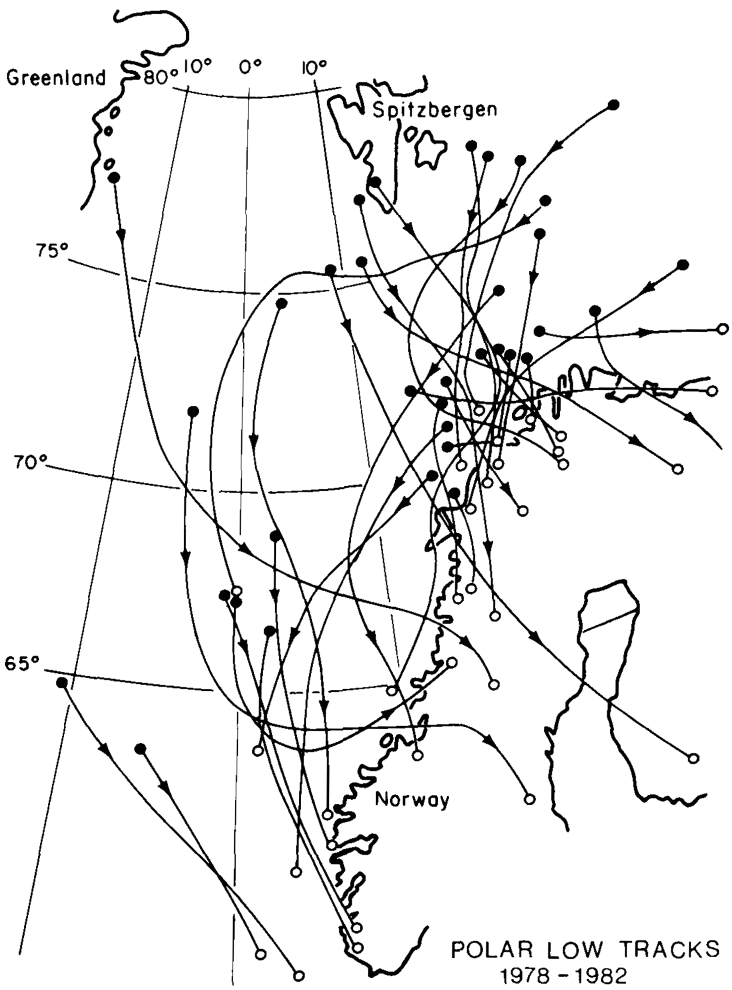


Fig. 4. Paths of polar lows over the Norwegian Sea 1978–1982 (K. Wilhelmsen, personal communication). Closed circles indicate point of origin, open circles indicate final position.

in an attempt to evaluate the spacial and temporal distribution of static stability in the vicinity of the polar low. Cold surface temperatures at Bear Island combined with low dew point temperatures resulted in statically stable soundings through the troposphere throughout the development period. However, surface air at Bodo was warmed to −3 °C and its dew point temperature rose to −4 °C by its passage over the warm open water to the north, resulting in conditionally unstable soundings to near 650 mb at 12 GMT November 21, as well as 00 GMT November 22. Although the air aloft remained cold, a gradual drying of the air near the surface increased the static stability over Bodo by 12 GMT November 22. The soundings over Murmansk showed the atmosphere to be neutrally stable for moist ascent to 700 mb at 12 GMT November 21, and 00 GMT November 22, while markedly colder and dryer boundary layer air from the interior of the continent resulted in a stable sounding at 12 GMT November 22.

Despite increasing stability observed with time in the sounding data after 00 GMT November 22, satellite photographs and surface pressure analyses show that the polar low maintained its strength while remaining nearly stationary over the Barents

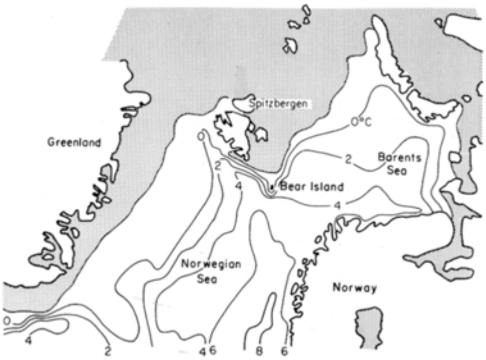


Fig. 5. Sea surface temperature (°C) and extent of the ice edge (shaded area) for February 9–12, 1984 (from the Norwegian Meteorological Institute).

Sea at 30° east longitude just north of the Norwegian coast, during the twelve hours between 00 and 12 GMT November 22. The polar low remained quasi-stationary over this position for another 24 hours while gradually filling.

4. Superposed epoch analysis

The 500 mb charts (Fig. 2) presented in Section 3 provide evidence of the importance of the middle troposphere to the development of polar lows. To further investigate this relationship, a compositing of National Climate Center (NMC) data was undertaken for a number of well-developed polar low cases that occurred in the region encompassed by the Norwegian and Barents Seas. Since this region is of limited extent, polar lows that form here lend themselves to analysis by a technique called "superposed epoch analysis" (Panofsky and Brier, 1965). Following this technique, the dates of all polar lows that developed to a mature stage, roughly in the triangle formed by Greenland, Norway, and Spitzbergen, during the period from 1970 through 1982, were noted, and termed "key days". The NMC 500 mb height data for the northern hemisphere for each of the key days were then averaged to obtain a 500 mb "polar low climatology" for that region. An anomaly map was then computed by subtracting the seasonal mean 500 mb height field (Fig. 6) from the polar low climatology field, thus indicating where the synoptic pattern was above or below the seasonal mean

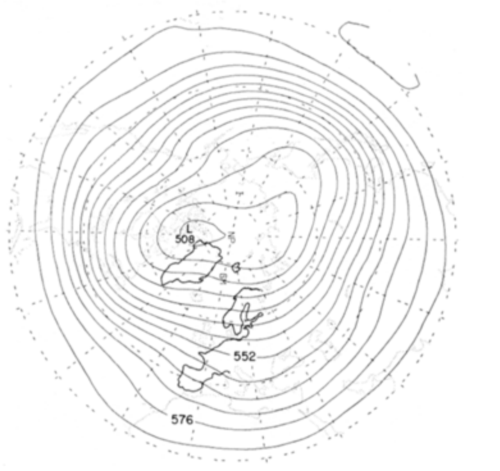
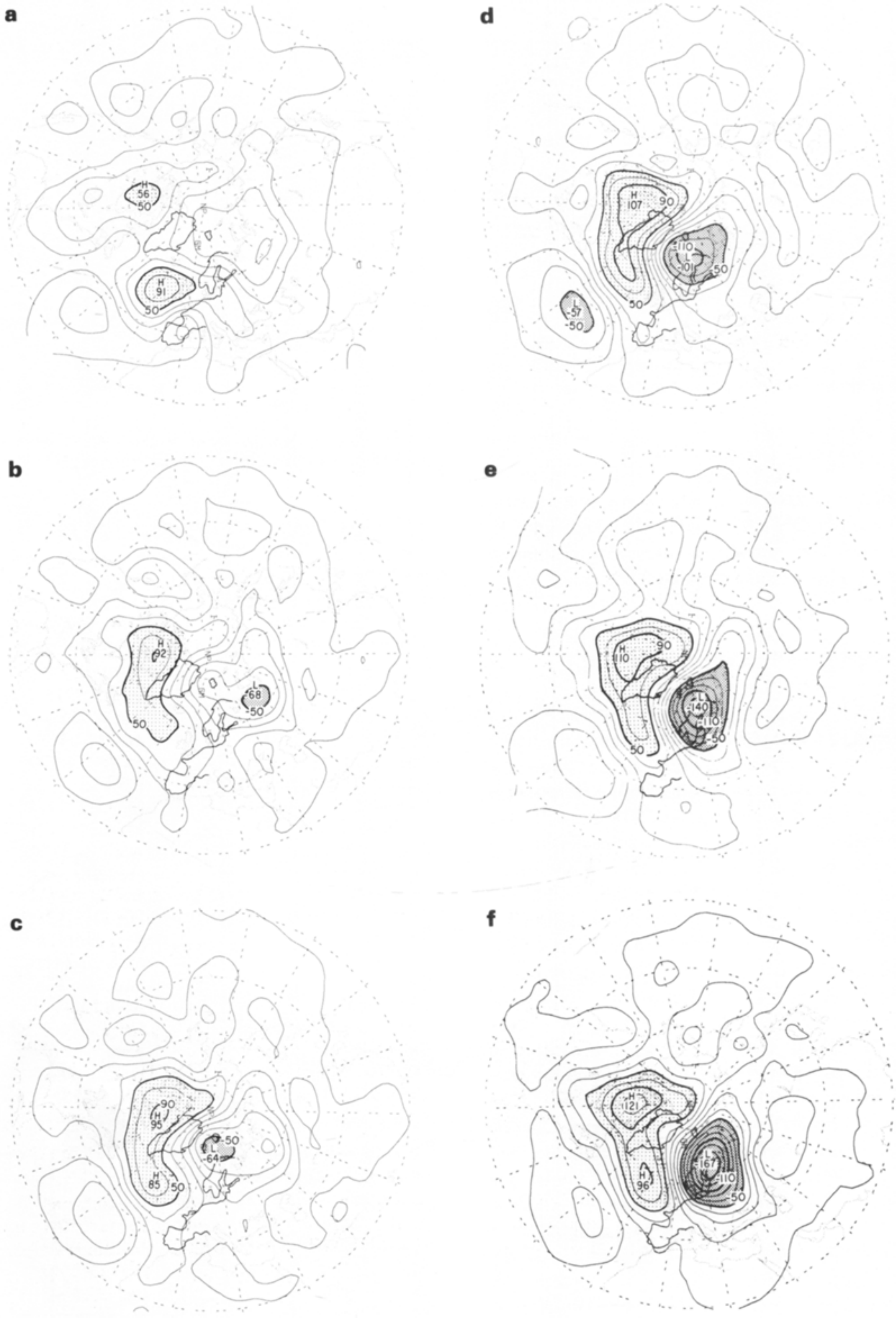


Fig. 6. 500 mb winter mean height field (contour interval: 60 m), October through April, 1965–1980.

Table 1

I. *Key days designated on the basis of synoptic and surface data from Norwegian coastal stations*	
Oct. 13, 1971	Nov. 19, 1975
March 22, 1972	Dec. 31, 1975
March 26, 1972	Jan. 4, 1976
Sept. 25, 1972	Jan. 12, 1975
Dec. 17, 1972	March 29, 1976
March 17, 1973	Nov. 23, 1976
April 14, 1973	March 5, 1977
April 25, 1973	March 26, 1977
April 27, 1973	April 18, 1977
Sept. 12, 1973	Nov. 18, 1977
Oct. 8, 1973	Jan. 12, 1970
Nov. 10, 1973	Dec. 25, 1978
Nov. 16, 1973	Feb. 18, 1978
Nov. 24, 1973	Nov. 20, 1978
Dec. 13, 1973	Dec. 26, 1978
Dec. 18, 1973	April 13, 1979
Feb. 8, 1974	Jan. 15, 1980
March 15, 1975	April 7, 1980
April 6, 1975	Dec. 2, 1980
April 11, 1975	Jan. 3, 1981
Oct. 17, 1975	Mar. 2, 1981
II. *Key days designated on the basis of satellite data over the Norwegian Sea*	
Jan. 2, 1979	Nov. 20, 1980
Jan. 27, 1979	Dec. 15, 1980
Feb. 22, 1979	Jan. 26, 1982
March 2, 1980	Dec. 13, 1982
Oct. 17, 1980	Dec. 22, 1982


a
H
56
50
H
91
50
d
H
107
90
110
L
101
50
L
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50
50
b
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92
50
L
68
50
e
H
110
90
L
140
110
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96
L
167
110
50

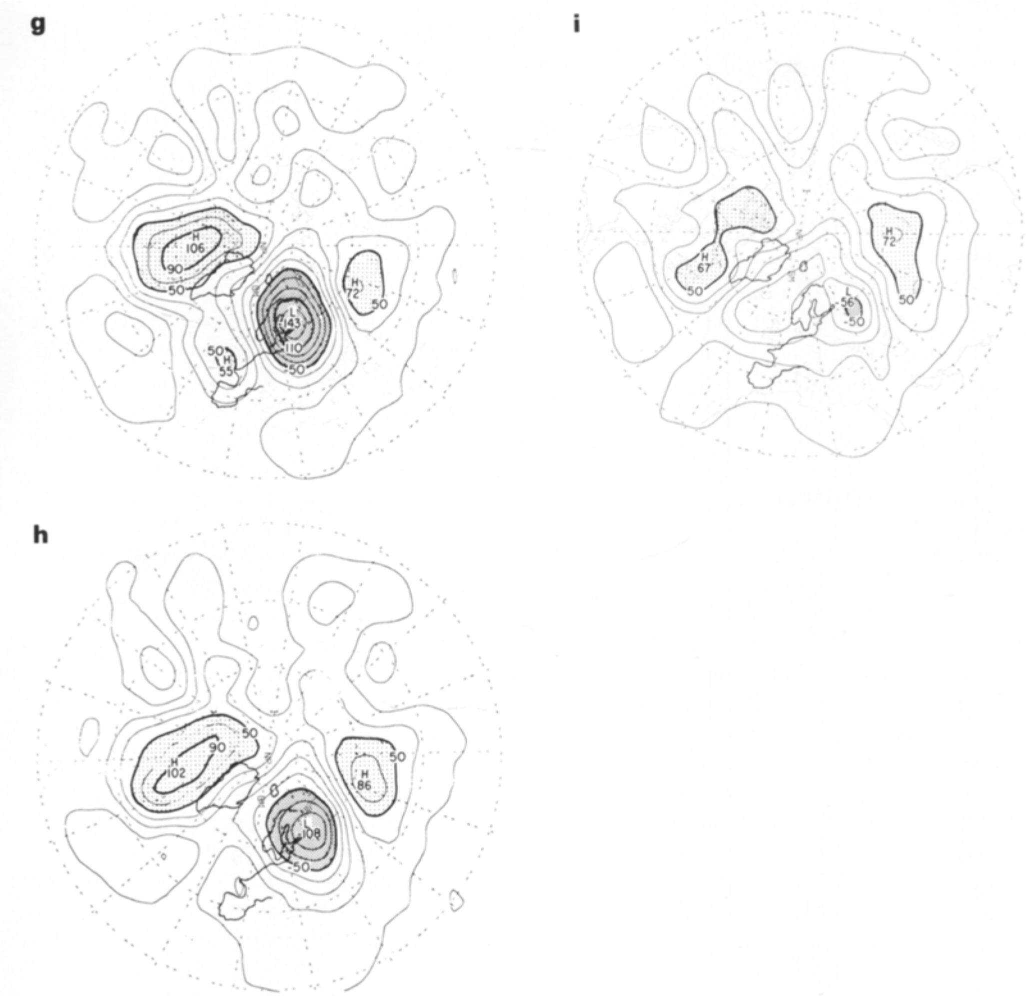

Fig. 7. Evolution of the 500 mb anomaly field (contour interval: 20 m). 42 cases: 1971–1981: (a) key day - 5, (b) key day - 3, (c) key day - 2, (d) key day - 1, (e) key day, (f) key day + 1, (g) key day + 2, (h) key + 3, (i) key day + 5.

during outbreaks of polar lows. Using the same procedure as described above, the anomaly field for each day during an 11-day window centered on the key day was computed, in order to show the evolution of the anomaly pattern from five days prior to five days after outbreaks. Additionally, the 500 mb temperature, 1000–500 mb thickness, and surface pressure data were composited to complete a "synoptic-scale" climatology for the key days.

Two studies were carried out, each with an independent set of key days (Table 1). For the first study, the list of key days was provided by K. Wilhelmsen (personal communication), and were chosen on the basis of synoptic and surface data (sharp surface pressure falls and rises, rapid changes in surface wind direction and speed, and rapid changes in precipitation rates; not associated with the passage of synoptic-scale, mid-latitude cyclones, or waves on the polar front), from stations along the northern coast of Norway. Fig. 4 (K. Wilhelmsen, personal communication), shows

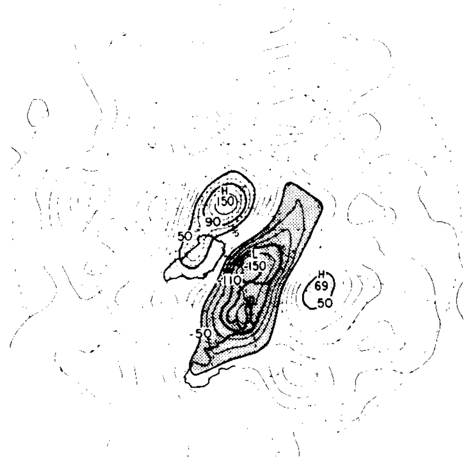

Fig. 8. 500 mb anomaly field (contour interval: 20 m), 10 cases: 1979–1982, key day.

the trajectories of polar lows over the Norwegian Sea, and the points at which they struck the northern coast of Norway. The closed circles indicate the position where a closed contour first appeared in the surface pressure analysis. Notice the concentration of starting points over the Barents Sea, coinciding with the warmest sea surface temperatures in Fig. 5, supporting the view that fluxes of sensible heat and moisture from the sea surface are important to the formation of polar lows. The shortness of the length of the trajectories over land, and the fact that no polar lows are observed to form over land, also support this view. The results of the 500 mb superposed epoch study for this set of key days are given in Fig. 7.

In the second study, infrared satellite photographs from the polar orbiting NOAA-6 and 7 satellites were carefully inspected. Only days during which vigorous polar lows (exhibiting a well developed spiral cloud structure with low cloud top temperatures), were present within the prescribed region were designated as key days (e.g. Fig. 1) (Table 1). The 500 mb height-anomaly field for the key day for this study is given in Fig. 8.

Finally, the two sets of key days were combined, and 500 mb temperature, 1000–500 mb thickness, and surface pressure data were composited to provide a "synoptic-scale" climatology for polar low outbreaks (Fig. 9).

5. Discussion of the results

In the first study, using key days for polar lows occurring along the Norwegian coast, a striking anomaly pattern evolves at the 500 mb level with a wavelength of about 2500 km (Fig. 7). On day zero (the key day, Fig. 7e) the pattern indicates that a 500 mb trough is located over northern Norway, with a northerly component to the geostrophic flow along most of the Norwegian coast, and a strong blocking ridge located just west of Greenland. The pronounced negative height anomaly to the north of Norway (140 m below the winter season mean) is evidence for the presence of strong positive vorticity over the region. Fig. 9a shows a 500 mb temperature anomaly of more than 5 °C below the winter season mean, centered very slightly to the west of the height anomaly at this time, indicative of low static stability over the Norwegian Sea. This temperature anomaly corresponds to a 500 mb temperature of less than −38 °C over the Norwegian Sea, where the sea surface temperature is greater than 4 °C (Fig. 4). A moist parcel of air warmed to near 4 °C at the surface, would attain a temperature surplus of approximately 3 °C, after rising moist adiabatically to 500 mb. These results support the view that the middle troposphere is important in the development of polar lows.

At the time the polar lows reach the northern coast of Norway (the key day), surface pressure gradients over Spitzbergen and Bear Island are maintaining a strong northerly flow (Fig. 9b). This flow direction is favorable for the formation of strong baroclinicity in the boundary layer, as discussed in Section 4. This highly baroclinic boundary layer is then super-imposed over a region of very sharp, horizontal sea-surface temperature gradient in the vicinity of Bear Island (Fig. 5); conditions that have been associated with explosive cyclogenesis in mid-latitude cyclones (Jager, 1983; Bosart, 1981; Sanders and Gyakum, 1980). Bosart (1981) describes the development of an intense mid-latitude cyclone that struck the Atlantic seaboard: "at the time of most rapid deepening, a mesoscale, asymmetric vortex, with a clear eye, formed, coincident with the outbreak of convection and hurricane force winds". Similar characteristics have also been attributed to warm-core, "hurricane-like" storms, which form within cold 500 mb troughs over the Mediterranean Sea (Ernst and Matson, 1983; Mayengon, 1983). The out-

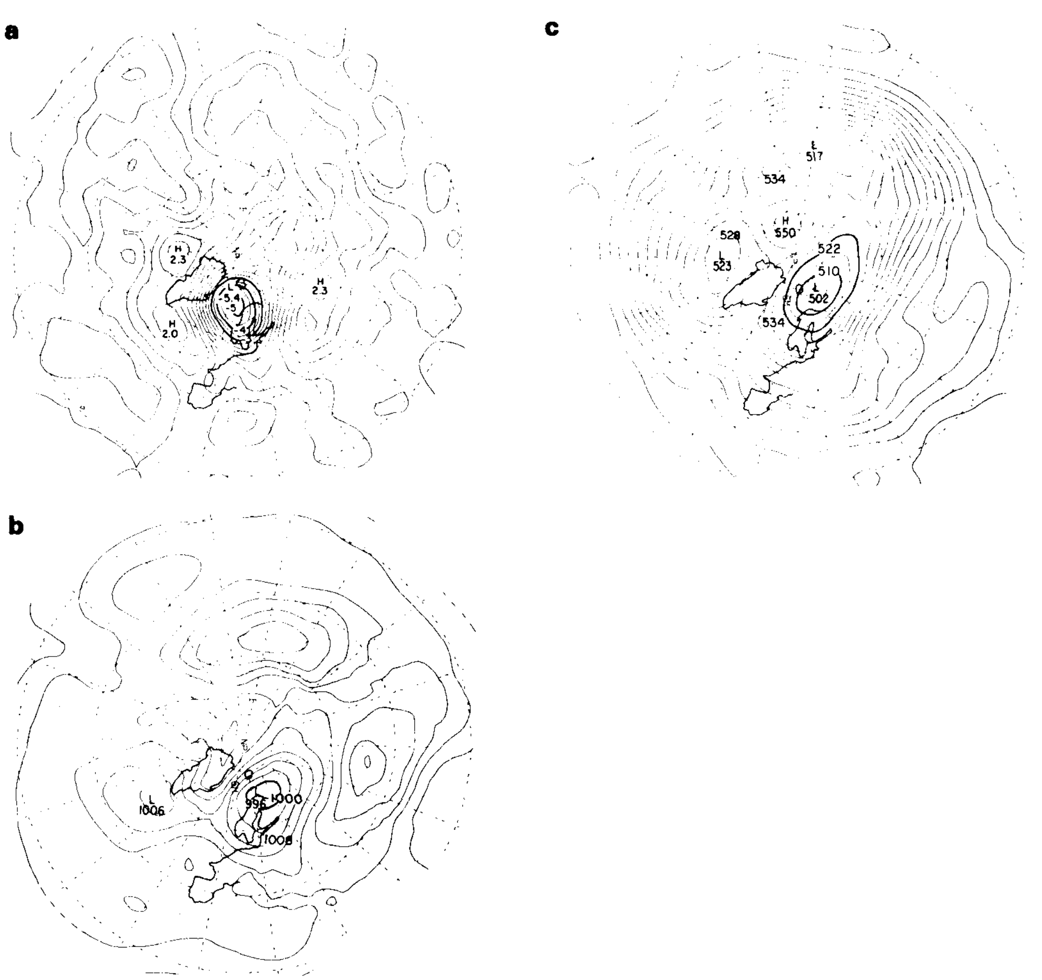

Fig. 9. (a) 500 mb temperature anomaly field (contour interval: 5 °C), 52 cases: 1971–1982, key day. (b) Surface pressure composite (contour interval: 4 mb), 52 cases: 1971–1982, key day. (c) 1000–500 mb thickness composite (contour interval: 60 m), 52 cases: 1971–1982, key day.

break of deep convection coincident with the time of most rapid deepening appears to be a common element of explosive cyclogenesis in polar lows, comma clouds, and mid-latitude cyclones.

The surface pressure and 1000–500 mb thickness composities (Fig. 9b, c) show pronounced pressure as well as thickness troughs along the northern coast of Norway on the key day. The presence of a thickness gradient across the Norwegian Sea is indicative of some deeper baroclinicity on the synoptic scale. In addition, Fig. 2 and Fig. 7d (day-1) give evidence that forcing by a migratory small synoptic-scale vortex, and possibly a short jet streak, may enhance the formation of polar lows (Sutcliffe, 1947; Uccellini et al., 1981). However, only slight asymmetry between the thickness and surface pressure contours, indicate that the vertical structure of the atmosphere was nearly equivalent barotropic on the synoptic scale at this time. (It should be noted at this point, that the data used in this study have insufficient resolution to adequately represent details of the atmospheric structure on the scale of the polar low itself; the NMC data set used has a grid spacing of approximately 396 km at 70 degrees north latitude, on the order of the diameter of a typical polar low.) The case-study presented in Section 3 shows the position of the polar low at the surface (Fig. 3), and the position of the 500 mb low center (Fig. 2) to be nearly concentric at 00 GMT November 22, when the polar low is most well developed. In addition, careful analysis of infrared satellite data show that temperatures corresponding to the sea surface can be seen in the "eye" of well developed polar lows (M. Shapiro, personal communication) indicating a vertical structure in this region of mature storms.

The evolution of the 500 mb anomaly pattern (Fig. 7), shows the tendency for *in-situ* development of both the positive and negative-anomaly features prior to the key day. The negative anomaly shows a slight westward motion early in the sequence, which suggests the effect of a migratory short wave at 500 mb deepening along the rear flank of the trough, resulting in retrogression. The negative anomaly then deepens *in-situ* over the Norwegian Sea. Following the key day the negative anomaly gradually slides southward (following the common trajectory of polar lows seen in Fig. 4), reaching its lowest value of 167 m below the winter mean one day after the key day, and rapidly weakening thereafter.

The positive anomaly strengthens *in-situ* along the west coast of Greenland, reaching its maximum value one day prior to the key day, suggesting that the development of such a feature could be used prognostically. Following the key day, the positive anomaly remains relatively stationary, gradually filling after the key day. The *in-situ* evolution of the marked anomaly pattern and its wavelength suggest that the presence of the high, cold Greenland plateau and the warm, open water of the Norwegian Sea provide topographical forcing that enhances the development of the anomaly pattern and the subsequent outbreak of polar lows. The magnitude and location of the features of the anomaly pattern are consistent with theory for a linear response of an equivalent-barotropic flow impinging on a mountain barrier (Hoskins and Karoly, 1981).

The second study, in which satellite photographs were used to determine the key day, is an independent test of the robustness of the results of the first study. Fig. 8 again shows a strong 500 mb height-anomaly pattern on the key day, with the negative anomaly (150 m below the winter season mean) centered over the Barents Sea just north of Norway.

It is interesting to compare the signature of the negative-anomaly pattern (Fig. 8) with the 500 mb height chart (Fig. 2). Note the similarity in placement and shape of the trough and anomaly patterns.

6. Summary and conclusions

The superposed epoch-analysis technique used in this study has proven useful in examining the evolution of the 500 mb synoptic-scale height field just prior to and following the outbreaks of polar lows over the Norwegian Sea. On days when well-developed polar lows occurred over this area, significant negative height and temperature anomalies were present, indicating strong positive vorticity and very low static stability over the area (Figs. 7e and 9a).

The surface pressure composite (Fig. 9b) shows a trough just north of Norway, with northerly surface winds across Spitzbergen and Bear Island, bringing arctic air over much of the Norwegian Sea, resulting in a rapid modification of the boundary layer over water, and the production of low level baroclinicity. Although the spacial and temporal variations of the static stability, and low level baroclinicity are of probable importance to the development of polar lows, a lack of detailed boundary layer and upper air data over the Barents Sea makes it very difficult to assess the degree to which baroclinic versus convective processes contribute to the formation of these disturbances. A common element of incipient polar lows appears to be the presence of a weak surface trough (Fig. 3a), (Rasmussen, 1985), and low level baroclinicity. The outbreak of deep convection along the surface trough, coincident with the time of most rapid deepening at the surface, suggests that there is cooperation between the baroclinic and convective components of polar lows. Identification of the exact mechanism of this cooperation awaits more detailed mesoscale data, close in the vicinity of developing polar lows.

The composite 1000–500 mb thickness field (Fig. 9c) shows a minimum just north of Norway, with some deeper baroclinicity present, on the synoptic scale, over the Norwegian Sea at this time.

The composite surface pressure and 1000–500 mb thickness fields reveal only slight asymmetries in the respective contours, suggesting that the structure of the atmosphere is primarily equivalent barotropic over these storms on the larger synoptic scale. Although the resolution of the data used in creating the composites is insufficient to resolve the structure of an individual polar low, some evidence that polar lows may be forced by a migrating short wave is provided by the evolution of the negative-height, anomaly pattern prior to the key day (Fig. 7), as well as the case study (Fig. 2).

The magnitude and location of the height-anomaly pattern (Fig. 7) is consistent with the view that topographic forcing by the high Greenland plateau and the warm Norwegian Sea may enhance the development of the anomaly pattern, and subsequent outbreak of polar lows. The evolution of the anomaly pattern may have application in forecasting the synoptic conditions conducive to the outbreak of polar lows. Ridging to the west of Greenland, and resulting northerly component of the flow aloft and at the surface over the Norwegian Sea, appear to precede the occurrence of polar lows. These conditions can be watched for on European Center for Medium Range Weather Forecase (ECMWF) maps to identify times during which the outbreak of polar lows is likely. Finally, the composite climatology may have application for initializing primitive equation models aimed at simulating the evolution of polar lows.

Continued work using the superposed epoch method seems warranted on the basis of these results. Of particular interest would be to study cases over the northern Pacific Ocean (work on this is in progress). Also of interest would be to study polar lows that form near Iceland and the southern tip of Greenland.

7. Acknowledgements

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