Tellus (1985), *37A*, 407–418, Polar Low Special Issue

A case study of a polar low development over the Barents Sea

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(Manuscript received October 16, 1984; in final form March 28, 1985)

ABSTRACT

The development of a polar low in the Bear Island region between the Norwegian Sea and the Barents Sea is studied. The polar low develops when an upper-level cold core vortex from the northeast is advected across the ice edge and the region of extreme sea surface temperature gradients in the Svalbard–Bear Island region. Strong convection is believed to play an important rôle in the transformation of the upper-level vortex into a polar low with greatest intensity near the surface.

1. Introduction

A necessary basis for the understanding of the dynamics of polar lows and for their numerical modeling are case studies of representative examples. However, since polar lows are of small horizontal scale and develop in data-sparse regions over the sea, very few case studies have been made. In this study, we will consider the development of a polar low, which may be typical for many polar low developments in the Barents Sea region. As the data coverage in this area is not dense enough to make a quantitative analysis, our approach will necessarily be primarily descriptive. It is not an easy task to define a polar low in an unambiguous way. The phenomenon to be discussed in this paper, from most points of view, however, must be classified as a polar low. Other cases are not so clear cut, and especially the so-called comma clouds (recently discussed by Tuleya and Kurihara (1984)) are difficult to distinguish from "true" polar lows. For a general discussion of polar lows, the reader is referred to Rasmussen (1979, 1983).

Polar lows develop only in certain geographical regions during cold air outbreaks. The most preferred regions seem to be the Barents Sea and the Norwegian Sea. Another, but secondary area of polar low formation is the sea west and south of Iceland. Polar lows formed in this region often move in a southeasterly direction and may cross the British Isles. These lows may, however, be different from those formed near Bear Island. Apart from the polar low development in the genesis regions mentioned above, there are few reports from other locations.

Polar lows have not previously been reported in the Gulf of Alaska region, where strong cold air outbreaks often occur over a relatively warm sea surface. Recently, however, as reported by Steven Businger (personal communication), polar lows have also been observed in this region.

On the other hand, comma cloud developments are common in the Gulf of Alaska region. Locatelli et al. (1982) in their discussion of comma clouds (by them called vortices) over the north-eastern Pacific, point out, that there is some evidence that two types of vortices may exist, and that the first type develop close to a trailing polar front. When fully developed, these vortices resemble mature cyclones. The second type, according to Locatelli, "develops farther back in the polar air, *and appears to be more convective than the first type*". Indeed the major difference between comma cloud developments and polar low developments of the type discussed in this paper, may be the degree to which the convection determines the developments. In cases with very strong cold advection over a sea surface with strong horizontal temperature gradient, the development may be controlled mainly by convective processes, whereas in case of more moderate cold advection, or less pronounced sea surface temperature gradients, baroclinic processes may become dominant. With this point of view, there is no need to distinguish sharply between polar lows and comma clouds.

To the author's knowledge, polar low developments have never been observed over land, and on the contrary, they almost invariably decay rapidly after landfall. This statement, of course, depends upon *how* a polar low is defined.

2. The pre-development stage

The surface map from 00 GMT December 12 (Fig. 1) shows the synoptic situation near the time when the disturbance, which later on developed into a polar low, could first be seen on the satellite images. No satellite images are available which show the conditions over the ice north and northeast of the Svalbard region, prior to the development beginning on December 12. On a satellite image from 0302 GMT December 12, a diffuse cloud cluster can be seen just southwest of Svalbard. The cluster drifts slowly towards the south, and at 0435 GMT, a center of rotation is discernible. The satellite image from 1257 GMT

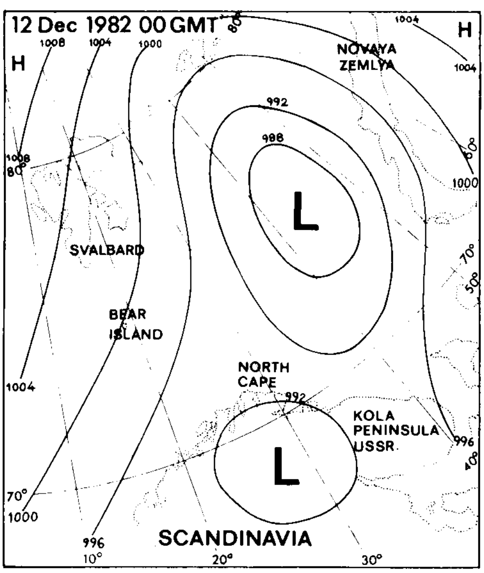

Fig. 1. Surface map 00 GMT December 12, 1982.

December 12 (Fig. 2) shows that the center of the disturbance passes only 100 km west of Bear Island. The disturbance at this time can hardly be seen at the surface map, but is clearly discernible on the 500 mb map. This upper level disturbance can in fact already be seen at 00 GMT December 11 in the Novaya Zemlya-region, and on the subsequent 500 mb maps. From 0435 GMT December 12, a center is discernible on the satellite image (not reproduced), and from this time all center positions shown in Fig. 3 have been derived from satellite images. Following the development of polar low A, the disturbances B, C, D and E subsequently develop in the same area. Note by comparing Figs. 1 and 3 that the trajectory of disturbance A on December 12 is markedly across the surface isobars, indicating an upper steering current.

3. The cloud-field development

On a satellite image from 1804 GMT December 12, the disturbance looks almost as it did 5 h previously at 1257 GMT. The brightness of the clouds indicates a cloud top temperature between that of the widespread low-level clouds around the disturbance, and that of a band of deep convective clouds along the Norwegian coast. Between 1804 GMT December 12 and 0243 GMT December 13, a marked development takes place by which the cloud cluster is transformed into a cloud-vortex (vortex A) shown on Fig. 4. While the cloud deck previously was rather uniform, the individual clouds, or mesoscale system of clouds, are clearly discernible on Fig. 4. Another interesting feature is the clouds radiating radially out from the western and northwestern part of the cloud system. These cloud bands are oriented perpendicular to the upper level flow and do not indicate a divergent flow out from the center.

On satellite images from 0423, 0604, 0748 and 0928 GMT, an eye-like feature remains clearly discernible. The fact that the sea surface can be seen in the center region during the whole development means that the axis of the vortex does not tilt much with the height.

On the image from 1245 GMT (Fig. 5), a secondary disturbance, B, is clearly seen east of vortex A.

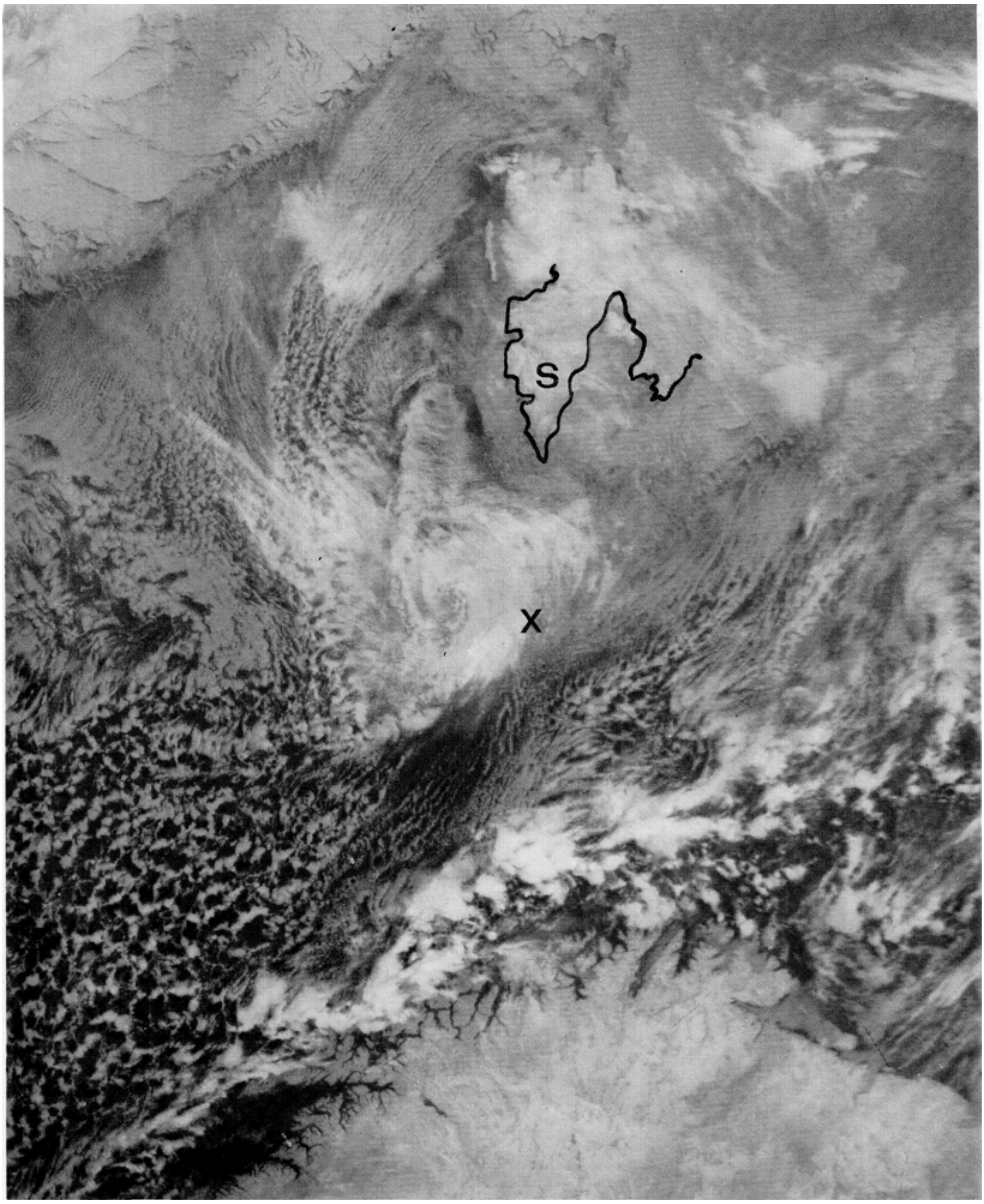

Fig. 2. NOAA-7 infrared satellite image 1257 GMT December 12, 1982. The center of the disturbance is seen in the middle of the picture, ~100 km west of Bear Island.The southern part of Svalbard has been marked by "S", and the position of Bear Island is shown by "X".Photograph courtesy of Department of Electrical Engineering and Electronics, University of Dundee.

Later on, on December 14, other disturbances are formed, also over the sea, as seen in Fig. 6. What on the synoptic map is analyzed as a relatively large-scale low or circulation system, therefore is a complex system composed of several mesoscale disturbances.

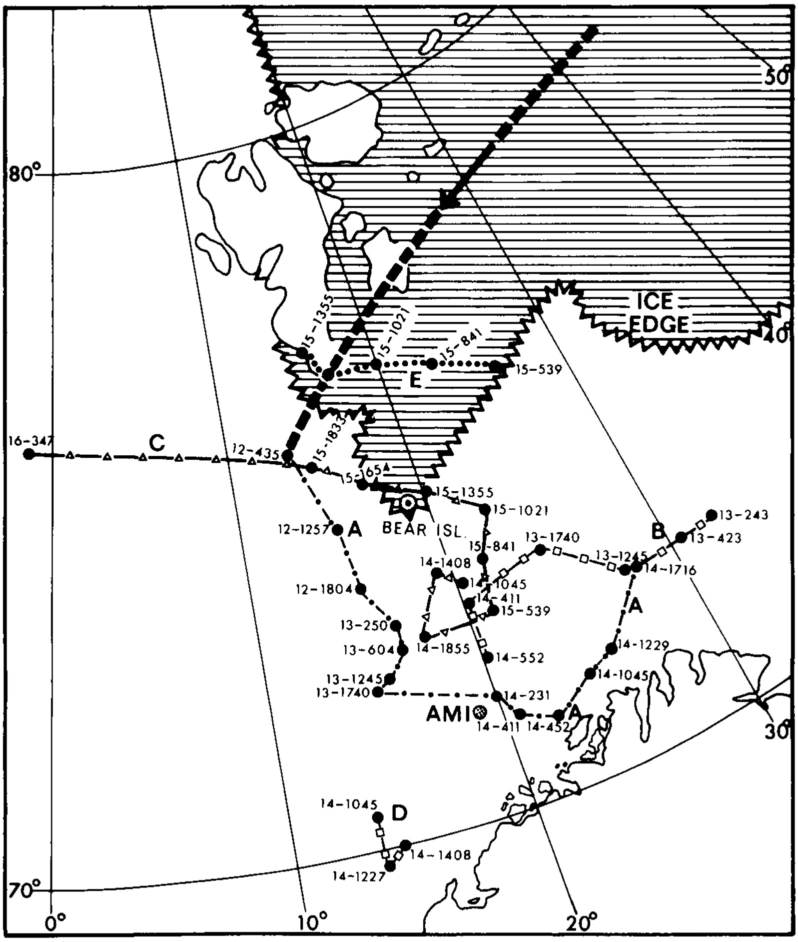

Fig. 3. Trajectories of polar low A and disturbances B to D, derived from satellite images. The thick dotted line in the upper part of the picture shows the trajectory of the upper-level cold core vortex, derived from the 500 mb maps, the cold core vortex, which later on developed into polar low A.

4. The development at the sea surface

Disturbance A, which later on develops into a polar low, starts as an upper-level phenomenon above snow and ice covered areas. After being advected southwards to an area with open water and relatively high sea surface temperatures, the disturbance gradually penetrates to the surface. This initial formation of a low near the surface may at least partly be due to baroclinic processes initiated by the upper level vortex in a secondary baroclinic zone near the ice edge. This problem, however, will not be elaborated on in the present study.

Figs. 7a to 7f show a sequence of surface maps covering the period from 00 GMT December 13 to 03 GMT December 14 reproduced from the routine maps from the Norwegian Meteorological Institute with only minor changes in the analysis. At 00 GMT December 13, there is relatively little indication on the surface of the disturbance, except the relatively strong pressure fall at Bear Island (see also Fig. 8). At 06 GMT, the system can be detected on the surface map by the observation from the Norwegian ship AMI at 71.5° N, 19° E, i.e. quite near the center of the low. Very little happens at the surface the next 6 hours from 06 GMT to 12 GMT. Another 6 hours later, at

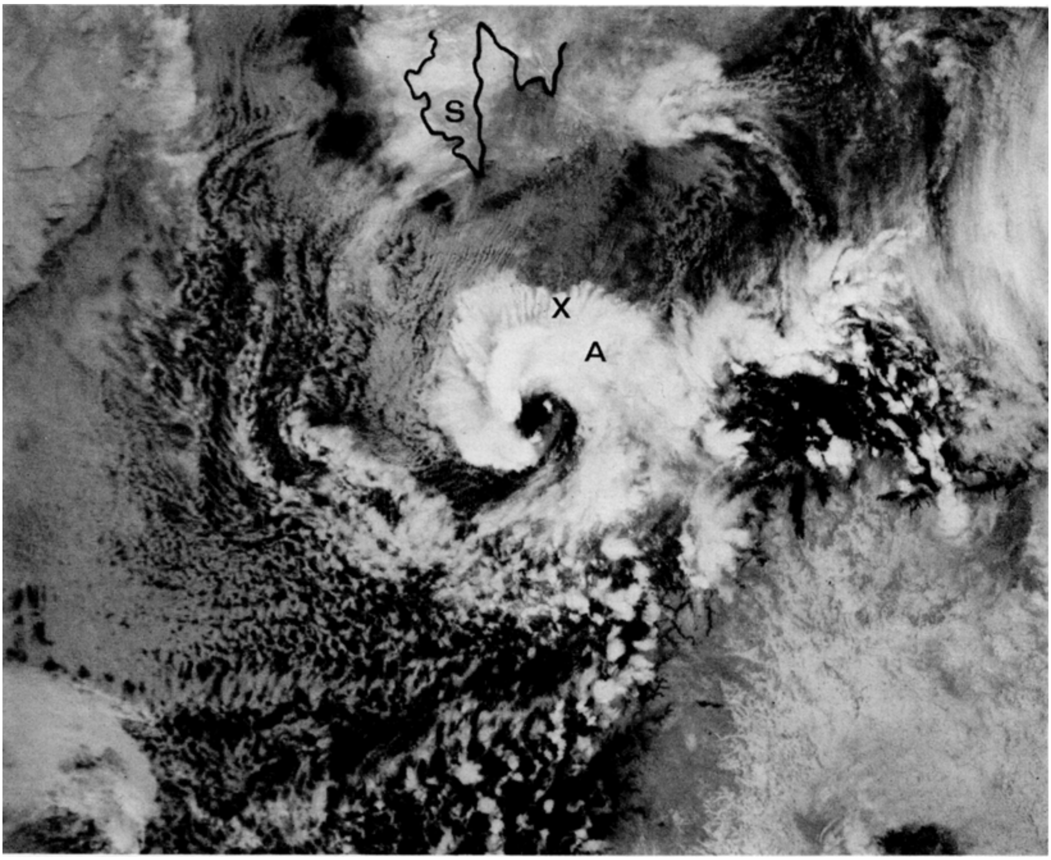

Fig. 4. NOAA-7 infrared satellite image 0250 GMT December 13, 1982. The southern part of Svalbard has been marked by "S", and the position of Bear Island by "X". Photograph courtesy of Department of Electrical Engineering and Electronics, University of Dundee.

18 GMT, a closed low can be analysed on the surface map, and the wind has increased to 15 ms^{-1} at the ship AMI. However, only small pressure falls are observed, The wind velocity is practically the same at AMI 3 hours later, but the pressure has decreased to 986.1 mb. Between 21 GMT and midnight, the pressure falls 5.9 mb, and the wind increases to 20 ms^{-1}. At this time, about 24 hours after the development of the cloud vortex, a strong polar low with a central pressure below 980 mb has formed at the surface with its center somewhat east of the center position at 1800 GMT (see Fig. 3).

As mentioned above, there are some indications that the development in the lower layers prior to 1800 GMT December 13 is of baroclinic nature while the rapid deepening from 1800 GMT to 2400 GMT December 13 is probably strongly connected with the occurrence of deep convection. The last map in the sequence shows the synoptic situation 3 hours later, where the central region of the polar low has moved northeast of AMI.

The surface wind, temperature and the 3-hour pressure changes for AMI and Bear Island are shown on Fig. 8 together with the sea surface temperature for AMI. The passage of lows A and C (see Fig. 3) are clearly seen at AMI and Bear Island, respectively.

The phenomenon marked X seen both in the wind and pressure field at AMI is, judging from the satellite images, a minor disturbance, difficult to track.

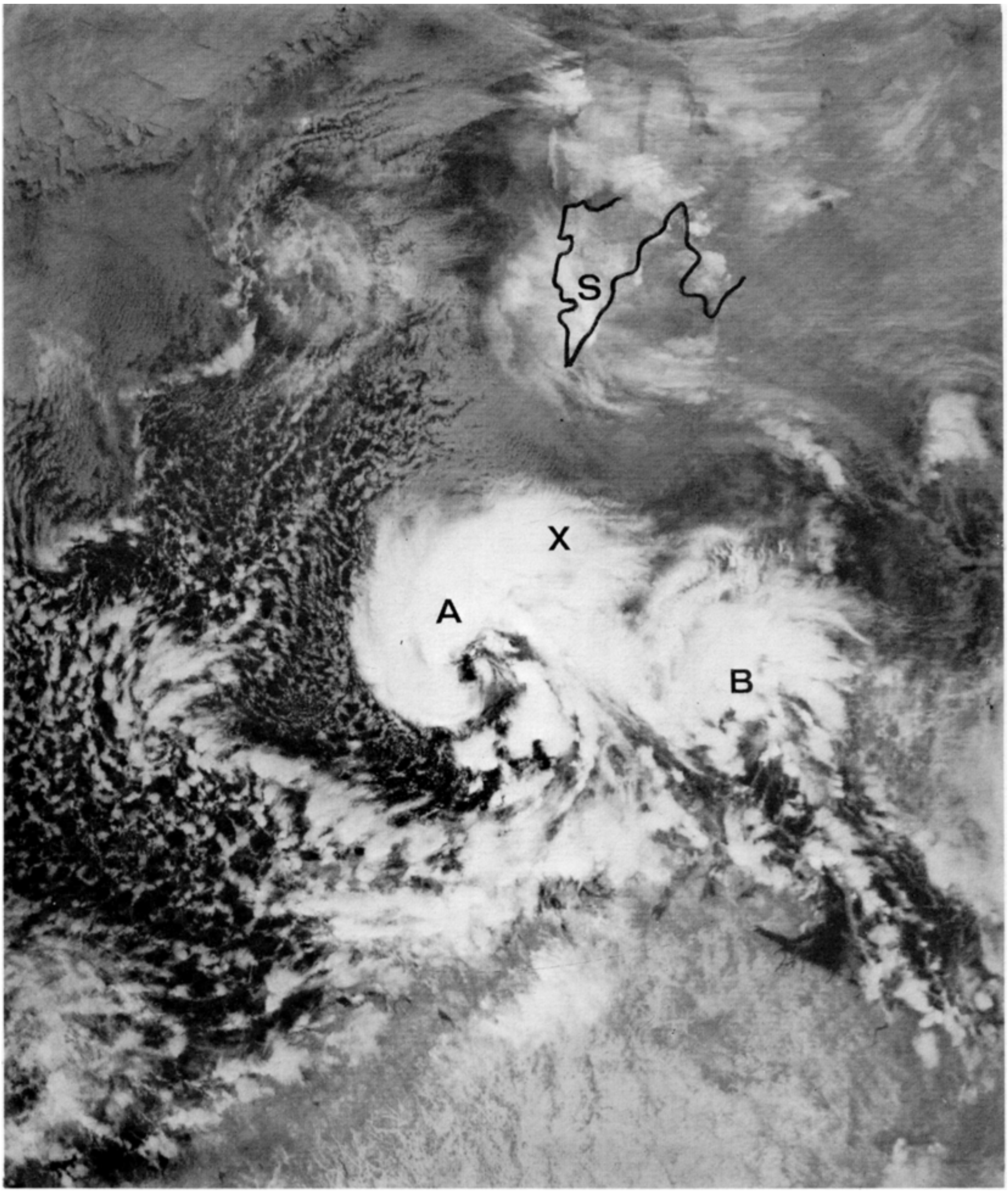

Fig. 5. NOAA-7 infrared satellite image 1245 GMT December 13, 1982. Polar low A and a secondary disturbance B are seen between Bear Island and North Cape. The southern part of Svalbard has been marked by "S", and the position of Bear Island by "X". Photograph courtesy of Department of Electrical Engineering and Electronics, University of Dundee.

5. The upper air conditions

The upper air conditions are rather certainly of primary importance for this and similar polar low developments in the Bear Island region. Whether some types of polar lows can develop through linear instability from infinitesimal small disturbances, through some kind of CISK-

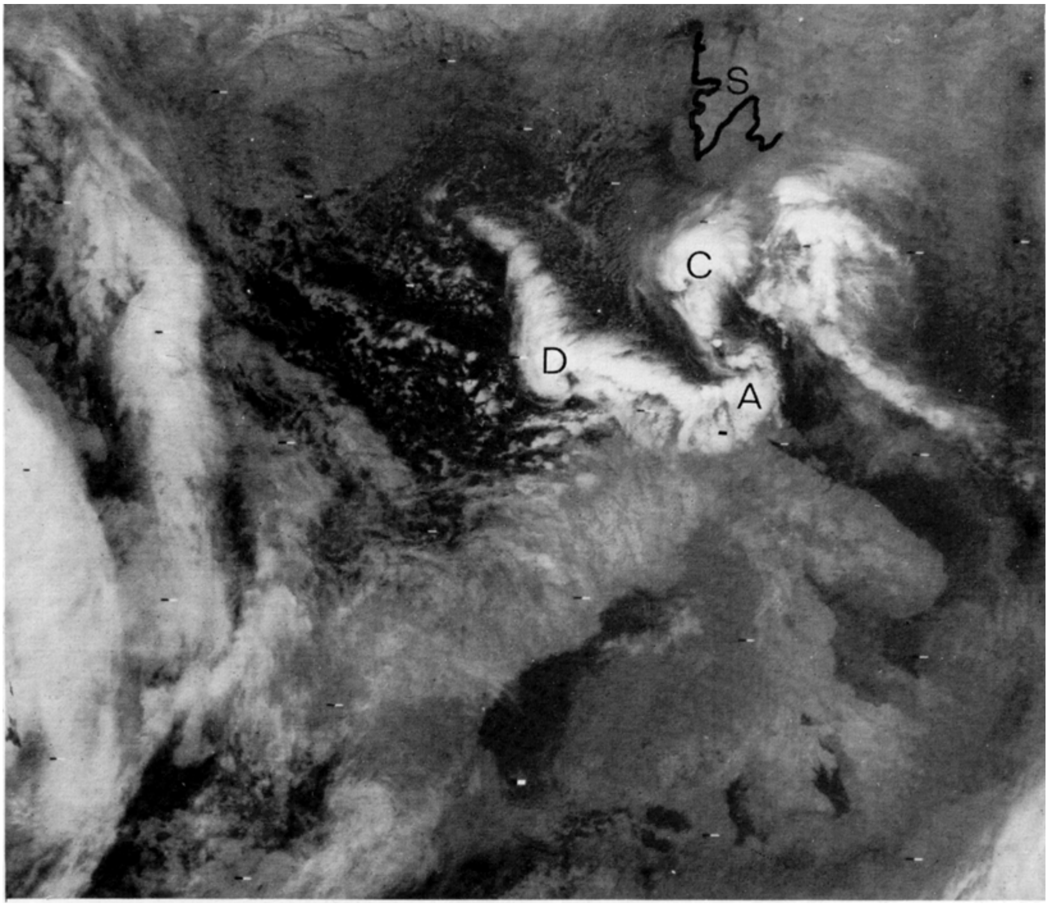

Fig. 6. NOAA-7 infrared satellite image 1227 GMT December 14, 1982 showing several polar lows/disturbances over the Norwegian Sea. The southern part of Svalbard has been marked by "S". Photograph courtesy of Observatory of Space Research, The Danish Meteorological Institute, Rude Skov, Copenhagen.

instability, is an open question. In this case, a finite upper-level disturbance causes the formation of a polar low of the same horizontal scale as the upper level disturbance itself. In the process through which an initial cold core disturbance seems to be transformed into a warm core system, convection undoubtedly plays an important rôle.

Fig. 9 shows the radiosonde ascents from December 12 at Bear Island, and from which it is seen that the wind directions from 850 mb to 300 mb, i.e., through most of the troposphere, are changed 180° between 00 GMT and 12 GMT. The reason for this is that a deep cold core upper level vortex of small horizontal scale passes just west of Bear Island around 12 GMT. It is this vortex, which can be followed on the satellite images as a rather diffuse cloud cluster during the pre-development stage of the polar low. In fact, the vortex can be followed as a trough or closed circulation at the 500 mb level in the inner cyclonic shear region of the large scale vortex, back to 00 GMT December 11, where it can be seen at the northern part of Novaya Zemlya. The 500 mb maps from 12 GMT December 11 and 12 GMT December 12 are shown in Fig. 10. At 00 GMT December 11, the temperature in the interior of the large-scale vortex over the Barents Sea is close to −40 °C, but near the small scale vortex it is −43 °C. This temperature minimum connected with low A can also be seen at 12 GMT and later on. Both

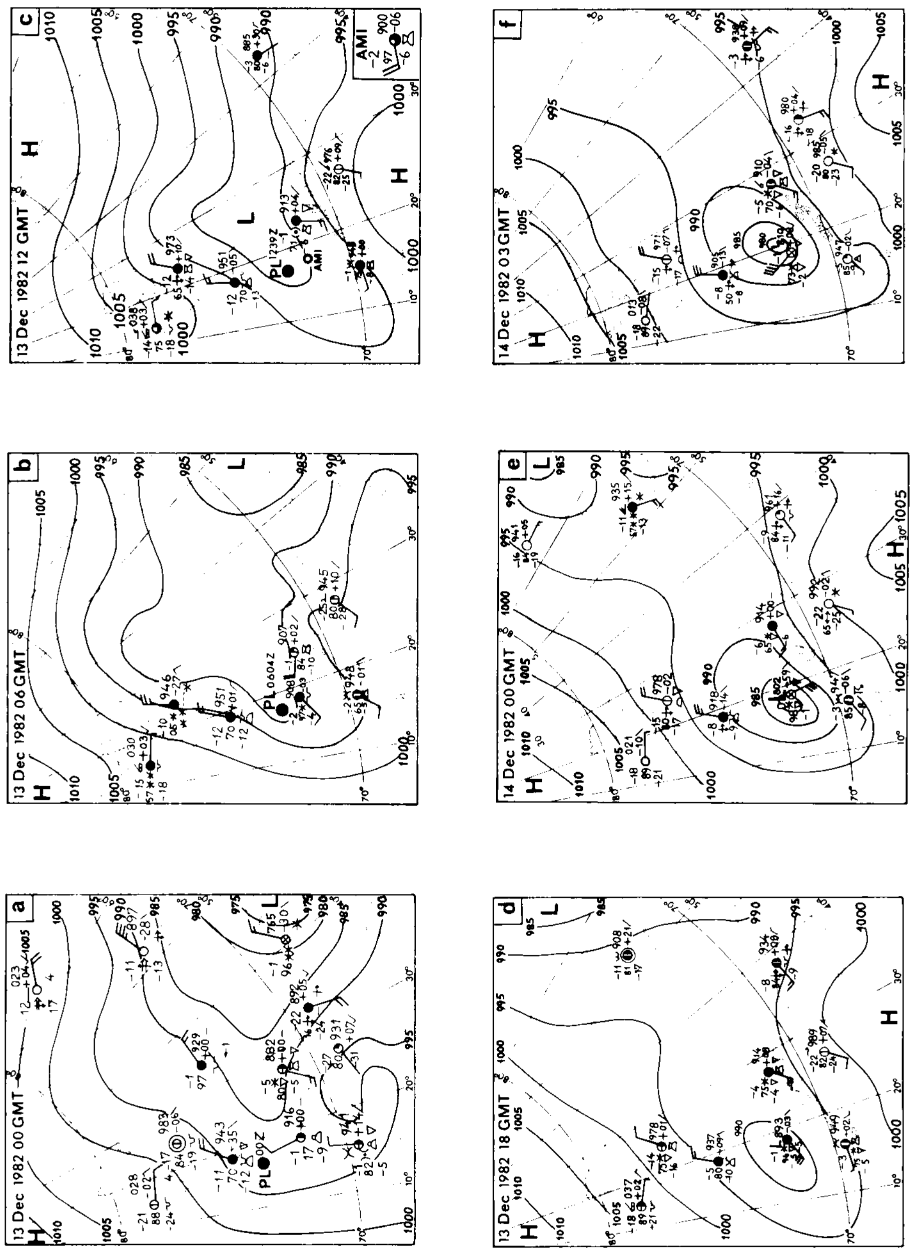

Fig. 7. Surface maps 00 GMT December 13, 1982 to 03 GMT December 14, 1982, showing development of polar low A. On Figs. 7a to 7c, the center position of the polar low as observed from satellite has been marked. Reproduced (with minor modifications) from the routine maps from the Norwegian Meteorological Institute.

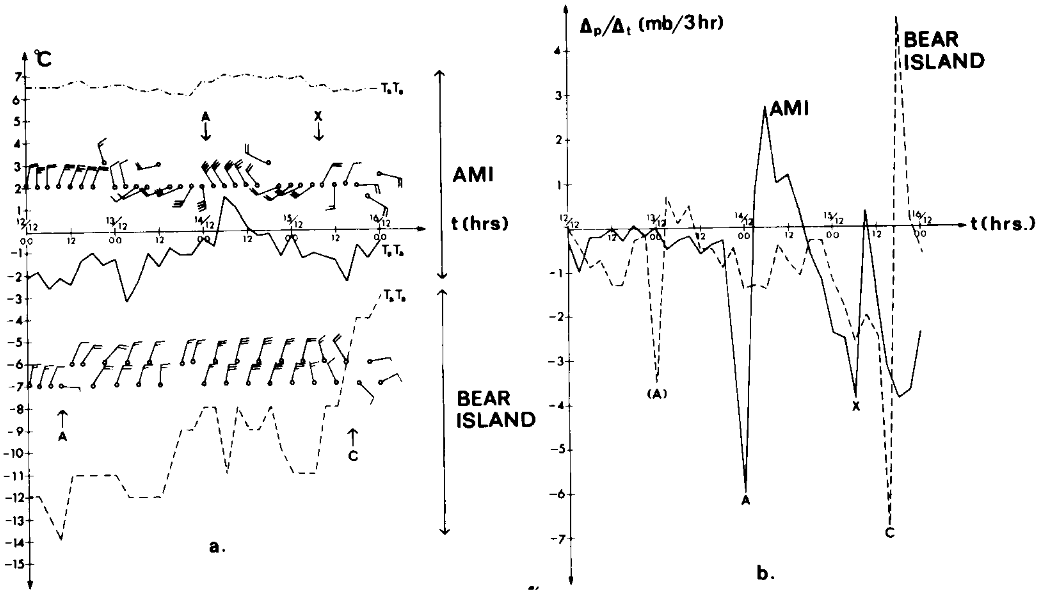

Fig. 8. Surface winds, (in knots and north "upwards"), air temperature (T_aT_a) and sea temperature (T_sT_s), from ship AMI (71.5 N, 19 E), and surface winds and temperature from Bear Island from 00 GMT December 12, 1982 to 00 GMT December 16, 1982. (b) Pressure tendencies (mbs per 3 hours) for AMI and Bear Island for the same period.

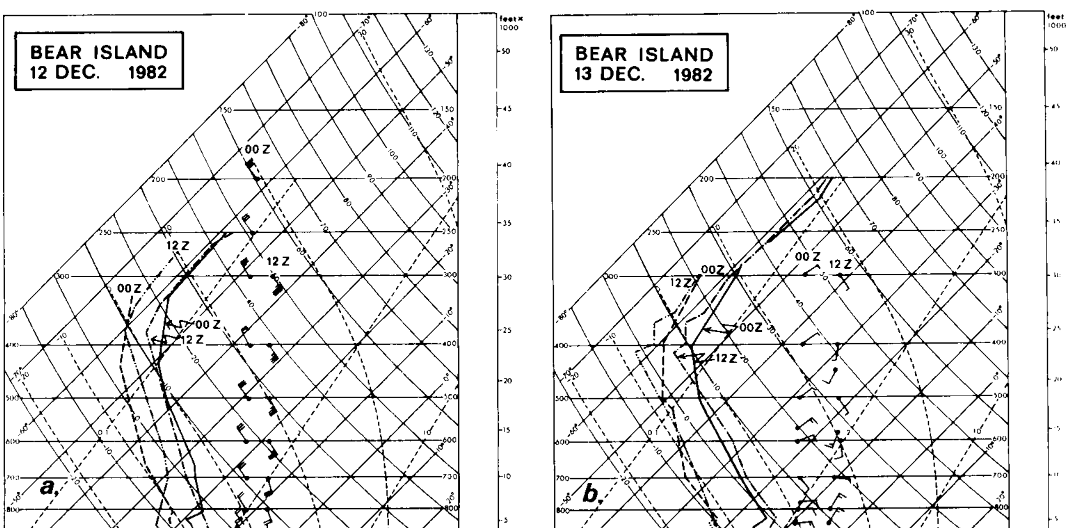

Fig. 9. Radiosonde ascents Bear Island. (a) 00 GMT and 12 GMT December 12, 1982 and (b) 00 GMT and 12 GMT December 13, 1982. Winds are given in knots with north "upwards".

the temperature minimum as well as the increased cyclonic circulation with height at the time when the vortex passes close to Bear Island, show that the vortex is of the cold core type.

In his discussion of upper lows, Riehl (1979) points out that due to the high vorticity values found in the inner regions of these systems, "it seems necessary to postulate very slight ascent

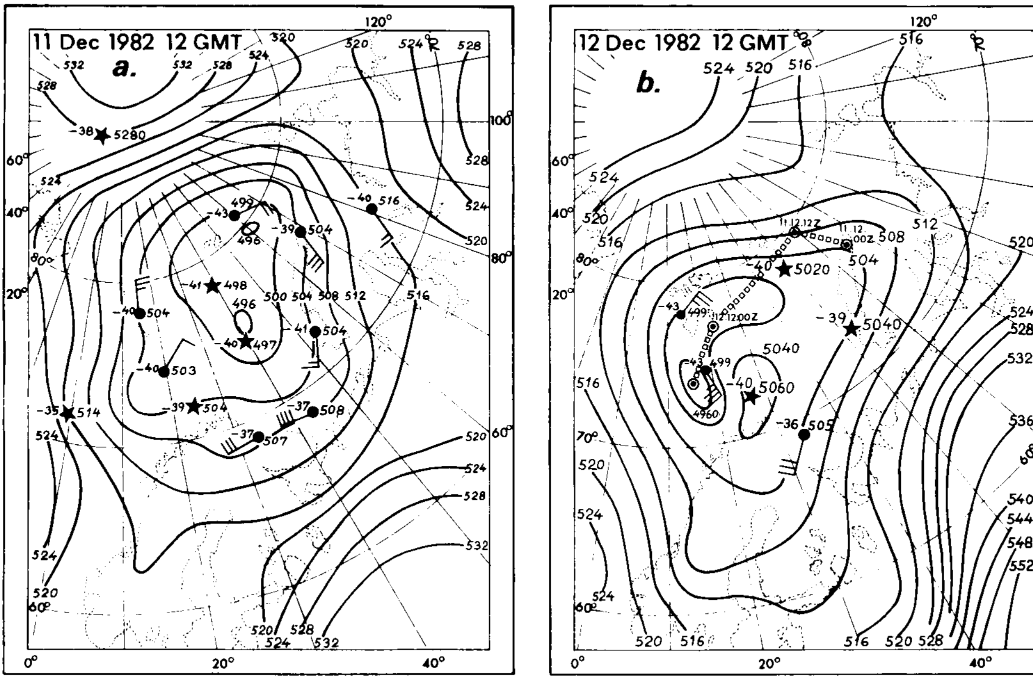

Fig. 10. The 500 mb maps from (a) 12 GMT December 11, 1982 and (b) 12 GMT December 12, 1982. Contours in dekameters, and temperatures in °C. Long barbs indicate 10 kts. The observations marked by an asterisk are derived from satellite data, and taken from the maps produced by the National Climatic Center, North Carolina, USA. On Fig. 10b, the track of the upper level low from 00 GMT December 11 to 12 GMT December 12, 1982, has been shown.

through the high troposphere". When the upper-level vortex passes Bear Island near noon on December 12, a typical relative vorticity is given by $\zeta \sim V/R \sim 10/10^5 = 10^{-4}\ s^{-1}$, i.e. a rather high value. The vortex at this time is still of the cold core type, and the high humidity above 700 mb (see Fig. 9) shows the slight ascent postulated by Riehl. The ascent that takes place at that time can also be seen on the satellite image from 1257 GMT (Fig. 2), where rather high-level clouds show the horizontal extent of the ascending motion.

While the formation of polar low A can be traced back to an upper-level disturbance, the subsequent formation of disturbances B to E (see Fig. 3), on the other hand, then seems more difficult to explain. Common for the synoptic situation during which these disturbances formed is the presence of a cyclonic circulation and cold temperatures aloft, at least on the synoptic scale. On the sub-synoptic scale, however, the situation is more complex. The 500 mb analysis, Fig. 10, from 12 GMT December 12, shows an asymmetrical structure near the cold core vortex with a high pressure cell on its eastern flank. Such upper level asymmetrical structures are well-known from hurricanes (Anthes, 1982), but have not been observed in connection with polar lows before. The upper-level high partly explains the asymmetrical structure of the upper-level cirrus-outflow seen in this, as well as in many other cases. Furthermore, the upper-level high and its associated region of horizontal divergence may explain the formation of the secondary disturbance, B, on the eastern flank of polar low A.

6. The dynamics of the polar low development

At 12 GMT December 12, when the upper-level vortex passes close to Bear Island, it is hardly discernible at the surface. 15 hours later, a well-defined cloud vortex (see Fig. 4) has developed, but at the surface the vortex is still relatively insignificant. At 06 GMT December 13, when the disturbance has drifted quite close to the ship AMI, we finally also see the signature of the vortex at the surface, and 18 hours later the surface disturbance has developed into a strong polar low. At the same time, the vortex seems to have changed from a cold core system to a warm core system. This is indirectly shown by the decreased surface pressure, which indicates a mean temperature rise of ~3 °C in the central parts of the low. Some evidence of a changed structure is also indicated by the upper-level wind field near the low, as revealed from the radiosonde ascents from Bear Island.

The radiosonde ascents from Bear Island from December 12 and 13 are shown in Fig. 9. During this period, Bear Island is passed by low A. The passage of the upper-level cold, moist vortex, is clearly seen in the soundings from December 12. At 00 GMT December 13, when the vortex is still fairly close to Bear Island, the circulation around the (vertical) axis is still cyclonic through the whole depth of the troposphere, but with generally decreasing intensity with height reflecting the beginning of a transformation from a cold core to a warm core system. 12 hours later, during which time the low has moved only little, this trend has continued. The wind measured at Bear Island will also of course be affected by the increasing distance to the vortex. Most of the time, however, the vortex remains so close to Bear Island, that the changes in the vertical wind field observed here are difficult to explain as a purely advective effect. At 00 GMT December 14, when the polar low is fully developed (Fig. 7e), Bear Island is clearly affected by the circulation of the low on the synoptic scale. Furthermore, at this stage of the development the cyclonic circulation at Bear Island is only a shallow phenomenon. After reaching a velocity of 15 ms^{-1} from northeast at 950 mb, the northeasterly wind decreases to 10 ms^{-1} at 800 mb. At 700 mb and 600 mb, the wind is only 5 ms^{-1} from a northwesterly direction turning southerly at still higher levels.

Fig. 11 shows the extension of the sea ice and the sea surface temperatures at the start of the period considered, and a comparison between Figs. 3 and 11 reveals many interesting features.

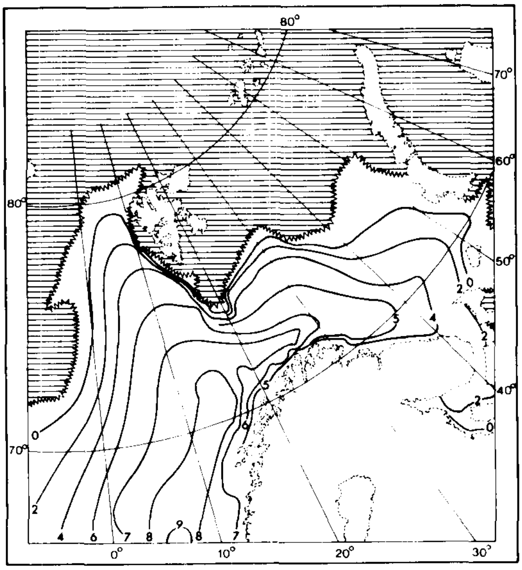

Fig. 11. Map showing the extent of the ice and sea surface temperatures (in °C) in the Norwegian and Barents Sea region on December 10 to 12, 1982. Areas wholly or partly covered by ice have been hatched. Reproduced from the Norwegian Meteorological Institute's Icechart.

On its way towards the southwest, the upper-level vortex crosses an area of intense sea surface temperature gradients immediately southwest of Svalbard, and shortly after this the development begins. On its continued way towards the south, the disturbance follows a path directly to the area with the highest sea surface temperatures, around 8 °C.

The existence of these extraordinary sea surface temperature gradients in the area, may be of decisive importance for the ensuing polar low development. Because of the southward movement of very cold air over an increasingly warm sea surface, a deep adiabatic layer will form near the surface, and air from this surface layer with a high equivalent potential temperature will be highly unstable. Very strong and deep convection as seen on the satellite images can then proceed, which may explain the transformation suggested above, from a cold core to a warm core system.

Finally in this section, we will consider the temperature variations at ship AMI during the passage of polar low A. As indicated on Fig. 3 and through the wind variations shown on Fig. 8, the center passes slightly north of AMI. Before and after the passage of low A, the air temperature fluctuates from around −2 to −1.5 °C, but during the short interval with strong northwesterly winds following the passage of the center, the temperature rises to a maximum of +1.5 °C. Even though the sea surface temperature, as seen from Fig. 11 is increasing towards the northwest (see from AMI), the observed temperature rise is hardly an effect of this, partly, because it is so strong, and partly because winds from the same direction a day before caused a substantial cooling. Instead, the increased air temperature may be the result of enhanced sensible heat transfer from the warm sea surface in the area with high wind velocities, and increased mixing in the boundary layer.

7. Summary

The formation of a polar low in the Bear Island region has been described. Key factors for the development are believed to be the pre-existence of a cold core upper level vortex of small horizontal scale and the extreme sea surface temperature gradients along the ice edge in the Svalbard–Bear Island region.

Probably due to deep convection organized on the scale of the upper level disturbance, the latter seems to be transformed from a cold core to a warm core disturbance, i.e. the polar low, with maximum intensity near the surface.

The surface conditions over the sea during the passage of polar low A are somewhat different from those ensuing were the disturbance of the classical frontal wave type. For example, the temperature rises during the period of strong northerly winds, probably as a consequence of the increased transfer of sensible heat from the warm sea surface during disturbed conditions with strong winds, and/or increased vertical mixing.

8. Acknowledgements

I would like to thank the Norwegian Meteorological Institute, which supported this research. I also want to thank Mr. Ib Andersen, who carefully processed the manuscript, and Mrs. A. Skjoldbo, of the Danish Meteorological Institute, for the excellent job of preparing the drawings.

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