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Polar lows affecting Denmark

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ABSTRACT

18 cases of polar lows (sub-synoptic cold air vortices) over Denmark in the 10 polar low seasons (November to April) from 1980–90 have been analysed. The different properties of the lows are discussed and examples are shown illustrating the variety of the lows ranging from relatively strong, rapidly developing, baroclinic disturbances down to weak lows of the horizontal scale of 100 km forming out of a small group of cumulo-nimbus clouds. They generally form in an almost moist adiabatic atmosphere with pre-existing large-scale positive vorticity, and it is suggested that this can explain why polar lows can have a horizontal scale down to 100 km and at the same time be stable systems persisting for several days. The strongest lows are found to have a strong baroclinic influence, but it is shown by using the model proposed by Craig and Cho (1988), that for most of the lows both baroclinic and convective processes can be of importance.

1. Introduction

In December 1981, 7 polar lows (sub-synoptic cold air vortices) passed Denmark in the course of one week. They left more than 50 cm snow on the ground and were the early warning of a very cold winter with record low temperatures in both December 1981 (−25.6°C on the 17th) and in January 1982 (−31.2°C on the 8th). Not only Denmark, but the whole north-eastern Atlantic experienced a large number of polar lows that winter. Forbes and Lottes (1985) counted 133 cases of mesoscale cloud vortices from 1 December 1981 to 5 January 1982. Challenor and Carter (1983) estimated the return period of the cold weather that followed after the polar low incident to be 250 years in England. This cold spell was indeed remarkable in terms of both the numbers of polar lows and the following low temperatures.

The winters in Denmark are very different from one year to the next. Lying in the coastal zone of the European continent, the winters will be cold or mild according to the prevailing large scale synoptic pattern. Heavy precipitation in the form of snow is most likely in connection with:

(1) Large-scale extratropical cyclones passing just south of Denmark. These lows may produce substantial amounts of snow especially in the southern part of Denmark.

(2) Showers and line convection forming over the relatively warm waters around Denmark during outbreaks of cold air from the east and northeast. These showers fall mainly on the north and east coasts (see Fig. 1 and the discussion in Section 2).

(3) Organized mesoscale systems like polar lows or troughs in cold air outbreaks from northwest.

This investigation discusses 10 years climatology of polar lows passing Denmark. A total of 18 cases have been found during these 10 years, showing that polar lows do occur over Denmark during most winters, although they are not very common. When polar lows do occur, they give a significant contribution to adverse weather conditions in Denmark.

2. Polar lows over Denmark 1980–1990

The present climatology covers the 10 polar low seasons (November to April) from 1980/81 to 1989/90. Around Denmark, polar lows have been observed during these months only, though they

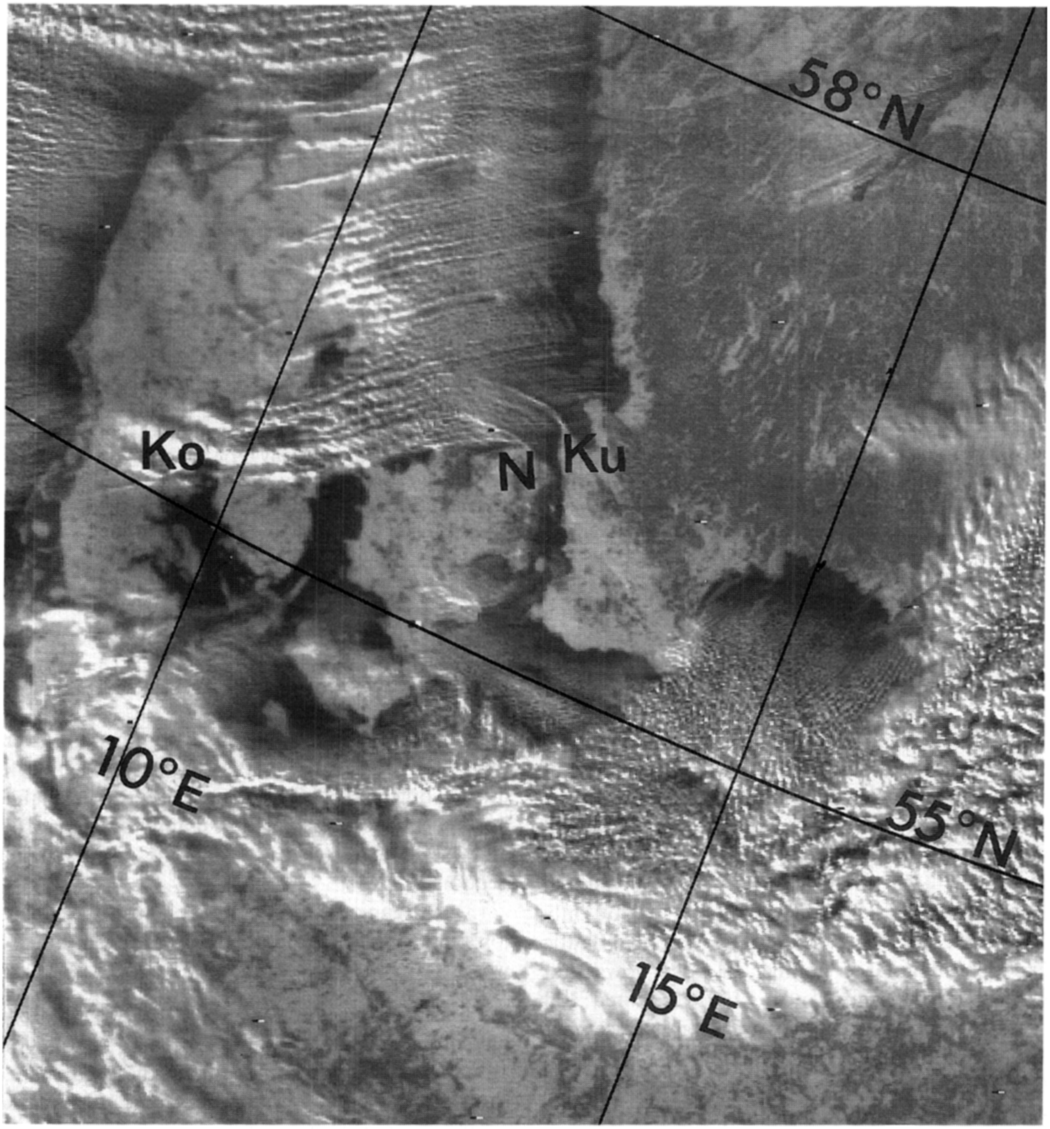

Fig. 1. NOAA-9 visible (channel 2) satellite image from 12.41 UTC 10 January 1987. The cliffs at Kullen and Nakkehoved are marked with Ku and N and the town of Kolding with Ko (see text for further explanation). Photograph courtesy of Observatory of Space Research, Danish Meteorological Institute.

further north along the Norwegian coast can occur almost throughout the year with the exception of the two summer months July and August (Wilhelmsen, 1985 and Lystad, 1986).

To identify the polar lows for this investigation the following criteria have been used:

(1) The disturbance of small horizontal scale must be poleward of the main baroclinic zone.

(2) The disturbance must exhibit a distinct pressure minimum on the surface map, i.e., troughs or upper-level disturbances are not considered.

(3) The center of the disturbance must cross

Table 1. *List of different surface parameters for the 18 cases of polar lows*

No.	Date	Strength (hPa)	Size (km)	Speed (m/s)	Duration (days)	Precip. (mm)	Wind (m/s)
1	4 Jan 1981	8	250	12	1.0	29	15
2	6 Dec 1981	12	400	12	4.5	32	18
3	7 Dec 1981	8	300	12	3.0	35 H	16
4	9 Dec 1981	4	100	8	3.5	32	11
5	10 Dec 1981	10	400	10	2.5	20	18
6	10 Dec 1981	2	250	12	1.5	14 H, T	14
7	13 Dec 1981	5	250	12	4.0	11	16
8	14 Dec 1981	6	300	10	3.0	6 H	15
9	27 Mar 1983	10	300	5	1.0	25 H	13
10	4 Jan 1984	7	200	13	0.5	11 H	25
11	19 Jan 1984	8	300	8	2.5	16	11
12	8 Feb 1984	5	250	13	0.5	5 H	14
13	29 Mar 1985	15	450	17	1.5	30 T	21
14	26 Apr 1985	3	100	12	1.5	7 H	15
15	2 Nov 1985	5	200	12	0.5	11 H, T	15
16	14 Mar 1988	5	300	12	3.0	19	14
17	22 Apr 1988	2	100	8	2.0	7 H	12
18	1 Mar 1990	4	200	10	4.0	10 H	18
	mean	7	260	11	2.0	18 H	16

If hail or thunder are observed during the passage over Denmark, it is marked with "H" or "T". The precipitation is the largest accumulated precipitation (melted water) during polar low passage and the wind is the largest observed 10 m wind (10 min averages). Only Danish land-based stations are used to estimate precipitation and wind (see text for further explanation).

the Danish coastline at least once, i.e., disturbances passing through the North Sea or Skagerrak are not considered.

18 cases meeting these criteria have been found by looking through 10 years of 3-hourly operational synoptic maps and the available satellite imagery from the Meteosat and NOAA satellites. The 18 cases are listed in the first column in Table 1 (the parameters shown in the Table will be discussed later in Section 4).

Polar lows do not occur every year (Fig. 2a). On the other hand, in some years, like 1981, several polar lows passed Denmark. Polar lows occur mainly in cold winters, but even in mild winters they can form in short periods of cold air outbreaks from the north and north-west. The latter situation occurred in the winters 1987/88 and 1989/90. Polar lows do not occur during extremely cold periods, since these periods are characterized by advection of cold, continental air from the east and northeast and relatively high pressure. In these situations there will be a tendency to form line

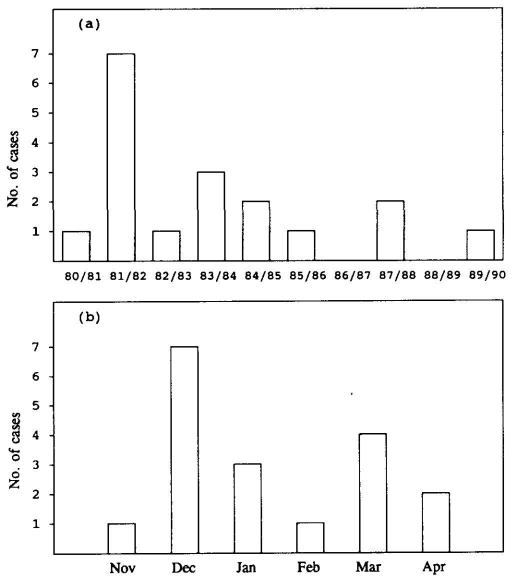

Fig. 2. Number of polar low cases affecting Denmark. (a) Each winter season from 1980/81 to 1989/90. (b) Each month from November to April for all 10 years.

convection over the warm water surfaces instead, as shown in Fig. 1. In this particular situation very cold air (−20 to −30°C) flowed off southern Sweden. Strong-line convection formed as the air was heated from below over the sea surface (see also Pike, 1990). This type of convection is termed "Kattegat showers" by Danish meteorologists since they are commonly seen in Kattegat during cold air outbreaks in winter. In Fig. 1 it is seen that even small islands in Kattegat can cast a "shadow" far downstream. Observe also the waves at a 45° angle to the flow initiated by the cliffs at Kullen (Ku) and Nakkehoved (N). The town of Kolding (Ko) was covered in deep snow (between 50–100 cm) in this situation, which persisted for more than two days.

Fig. 2b shows the montly distribution of the 18 polar lows. Even though the sample is limited there is a clear tendency for the polar lows to appear early and late winter, while there is a minimum in mid-winter. This has also been reported by Wilhelmsen (1985) for lows close to Norway. The reason probably being that mid-winter is often characterized by a rather persistent continental high. This high will tend to block lows from the north Atlantic moving towards Denmark.

2.1. Origin

The 18 polar lows have been traced backwards in time to their origins mainly by using satellite imagery. These positions as well as polar low tracks are shown on Fig. 3.

It is seen from the figure that the polar lows all develop in the north-eastern Atlantic, the Norwegian Sea or the North Sea, and that they travel to Denmark between the mountains of northern Scotland and southern Norway. So far, no polar lows have been observed to form in

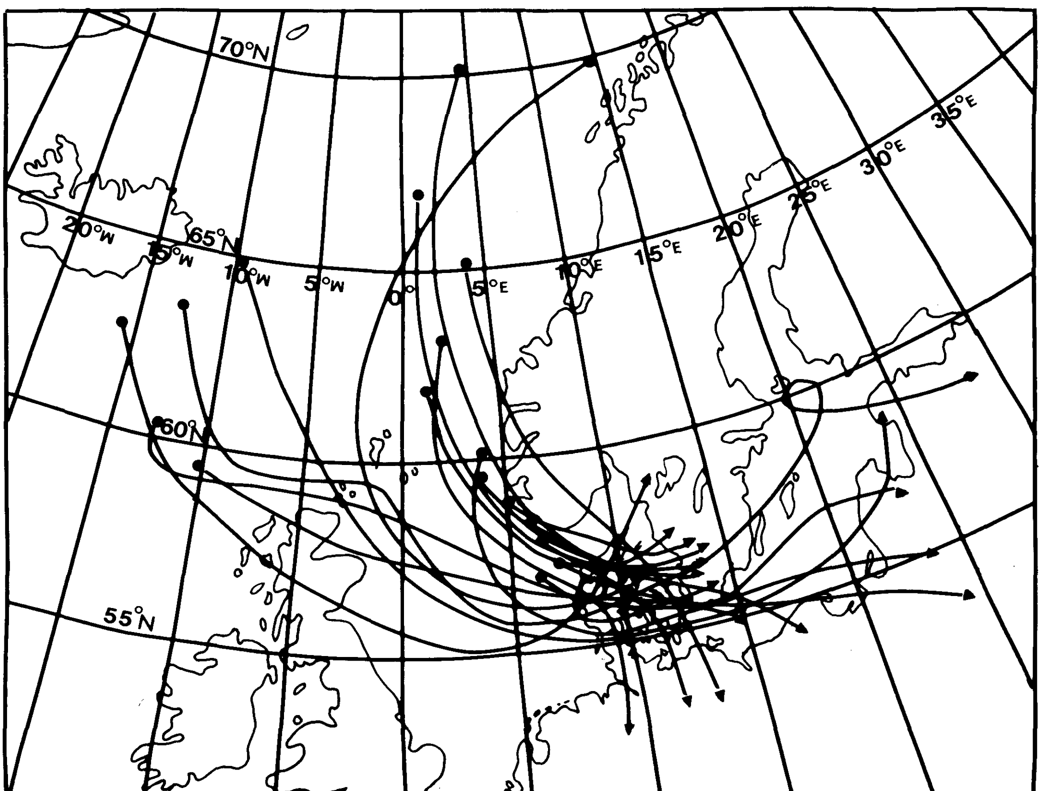

Fig. 3. Map showing the origin and tracks of the 18 polar low cases.

easterly flows over the Baltic, even though the air in these situations can be very cold. Easterly winds over Denmark normally occur with a high over Scandinavia or Finland/Eastern Soviet Union. This synoptic situation is not favorable for polar low formation.

The 18 cases show that polar lows may occur in a number of situations. Some of the lows form in lee troughs near Iceland or southern Norway (Fig. 3). The lows further north off the Norwegian coast are often formed in the central region of an occluded extratropical cyclone (see also Section 3).

All of these places of origin are in regions with relatively high sea surface temperatures (SST). The positions of origins are shown on a map of SST's from December 1981 (Fig. 4). The SST's change, of course, during the polar low season and from year to year. However, they always show the same general pattern as in Fig. 4 due to the persistent warm and cold sea currents. These relatively high SST's are known to favor the formation of polar lows of predominantly convective nature (Rasmussen, 1985).

The large-scale circulation at the time of origin has been investigated using the temperature, height and vorticity fields in 500 hPa (Fig. 5). The data are taken from the ECMWF model analysis in a 1° latitude × 2° longitude grid. The temperature and height fields are taken directly from the model analysis, while the vorticity is calculated geostrophically from the height field, z, due to lack of archived model vorticity from the whole 10-year period. The geostrophic vorticity is calculated from the expression:

$$\zeta_g = \frac{g}{f} \nabla^2 z_{500\,\mathrm{hPa}}.$$

Since the lows originate in different geographical positions, the mean of the fields is calculated relative to the point of origin. Fig. 5a shows that the polar lows form in large scale cold air outbreaks and that the mean environment of the 18 polar lows is characterized by large scale upper level cold advection on the western side of the large scale upper level trough. This is in accordance with criteria 1 in Section 2 for selection of the lows.

In Fig. 5b it is seen that the maximum of positive

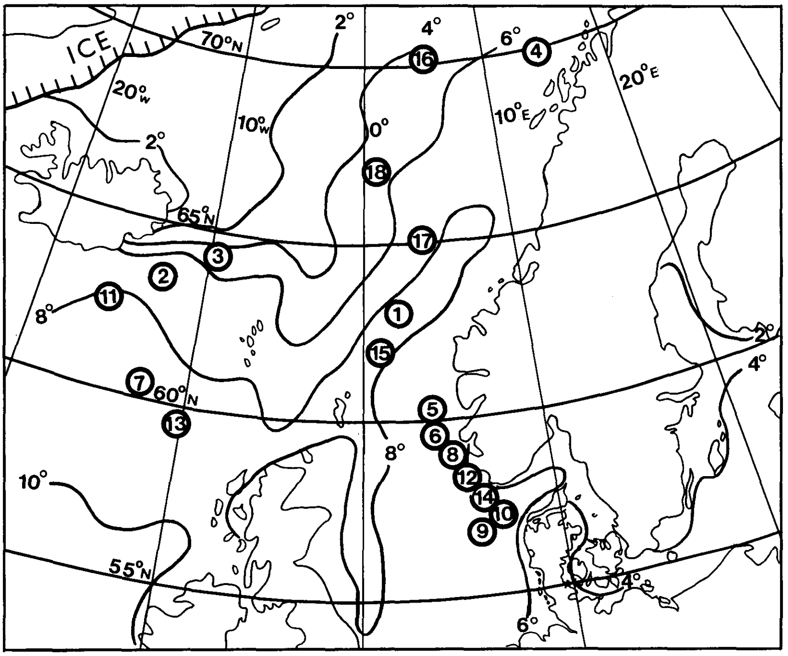

Fig. 4. Map showing the origin of the 18 polar low cases on a SST map from UK Met. Office from 9–12 December 1981. The encircled numbers refer to Table 1.

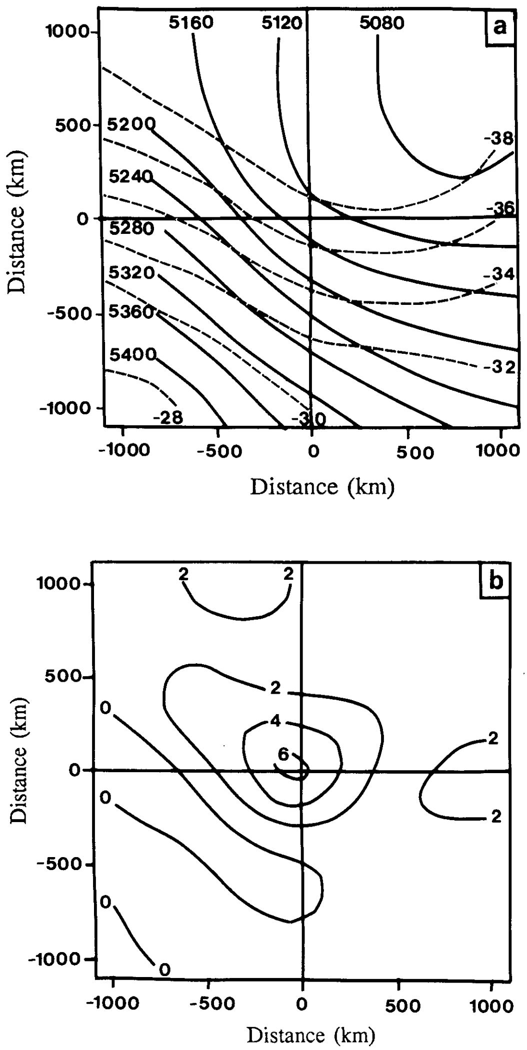

Fig. 5. Large scale circulation in 500 hPa for all 18 polar low cases averaged around the point of origin. (a) shows the average height field in decameter (solid lines) and average temperature field in °C (broken lines). (b) shows the relative geostrophic vorticity field in units of $10^{-5}\ s^{-1}$.

vorticity in the mean is found very close to the point of origin. By inspecting the fields from the 18 lows (not shown) this can be found in almost every case. It is remarkable that the upper air pattern shows this clear signal since the polar lows at the point of origin in general are seen only as a poorly defined cloud structure in the satellite images with no surface pressure disturbance. Thus the vorticity seen in Fig. 5b is typical for the large scale environment and not connected with the circulation around the incipient polar low itself, since this latter circulation is very weak or missing at the time of origin.

These results are in accordance with similar investigations of the climatology for polar low outbreaks in the Norwegian and Barents Sea (Businger 1985) and in the northern Pacific Ocean region (Businger, 1987).

Thus the polar lows are, in general, formed near a pre-existing maximum of positive vorticity aloft, like in a lee trough or in an old occluded cyclone. The environment is also characterized by advection of cold air over a relatively warm sea surface.

3. Types of polar lows

Due to the limited number of cases, it is not possible to make a general classification of polar lows affecting Denmark. The lack of observations during most of their lifetimes makes it difficult to be precise as regards to the important physical processes involved. In this section, examples documenting the diversity of the polar low sample are given. It is, however, outside the scope of this paper to elaborate on the individual cases. In Section 4 different properties of the sample as a whole are discussed in more detail.

Businger and Reed (1989) reviewed the literature on the general characteristics of polar lows. They, like other authors, recognize that the great spawn of phenomena included in the term polar low makes it difficult to make a clear classification. They discuss three main types of polar lows: (1) the short-wave/jet-streak type, also called comma clouds; (2) the arctic-front type, associated with low level baroclinicity often near the ice edge also called the reversed shear type; and (3) the cold-low type, characterized by weak baroclinicity and strong surface fluxes. In a discussion of different types of polar lows affecting Scandinavia, Rasmussen (1986) added a fourth type of polar lows to the list: (4) the lee-trough type. Most of the 18 cases in this sample can be fitted into these four types.

None of the polar lows are of the typical comma cloud type, as, for example, seen along the US west

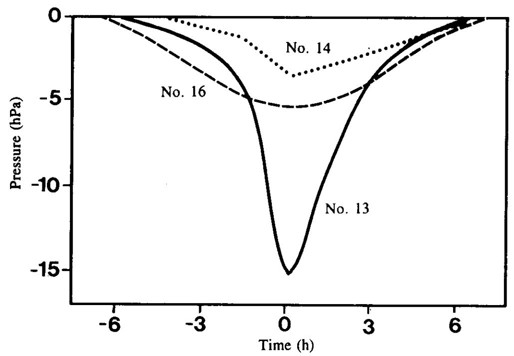

Fig. 6. Barograph curves for the three polar lows nos. 13, 14, and 16. The large scale pressure tendency has been removed to demonstrate the polar low disturbances clearer. The data from lows 13 and 16 are from Copenhagen Airport and low 14 are from Christiansø near Bornholm in the Baltic (see Fig. 8 for position).

coast. But the arctic-front type with the typical reversed shear cloud structure is seen in several of the lows, e.g., nos. 7, 17 and 18. The reversed shear cloud structure (see e.g., Reed and Duncan, 1987) is mainly seen in the first 1–2 days of their lifetimes after which time they begin to decay.

The third type are formed within old occluded cyclones or cold lows. The symmetric type, which Rasmussen (1986) termed "real" polar lows, has only one example in low no. 4. However, when it reached Denmark it was very weak and it dissipated while crossing Jutland. However, other lows along the Norwegian coast also form inside old occluded cyclones, e.g., lows nos. 12, 15 and 16. They are seen on satellite imagery to consist of loosely organized cloud clusters. Some, like low no. 16, develop shallow fronts, while moving southward approaching the main baroclinic zone. This low has been discussed in detail by Rasmussen and Aakjær (1989), and this change of appearance will be discussed further in Section 5.

The largest group of lows is the lee-trough type. They are typically formed in lee-troughs south or south-east of Iceland in northerly flows (nos. 2, 3 and 11) or in lee-troughs west and south-west of southern Norway in easterly to north-easterly flows (nos. 5, 6 and 8). Lows 5 and 6 are par-

Table 2. *List of wind and temperature observations from the Copenhagen sounding (06181) from the time the polar lows passed Denmark*

	Surface				500 hPa					N_0			
No.	U	T	θ	θ_e	U	T	θ	ζ	H	dry	eff.	R	$\frac{\delta U}{\delta z}$
1	6	0	1	10	9	−36	16	2.0	6.7	9.4	6.8	515	1.1
2	5	2	3	11	30	−39	12	3.1	5.2	7.9	3.5	335	4.8
3	5	−5	−3	3	15	−37	15	7.4	4.2	9.4	6.1	325	2.4
4	5	−3	−1	6	12	−39	12	2.8	6.6	9.0	6.7	485	1.1
5	5	0	2	11	18	−39	12	5.3	6.8	7.1	2.5	395	1.9
6	10	−2	−1	6	17	−40	11	−1.5	7.5	7.6	5.2	465	2.0
7	3	−1	0	8	4	−38	14	5.1	6.7	9.0	6.3	495	2.2
8	10	−1	0	8	30	−37	15	0.6	4.6	9.7	6.2	365	4.3
9	5	1	1	10	18	−31	22	9.9	4.2	10.7	6.4	370	2.4
10	15	3	5	14	25	−35	17	5.7	7.3	8.5	5.0	510	1.4
11	5	0	0	9	8	−38	14	4.9	6.5	9.0	6.0	480	2.0
12	8	3	4	13	8	−34	19	5.0	6.6	9.0	5.2	485	0.6
13	7	−2	−1	5	15	−38	14	11.2	5.6	8.3	5.5	380	4.5
14	10	2	3	12	15	−38	14	11.1	5.9	8.5	5.5	410	1.6
15	5	4	6	15	13	−32	21	10.5	6.9	9.1	6.4	515	1.9
16	4	−1	0	7	10	−41	10	10.0	6.2	8.3	5.2	420	1.1
17	5	0	−1	8	10	−40	11	21.8	5.1	9.1	4.9	380	2.0
18	6	2	2	10	17	−39	12	18.6	6.9	8.3	5.5	470	2.2
mean	7	0	1	9	15	−37	15	7.4	6.1	8.8	5.5	430	2.2

The horizontal wind-speeds (U) are in m/s, temperatures (T, θ, and θ_e) are in °C. The relative vorticity (ζ) is in $10^{-5}\,s^{-1}$. H and R are in km. The N_0's and $\delta U/\delta z$ are in $10^{-3}\,s^{-1}$. See text for further explanation of the symbols.

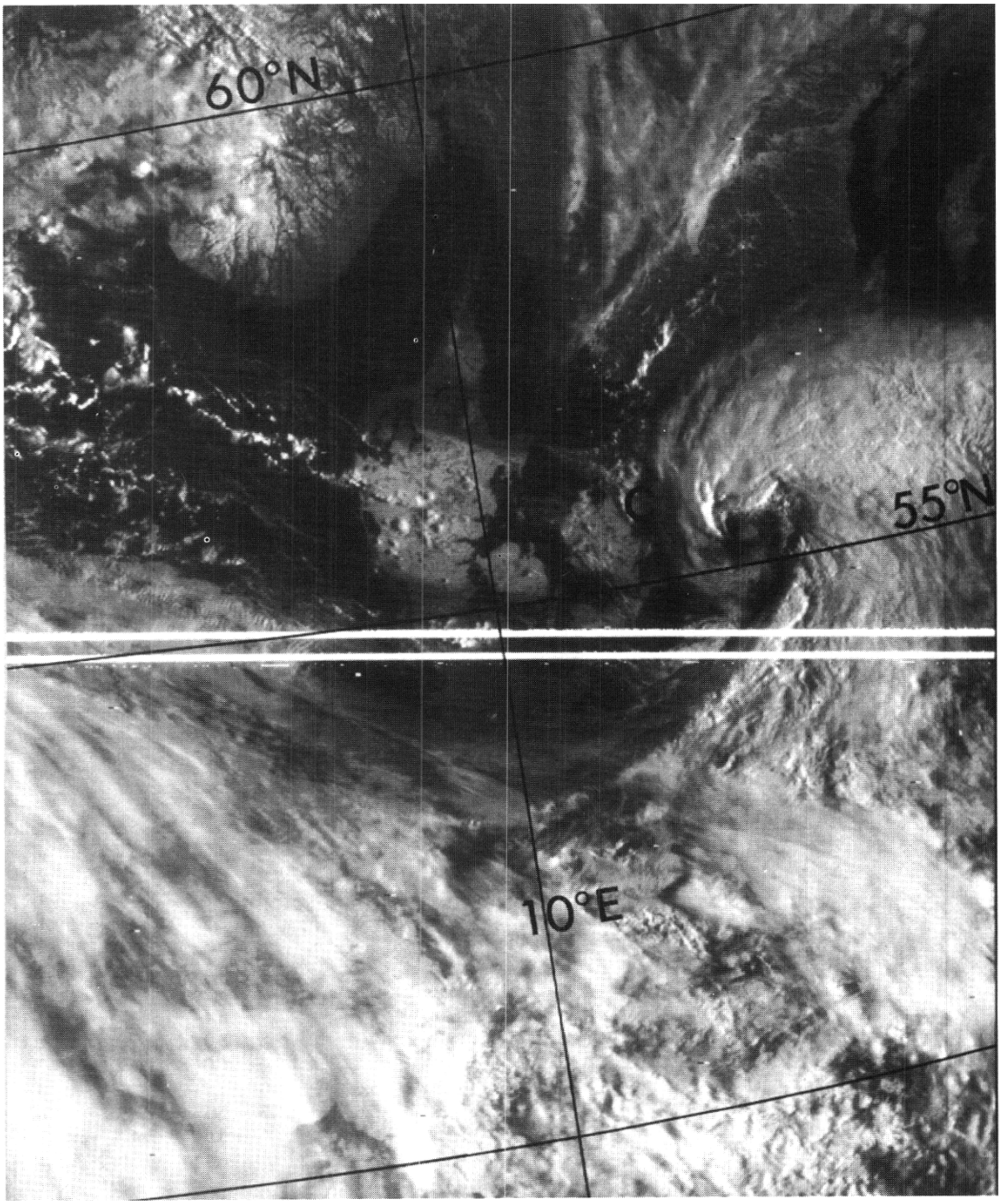

Fig. 7. NOAA-6 visible (channel 2) satellite image from 06.41 UTC 29 March 1985 (low no. 13). The low is situated just east Copenhagen (C). The strongest precipitation area is seen just west-north-west of the low center. Photograph courtesy of Observatory of Space Research, Danish Meteorological Institute.

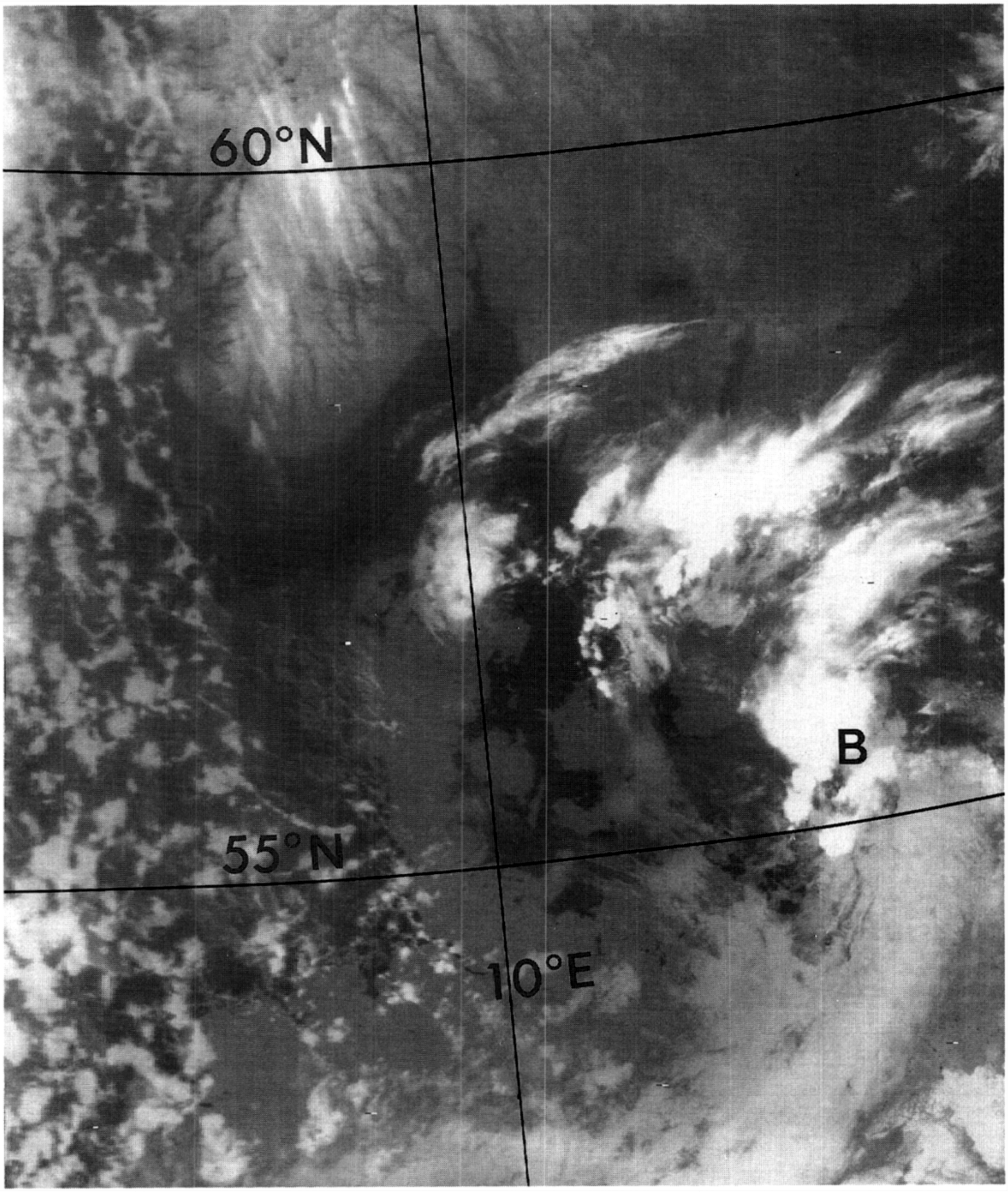

Fig. 8. NOAA-9 infrared (channel 4) satellite image from 01.35 UTC 26 April 1985 (low No. 14). The island of Bornholm is marked with (B). Photograph courtesy of the Observatory of Space Research, Danish Meteorological Institute.

ticularly interesting, since they are formed in the same persistent lee-trough in more or less the same place within 12–18 h. Also this type can form shallow fronts, as they get closer to the main baroclinic zone (e.g., low no. 2, see Rasmussen (1989), his Fig. 2).

To illustrate the variety of the polar low sample three barograph traces are shown in Fig. 6 as examples of a fast developing (no. 13), a moderate (no. 16) and a weakly developed polar low (no. 14). Two of these lows are not easily fit into the four polar low types discussed above, thus they merit a short description.

Low no. 13 developed strongly as it passed Denmark (close to 10 hPa in 3–4 h). It has been discussed in some detail by Rasmussen and Aakjær (1989), who termed it a "baroclinic" polar low. It was first found on 28 March 1985 near Iceland in a fronto-genetic zone as a small-scale baroclinic wave developing below a strong inversion around 700 hPa. As shown by Rasmussen and Aakjær the low resembled a small-scale extratropical cyclone including shallow fronts as it passed Denmark (Fig. 7). However, the barograph trace in Fig. 6 has the strongest pressure tendency very close to the low center, a feature which is more typical for

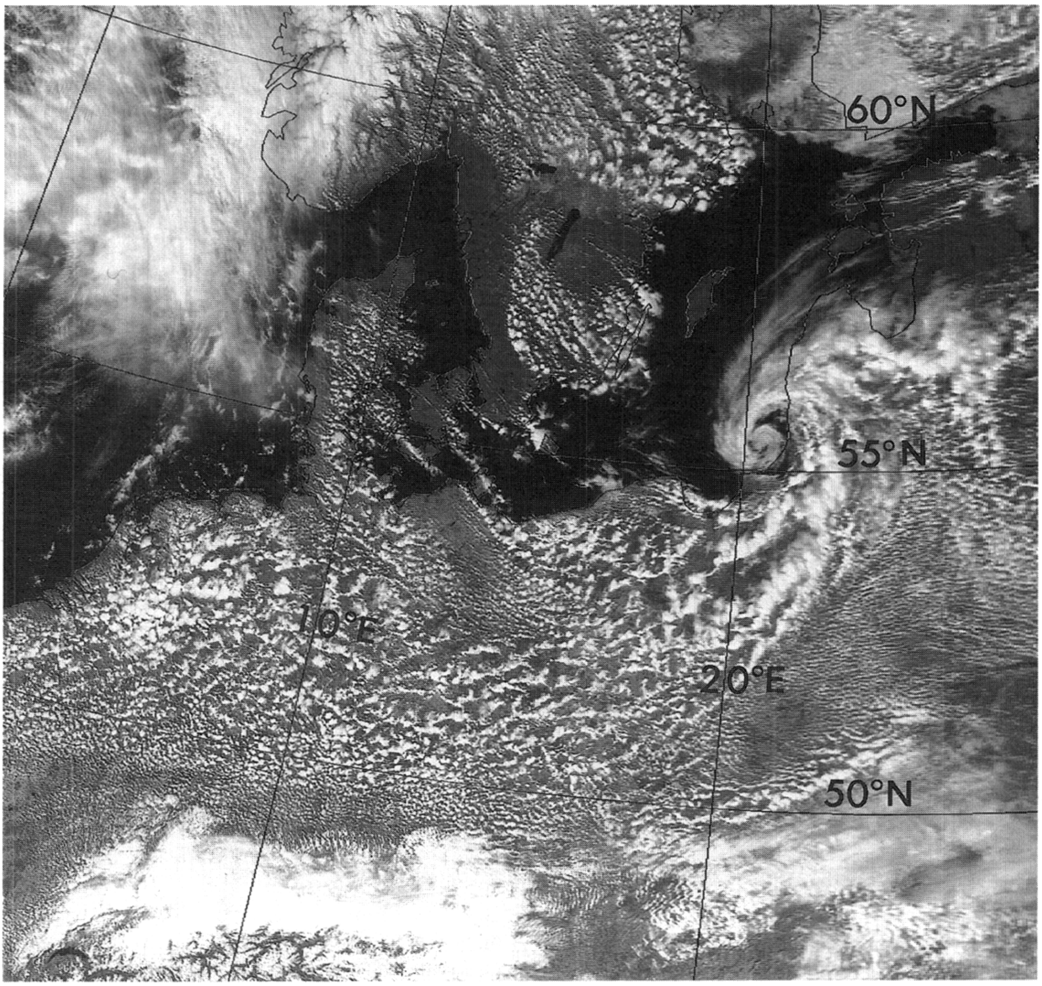

Fig. 9. NOAA-9 visual (channel 2) satellite image from 13.18 UTC 26 April 1985 (low no. 14). Photograph courtesy of Department of Electrical Engeneering and Electronics, University of Dundee.

tropical cyclones. Thus, they concluded that the rapid deepening was probably reinforced by the convection, which was observed near the low center.

The second interesting polar low is a weak development over Denmark occurring on 26 April 1985. It originated as a weak disturbance off the south-west coast of Norway in a cold air outbreak. As it passed over Denmark, it was still only around 3 hPa deep, as seen in Fig. 6. In the satellite imagery from 01.35 UTC on 26 April (Fig. 8) the low is seen to consist of a small group of large Cb-clouds. The size of the largest anvil is approximately 100 km across. At the time of the image the atmosphere was just below freezing over the land surfaces, while the sea was approximately 1.5°C. This favors convection over sea due to the cold air aloft (Table 2). At this time several of the synoptic stations reported hail and snow showers. However, the low passed quickly and 12 h later (Fig. 9), at 13.18 UTC, the Cb-clouds had developed into a beautiful vortex in the south-eastern Baltic of the same size as the anvil in Fig. 8. At that time the low was still weak. As seen in the surface analysis from 12 UTC (Fig. 10) the low never became deeper than 3–5 hPa. The cloud formation looked very much like other polar lows at this stage (see, e.g., Rasmussen and Aakjær, 1989, their Fig. 9, low no. 13). However, the horizontal scale of 100–150 km was remarkably smaller than low no. 13 (400–450 km). As will be discussed later in Subsection 4.7, the small scale of the polar lows, which sometimes is observed, is probably due to the fact that they form in an almost moist adiabatic environment near an upper level vorticity maximum. Why this particular low

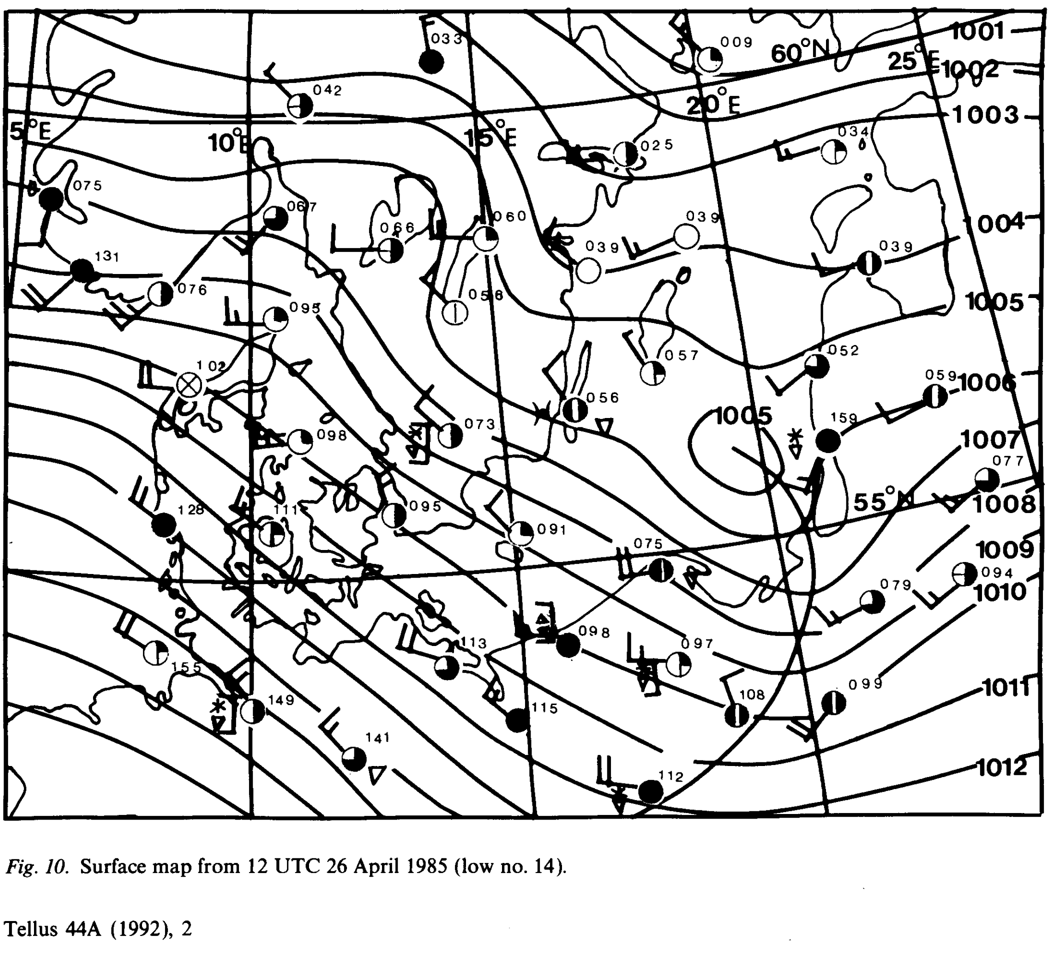

Fig. 10. Surface map from 12 UTC 26 April 1985 (low no. 14).

attains this very small scale is not clear, but it is suggested that possible reasons can be the small scale of the original disturbance (Cb-clouds), and that the forcing from the Baltic Sea has the same dimension.

4. Discussion of polar low properties

In this section some of the properties of the 18 polar lows will be discussed in more detail. Table 1 lists values of different parameters associated with the lows. Each of these parameters and their importance for polar low development will also be discussed.

4.1. Size

It can be difficult to define the size of a polar low. Looking at the surface observations, the horizontal scale, as defined by the diameter of the largest closed isobar, tends to be rather small, especially in situations with a strong background flow. On the other hand, looking at the satellite imagery, which sometimes is the only source of information, the cloud pattern indicates a much larger scale. In order to define the horizontal scale of a polar low more precisely, a method from Maddox (1980) is used. Maddox calculated the so-called structure function, i.e., the mean of the squared pressure difference between any two observations, as a function of the distance between them. It is only possible to use this method in situations where a sufficient number of pressure observations are available.

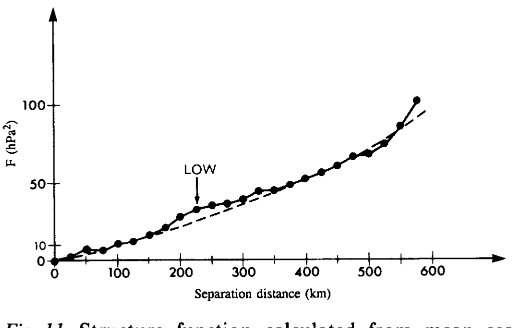

Fig. 11. Structure function calculated from mean sea level pressure data from 29 March 1985 at 06 UTC (low no. 13). The broken line indicates the function in case of a smooth pressure field without mesoscale disturbances. The "hump" indicates half the size of the low.

In Fig. 11, an example from low no. 13 is shown. The data used are mean sea level pressure data from all surface stations reporting at 06 UTC 29 March 1985 in an area of 500 km × 500 km around Denmark. The value of the structure function, F, is averaged and plotted for 25 km increments of station separation distance.

$$F(\text{dist}, \text{dist} + 25\text{ km}) = \frac{1}{n_{\text{dist}}} \sum_{n_{\text{dist}}} (P_i - P_j)^2.$$

Here P_i is the mean sea level pressure at station i, and n_{dist} is the number of station pairs (i, j) which have a horizontal distance in the interval [dist; dist + 25 km], where dist $= k \cdot 25$ km and $k = 0, 1, 2, \ldots$. The summation is done for these n_{dist} station pairs only. Maddox (1980) showed that in the absence of significant meso-scale disturbances, the structure function should be a smooth concave curve, as indicated by the broken line in Fig. 11. According to Maddox (1980) the "hump" at the 225 km distance indicates a feature in the pressure field on the 450 km scale. This size compares rather well with the dimension defined by the barograph trace shown in Fig. 6 and the satellite imagery in Fig. 7.

However, for most of the lows the size is subjectively estimated within an accuracy of 50 km. The sizes vary between 100 km or less for the very weak lows and up to 450 km for the strongest lows with a mean of about 260 km.

4.2. Strength

The strength of the lows is measured by the pressure perturbation of the low, i.e., the pressure difference between the center of the low and a hypothetical pressure at the same point, had the low *not* been present. This value can be estimated subjectively in two ways: either by inspecting the surface maps or from a barograph trace at a nearby station (Fig. 6). The methods give results which do not vary by more than a few hPa. The strengths of the 18 polar lows range from 2 to 15 hPa with a mean of 7 hPa.

4.3. Speed and duration

The polar lows are followed from their origin until they dissipate, and their speed as they pass over Denmark is estimated within 1–2 m/s. The lows from northern Norway and Iceland have travelled especially long distances, up to 2500 km, with an almost constant strength and size for more than 4 days. Some polar lows are seen to be very persistent features as long as they travel over a relatively warm sea surface. When they arrive over Denmark their speeds are generally around 10 m/s.

It should be noted that most of the polar lows are seen to pass Denmark without weakening. The only exceptions are weak polar lows, like no. 4, which dissipated trying to cross Jutland. Normally, polar lows, at least of the convective type, dissipate quickly after landfall (see, e.g., Rasmussen, 1989). Apparently, the polar lows crossing Denmark are either predominantly baroclinic systems, or, in case of mainly convective systems, there is "enough" warm sea surface in the Danish waters to sustain their circulation.

4.4. Precipitation

The precipitation from the lows is normally in the form of snow, in some cases mixed with sleet or rain, and it is recorded by almost 500 climatic stations in Denmark. These stations observe only once a day, and in some cases, it has been difficult to distinguish between the precipitation from the polar low and precipitation from other weather systems. The maximum precipitation recorded for a polar low is a total of 30–35 mm of (melted) snow corresponding to at least 50 cm of snow on the ground. The precipitation typically falls in a narrow 50–100 km zone to the left of the low track (Fig. 12).

Hail and thunder are sometimes observed, but these phenomena are not correlated with the largest amounts of precipitation. Large amounts can occur both in convective and non-convective situations.

4.5. Wind

Winds of gale force (> 13 m/s) are commonly observed in connection with the polar lows. In only one case a wind speed greater than 24 m/s was

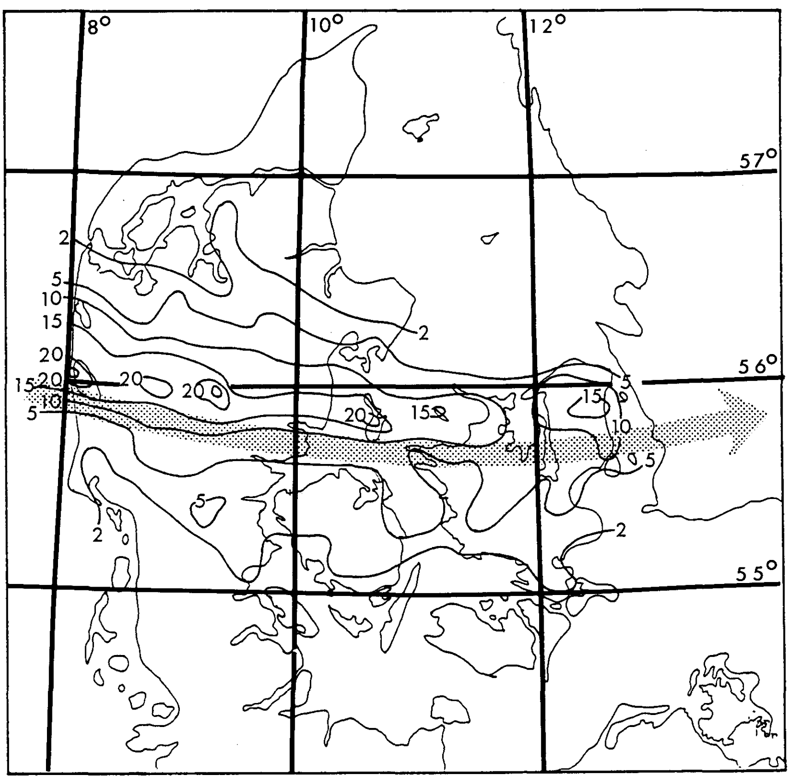

Fig. 12. Precipitation from the polar low 28–29 March 1985 (low no. 13). The arrow indicates the path of the low pressure center. Values are in mm of melted snow. Compare with the snow track seen in Fig. 7.

observed. This was mainly due to a very strong background flow. The pressure disturbances associated with the lows are in general rather weak. The resulting *relative* wind field around the low seldomly exceeds 10 m/s, except for the few strong lows. Therefore, the background flow gives a significant contribution to the resulting wind field. In most cases there is a weakening of the winds upstream of the low and a strengthening of the wind field downstream of the low.

4.6. Correlation between parameters

To investigate the extent to which the different observations of the polar lows in Table 1 show common characteristic properties for all the 18 cases, correlation coefficients between the parameters have been calculated. It will be assumed that correlation coefficients with an absolute value above 0.54, which corresponds to a 1.0% significance level, reflect common features for the polar low sample. Most of the correlations are small, however, and only 3 of the correlations can meet this criteria.

The highest correlation coefficient, 0.84, is found between strength and size of the lows. A rather high correlation of 0.63 is also found between polar low strength and maximum precipitation. However, there is no correlation between strength and adverse effects like wind, hail or thunder. The weak low no. 10 had, for example, recordings of storm (25 m/s) due to a strong background flow.

The wind is found to correlate with polar low speed with a correlation coefficient of 0.62. Thus, the maximum wind is more correlated to the general synoptic flow than to the strength of the low itself. This is consistent with the fact that the lows in general are rather weak phenomena.

Thus, the correlation analysis shows only few common characteristic features from the sample as a whole, e.g., that the largest lows are also the strongest and those with the most precipitation. It is suggested that one reason for this result can be that polar lows are in rather different stages of development, when they pass Denmark. Some are newly formed, while others are in their dissipating stage. This fact makes the comparison of all 18 cases as a whole difficult.

4.7. Discussion of upper air parameters

In Table 2, upper air winds and temperatures are shown for all 18 cases from the Copenhagen sounding (06181) at the time the lows passed Denmark. The height (H) of the inversion or tropopause below which the polar lows develop is also shown together with a stability parameter (N_0), the Brunt-Väisälä frequency:

$$N_0^2 = \frac{g}{\theta_0} \frac{\delta\theta}{\delta z}.$$

Here, θ is the potential temperature and θ_0 a reference value. In Table 2, θ_0 is set to 0°C and $\delta\theta/\partial z$ is calculated as a mean over the height H. Though there are differences from low to low, the polar low environment is generally seen to be characterized by a rather deep layer with a almost moist adiabatic stratification.

The horizontal winds in Table 2 show little mean wind shear over the height H, $\delta U/\delta z$, indicating only weak baroclinicty. However, in a few cases (nos. 2, 8, and 13) a significant vertical wind shear is present indicating that baroclinic processes may play an important role, a point which will be elaborated in Section 5.

It is evident from Table 1 that the sizes of the polar lows are small some even down to a scale of 100 km. This small scale is often discussed in terms of the Rossby radius of deformation as defined by:

$$R = \frac{N_0 H}{f}.$$

Here f is the coriolis parameter. According to Frank (1983) a vortex will be dynamically stable if its scale is equal to or larger than R. In general, R will be small if the atmosphere has a low stability, a low scale height (H), or if the vortex is situated far north with a large coriolis parameter.

R has been calculated for the 18 cases, as shown in Table 2. It can be seen that the values of R are fairly similar, ranging from 325–515 km. The values do not correlate significantly with polar low size (correlation coefficient of -0.43), indicating that other factors than R determine the actual polar low scale. R is rather large, in the mean 430 km, as compared to the mean size of 260 km found in Table 1. However, there are at least two factors in the polar low environment that will act to lower the limit for dynamical stability.

Firstly, the atmosphere is almost moist adiabatic. This means that the atmosphere is almost unstable to moist adiabatic processes. The influence on R can be estimated by calculating an effective N_{eff} using the equivalent potential temperature:

$$N_{\text{eff}} = \frac{g}{\theta_0} \frac{\delta\theta_e}{\delta z}.$$

As seen in Table 2, N_{eff} is some 40% smaller than N_0. Using this value in the expression for R gives a mean deformation radius of 270 km.

Secondly, the polar lows form and develop in an atmosphere with cyclonic rotation (see Subsection 2.1). This relative rotation will lower the radius of deformation. A modified local radius of deformation can be defined by (Frank, 1983):

$$R_1 = \frac{N_0 H}{\sqrt{\zeta + f}\sqrt{2(U/R_c) + f}}.$$

Here ζ is the relative vorticity, U is a typical horizontal wind speed and R_c is a typical radius of curvature.

The relative vorticity has been estimated over Denmark geostrophically from the ECMWF height analysis, as discussed in Subsection 2.1 and shown in Table 2. ζ varies from 0–2 times the coriolis parameter with a mean of $0.6f$. U and R_c are not easily calculated for each polar low due to the small scale of the lows. However, it can be estimated from the surface maps that typical values of U and R_c are 5–10 m/s around the 100 km radius. This makes the factor $2U/R_c$ of the order of 1–2 times the coriolis parameter. In Aakjær (1987) it was shown by calculating the relative wind around polar low no. 13, that the winds were as high as 15–20 m/s just 25–50 km from the center. This makes the factor $2U/R_c$ of the order of 10–15 times f close to the center of low no. 13. This is, however, a result of the low itself, and not the polar low environment.

Using $\zeta = 0.6f$ and $2U/R_c = 1.5f$ we get

$$R_1 \approx 0.5R.$$

Combining the two factors gives an "effective, local" radius of deformation of 135 km. In the case of the small scale low No. 14, as discussed in Subsection 3, an "effective, local" radius of deformation of 110 km ($\zeta = 1.0f$ (from Table 2) and $2U/R_c = 2.0f$ (from Fig. 10)) is found. This case has, indeed, a small radius of deformation indicating a possible stable vortex of this size, as was observed.

Thus, it seems that both the almost moist adiabatic lapse rate and the positive relative vorticity in the polar low environment contribute significantly to reduce the scale of the lower limit for a stable (dynamically large) polar low.

5. Comparison with linear theory

10 years ago, it was questioned whether polar lows were of mainly baroclinic or convective nature. Later, it was realized that there exist a broad variety of different types, ranging from purely baroclinic types to predominantly convective types (see, e.g., Rasmussen and Lystad, 1987). The question of the nature of the polar lows near Denmark will be investigated in this section using a theoretical model. A linear model of baroclinic instability with a simple parameterization for cumulus heating was developed and discussed Craig and Cho (1988 and 1989), hereafter called CC88. They showed that both baroclinic instability and CISK can contribute to polar low development. The relative importance depends on the so-called heating parameter ε. Craig and Cho's model will in the following be applied to the 18 polar low cases presented in this paper.

The ε-parameter in CC88 is given by

$$\varepsilon = \frac{g}{\theta_0} \frac{f}{Q} \frac{1}{H} \frac{L_c}{c_p} (1-b)\, q(1+r+\eta),$$

where L_c is the latent heat of condensation of water, c_p is the specific heat of air at constant pressure, H is the height of the atmosphere, $(1-b)$ is the portion of moisture condensed out during cumulus cloud formation, q is the specific humidity in the boundary layer, r and η are the approximated contribution to column moisture from the surface evaporation and moisture convergence above the boundary layer. Q is a stability parameter defined by

$$\frac{Q}{f} = N^2 = N_0^2 - \left(\frac{\delta U}{\delta z}\right)^2,$$

where U is the horizontal wind speed, f the coriolis parameter, and N_0^2 is the (dry) Brunt-Väisälä frequency.

The vertical changes in U and θ should be taken as mean values over the entire vertical column from the surface to H, the height of the inversion below which the polar low is confined. In most cases H is the height of the tropopause.

In CC88 it is shown that for values of ε below 1.4 the modes with fastest growth resemble baroclinic modes and that they resemble CISK modes for values above 2.0. For values of ε between 1.4 and 2.0 the modes can have significant contributions from both baroclinic and CISK processes. To calculate ε it is necessary to estimate the parameters b, r and η. This is, however, difficult for the 18 polar low cases. The calculations can be facilitated by using the empirical fact that the product $(1-b)(1+r+\eta)$, which goes into the expression for ε, is approximately constant. Using the CC88 values for the 6 polar low cases in their Table 2, that covers a broad range of different types of polar lows and comma clouds at different latitudes, the constant can be estimated to be:

$$(1-b)(1+r+\eta) = 2.5 \pm 0.2.$$

The rest of the parameters, Q/f, H and q, can easily be estimated from the Copenhagen soundings as shown in Table 2.

Table 3 lists the results of the calculations. It should be emphasized that the ε-parameter is sensitive to even small changes in the vertical stratification and the vertical wind shear. This introduces a rather large uncertainty in the estimation of the parameter. However, most of the lows have ε in the transition region between 1.2 to 1.9, except for three of the stronger polar lows (nos. 2, 5, and 13), which have values above 2.0. These values suggest that both baroclinicity and convection can be active processes for most of the lows.

The ε-values for the 2 strongest developing lows, nos. 2 and 13, indicate from the conclusions made by Craig and Cho, that the lows primarily are of convective nature. It can be seen in Table 2 that the high ε-values for these two lows are caused by a low stability parameter Q/f. This parameter is in turn small due to a strong vertical wind shear, indicating that the disturbances also have a strong baroclinic influence. Apparently, this last result is in contradiction with the conclusions of CC88.

It is noted in CC88 that the wind shear term in Q/f is normally quite small, around 5% of Q/f. Thus, in the discussion that follows, they use the term Q/f synonymous with the static stability, N_0^2. In most of the polar low cases shown here this is also true. However, for the lows nos. 2 and 13 the wind shear significantly reduces the stability term Q/f. In these (from their point of view) extreme cases, the conclusion of linking a large value of ε to a pure CISK mode does not hold, since we only have CISK modes, when $\delta U/\delta z$ is small.

For polar low no. 16 Rasmussen and Aakjær (1989) showed that it changed type during its lifetime according to the satellite imagery. For this low, ε and related parameters are calculated over the Norwegian Sea, where it was seen to consist of mainly convective cells and again later over Denmark, where shallow fronts developed indicating a possible baroclinic influence. The results are shown in Table 4. Here ε is seen to be large over the Norwegian Sea and smaller over Denmark, which is in agreement with the general conclusions of CC88.

CC88 found good agreement between the observed polar low size and the wavelength of the most unstable mode in the model. This result is not found for the 18 polar lows in our sample. The

Table 3. *Estimates of the heating parameter, ε, the wavelength, growth rate and phase speed of the most unstable mode in Craig and Cho (1988)*

No.	ε	Wavelength (km)	Growth rate ($10^{-5}\,s^{-1}$)	Phase speed (m/s)
1	1.2	650	1.4	4.1
2	3.2	700	13.1	23.8
3	1.5	380	4.2	6.4
4	1.2	600	1.3	3.6
5	2.3	680	5.2	11.4
6	1.4	540	4.0	9.1
7	1.4	570	3.5	8.7
8	1.8	470	9.0	14.8
9	1.7	510	3.8	7.0
10	1.6	640	2.8	6.5
11	1.5	560	3.3	7.9
12	1.7	630	1.1	2.7
13	2.0	470	11.7	19.3
14	1.5	520	2.9	6.0
15	1.3	610	2.8	7.5
16	1.6	520	2.1	4.5
17	1.8	500	4.0	7.4
18	1.5	540	4.0	9.2
mean	1.7	560	4.4	8.9

wavelengths are in the mean 560 km or more than twice the mean of the polar low size. However, the CC88-model is dry, except for the parameterization of convective heating in the temperature equation, and the effect of an existing large scale rotation for the polar low environment is not considered. As shown in Section 4.7 this can significantly reduce the length scale N_0H/f, as used by CC88. Taking these limitations into account, we can conclude that the CC88 model describe the mean polar low size reasonably well.

However, the model does not describe the individual polar low sizes well, since the model wavelengths do not correlate with the observed polar low size (correlation coefficient: 0.07). There can be several reasons for this discrepancy. First of all, there is no reason why the results from a linear model should match exactly with observations, they probably merely give an order of magnitude. Secondly, the lows are in very different stages of their development when they pass Denmark, some in a growing phase, some in a decaying phase. Thus, they might not all be described well by the model. Thirdly, and probably the most important, the actual polar low size may be determined by other factors than those used in the model, e.g., the size of the forcing from the sea surface, the size of the upper level vorticity maximum, etc.

In terms of growth rates, we find the largest growth rates calculated from the model for the strongest lows, i.e., nos. 2 and 13, which both developed rapidly when passing Denmark. Finally, the calculated phase speeds from the CC88 model do not correlate significantly with the speed of the low (correlation coefficient: 0.21), as might be expected.

The CC88-model does seem to explain qualitatively some of the observed polar low features, like mean size and growth rate for the 18 polar low cases. The analyses also showed that for most of the polar lows both convection and baroclinic processes could be of importance. However, it is not capable, in general, of distinguishing the strong and clearly baroclinic polar lows from the others by the single parameter ε.

Table 4. *As Table 3 for polar low no. 16; the data are from weather ship Mike 00 UTC 13 March 1988 (a) and from Copenhagen 12 UTC 14 March (b)*

No.	ε	Wavelength (km)	Growth rate ($10^{-5}\,s^{-1}$)	Phase speed (m/s)
(a)	2.2	550	2.4	4.3
(b)	1.6	520	2.1	4.5

6. Conclusions

This paper describes 18 cases of polar lows passing Denmark in the 10 polar low seasons (November to April) from 1980/81 to 1989/90. Their different properties have been analysed by surface observations, upper air observations and by satellite imagery. The Craig and Cho (1988, 1989) model has been applied to investigate the nature of the disturbances.

It was found that the polar lows are initiated in an atmosphere characterized by a deep, almost moist adiabatic atmosphere with pre-existing large scale positive vorticity and cold air advection aloft over a relatively warm sea surface. The lows are rather different from one another both in size and strength, as well as in terms of adverse effects like precipitation and winds. The strongest lows show large precipitation amounts of up to 50 cm of snow and strong winds up to gale force. The most common types are the lee-trough and occlusion induced types. Not all lows fit into the general classifications and two lows, a rapidly developing "baroclinic" polar low and a weak small scale low forming out of a small group of Cb-clouds, are discussed. Dispite their small size, the lows are rather stable systems that can persist for up to 4 days and travel as far as 2500 km. It is suggested that a possible reason for the small size of the lows is that they form in an almost moist adiabatic atmosphere with significant large scale positive vorticity. In most polar lows, both baroclinic as wel as convective processes are important, but the two strongest developing lows have strong baroclinic influence.

The linear theory of Craig and Cho (1988 and 1989) is used to describe the lows. The model is found to be able to account for some polar low observations such as mean polar low size and large growth rates. However, a distinction between the clearly baroclinic polar lows and the more convective ones is not possible by using a single parameter ε.

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