# POLAR LOWS

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Summary: This paper reviews (1) observed features of polar lows, (2) theoretical ideas concerning their origins and (3) results of numerical modelling experiments aimed at simulating their development.

## 1. INTRODUCTION

Since some controversy surrounds, or at least in the past has surrounded, the use of the term polar low, it is important to begin any discussion of the subject with a definition of what the author means by the term. We will use it here in a broad sense to denote any type of small synoptic or subsynoptic cyclone, of an essentially non-frontal nature, that forms in a cold air mass poleward of major jet streams or frontal zones and whose main cloud mass is largely of convective origin. The cloud mass in question may appear on satellite images as a small comma-shaped system or alternatively as a spiral or circular pattern, sometimes with an eye-like center. The former type of system generally occurs in proximity to a trailing front or the jet stream axis and the latter tends to be located farther back in the polar or arctic air mass (Locatelli et al., 1982). Rasmussen (1983) in a review article on mesoscale disturbances in cold air masses refers to the former type as comma clouds and the latter as "true" or "real" polar lows. Locatelli et al. refer to both types as "vortices in polar air streams". Here we use the term polar low in a generic sense to include all phenomena that fit the above description. Some justification for this usage is provided by reexamination of cases that have gone under the rubric of polar lows in the early literature. It is not at all clear that the cases can be relegated to a single category.

The object of this paper is to present a brief overview of polar lows, as just defined. Three aspects of the subject will be considered. In Section 2 observed characteristics of the systems will be described. In Section 3 theoretical ideas and studies concerning their origins will be reviewed. The results of recent experiments in polar low prediction that

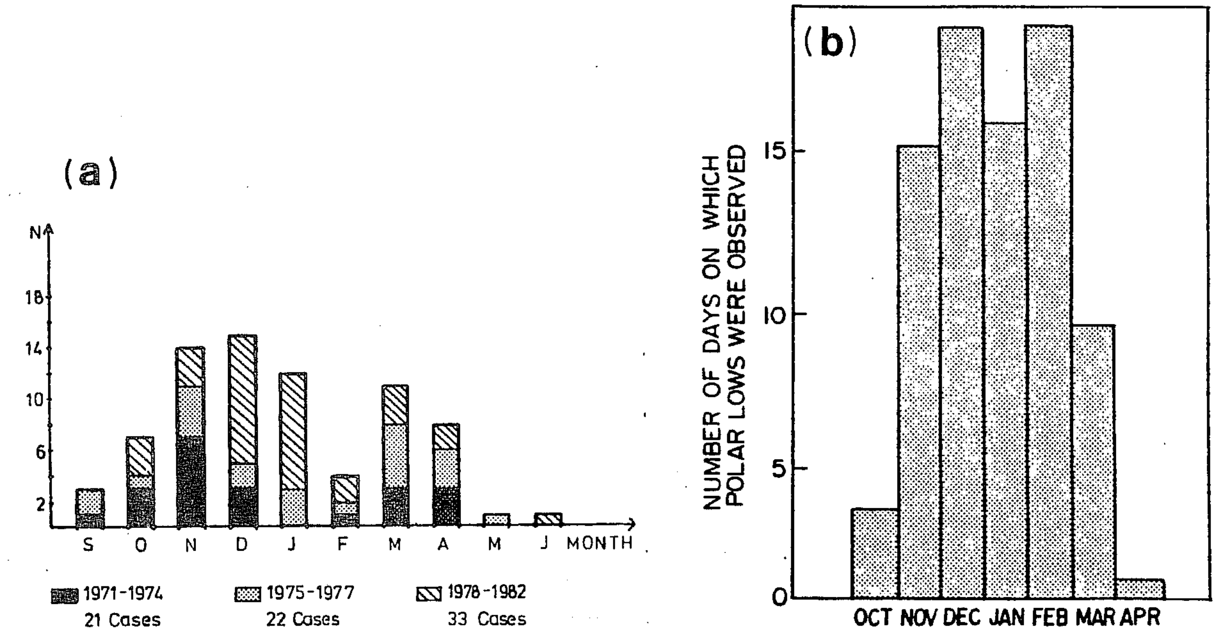



Fig. 1.(a) Frequency distribution of polar lows near Norway for the period 1971-1982 (from Lystad, 1986) and (b) frequency distribution in the Bering Sea and Gulf of Alaska for the period 1975-1983 (from Businger, 1987).

have made use of real data and advanced mesoscale prediction models will be presented in section 4.

## 2. OBSERVED FEATURES

### 2.1 General characteristics

Polar lows are essentially cold season, maritime events. The seasonal variation of systems affecting the Norwegian coast or ships near the coast is illustrated in Fig. 1a. The maximum frequency occurs in the period between October and April. A nine year climatology of polar low occurrence in the Bering Sea and Gulf of Alaska (Fig. 1b) reveals an even sharper winter peak.

The airstreams within which polar lows form are invariably characterized by cyclonic flow or shear (Reed, 1979; Mullen, 1979) by small static stability in the boundary layer with conditionally unstable lapse rates extending locally as high as the mid troposphere (e.g. Mullen, 1979) and by substantial heat and moisture fluxes from the underlying ocean (e.g. Reed and Blier, 1986b; Shapiro et al., 1987). Composite charts (Fig. 2)

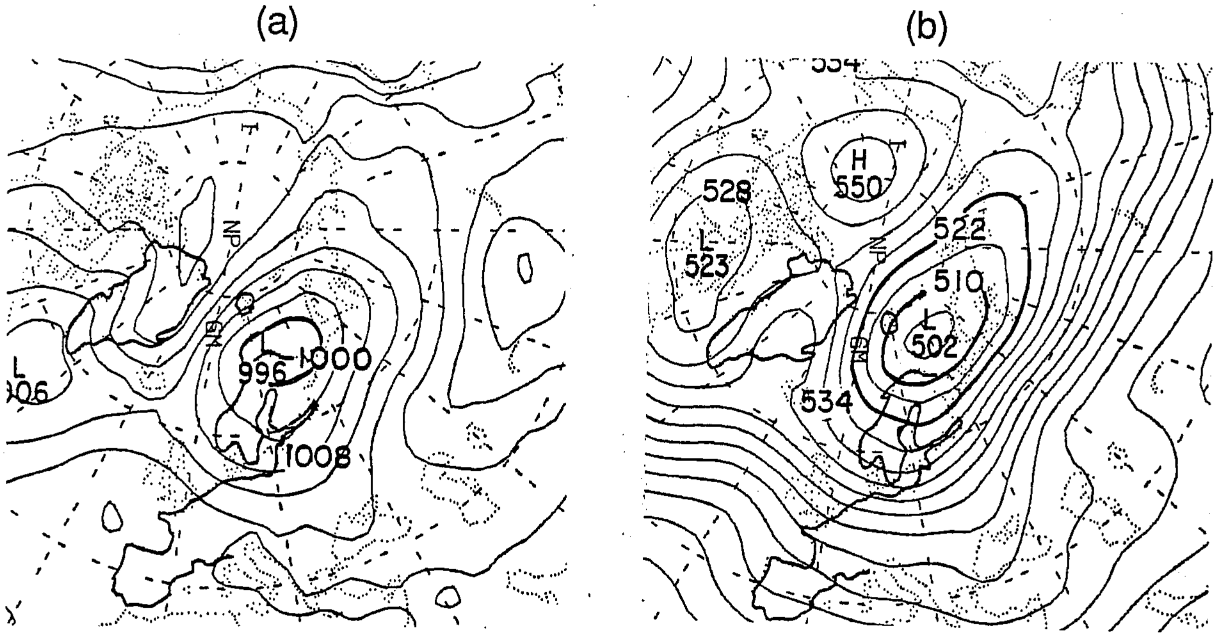



Fig. 2. Composite charts of (a) surface pressure and (b) 1000-500 mb thickness for 52 cases (1971-1982) of polar lows in the Norwegian Sea. (From Businger, 1985)

of surface pressure and 1000-500 mb thickness for 42 cases of polar lows in the Norwegian and Barents Seas, reproduced from Businger (1985), clearly show that large cold pools of cyclonically rotating air provide the most favorable environment for polar low outbreaks.

Favored regions of formation and travel are the Greenland, Norwegian and Barents Seas, and the area from south and east of Iceland to Great Britain, and the North Sea. It has recently been documented that polar lows commonly occur in the Bering Sea and the Gulf of Alaska within large-scale environments similar to those portrayed in Fig. 2 for the North Atlantic (Businger, 1987). The aforementioned are all regions of relatively warm, open water that lie adjacent to ice fields or cold continents.

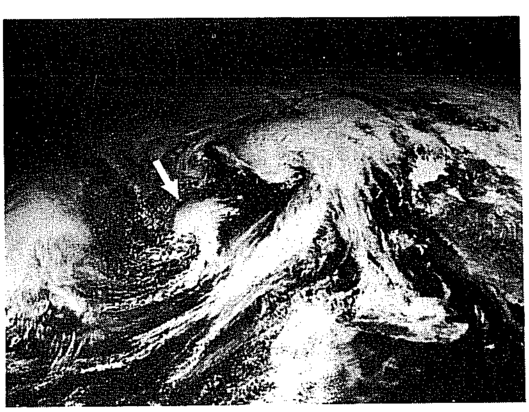
The comma cloud type can occur anywhere in the extratropical Pacific or Atlantic, but are most likely to form in the western oceans where the prevailing winds often transport cold, continental air across warm oceans currents.

## 2.2 Types of polar lows based on a synoptic-physical classification

As yet no widely accepted method exists for classifying polar lows though schemes have been proposed based on their appearance in satellite imagery (Carleton, 1985; Forbes and Lottes, 1985) and on the synoptic situation (Lystad, Hoem and Rabbe (in Lystad 1986)). We propose a classification that is based on a combination of synoptic features and physical considerations. We regard our scheme as highly tentative and more aimed at diagnosing common types of developments than at classification for its own sake.

### 2.2.1 Upper level, short-wave/ jet streak type

This is the aforementioned comma cloud type. Examples can be found in Reed (1979), Mullen (1979) and Reed and Blier (1986 a, b). Satellite manuals (Anderson et al., 1969; World Meteorological Organization, 1973) also contain descriptions. Figure 3 shows a satellite image of a well developed small comma cloud located to the rear of a synoptic-scale frontal cyclone. Typically the comma cloud starts as a region of enhanced convection in the positive vorticity advection (PVA) region ahead of an upper-level short-wave trough (or from an alternative point of view in the



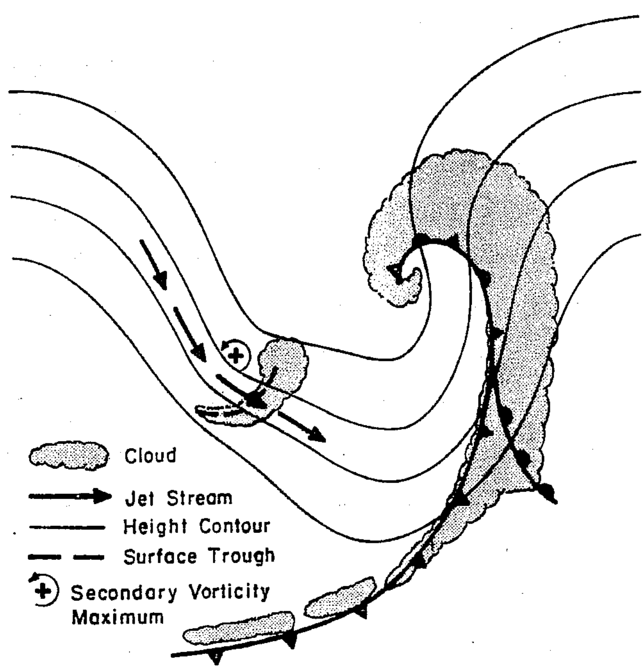



Fig. 3. Satellite visible image of small comma cloud (arrow) in the North Pacific.

Fig. 4. Schematic diagram showing typical relationship of comma cloud to major frontal cyclone and upper-level jet.

left front exit region of a jet streak). A surface trough (often marked TROF by U.S. analysts) lies near the rear of the comma tail. In the more strongly developed cases a low pressure center lies beneath the comma head and the trough may assume briefly a front-like structure. Weak to moderate baroclinity exists within the cold air mass throughout the depth of the troposphere. A schematic representation appears in Fig. 4.

2.2.2 <u>Reversed shear type</u>

This type is commonly found over the seas to the west and north of Norway. Reversed shear refers to a situation in which the storm motion (or wind at the steering level) is in the direction opposite to the thermal wind, unlike the situation that prevails with the comma cloud type which propagate in the direction of the thermal wind. Duncan (1978) was first to identify the reversed shear case and to elucidate the structure and dynamics of the disturbances.

A particularly striking and clean-cut example of reversed shear polar lows, involving a succession or train of four lows that formed during a two day period, is shown in Figs. 5-7. Figure 5 shows infrared images of the four lows (labelled 1, 2, 3,4) at approximately 12 h intervals. The disturbances are spaced about 5-600 km apart and are moving southwestard at about 5 $ms^{-1}$. Representative constant pressure charts for the period appear in Fig. 6. It is evident that the lows are being steered southwestward in conformity with the low-level winds and that the latter are strongest near the surface where the thermal gradient is also strongest. From the orientation of the isotherms, it is apparent that the thermal wind is directed opposite to the low-level flow. Figure 7 depicts a cross section taken along the line AB in Fig. 6. The storm track is located near the low-level jet core. An increasingly deep layer with a near adiabatic lapse rate extends outward from the ice edge to the vicinity of the storm track. It is clear that the polar lows are forming within a shallow baroclinic zone of small static stability and that the thermal contrast is produced at least in part by differential surface heating. Air to the north flows mainly over the ice and experiences little heating; air to the south flows over relatively warm water and is strongly heated and moistened from below.

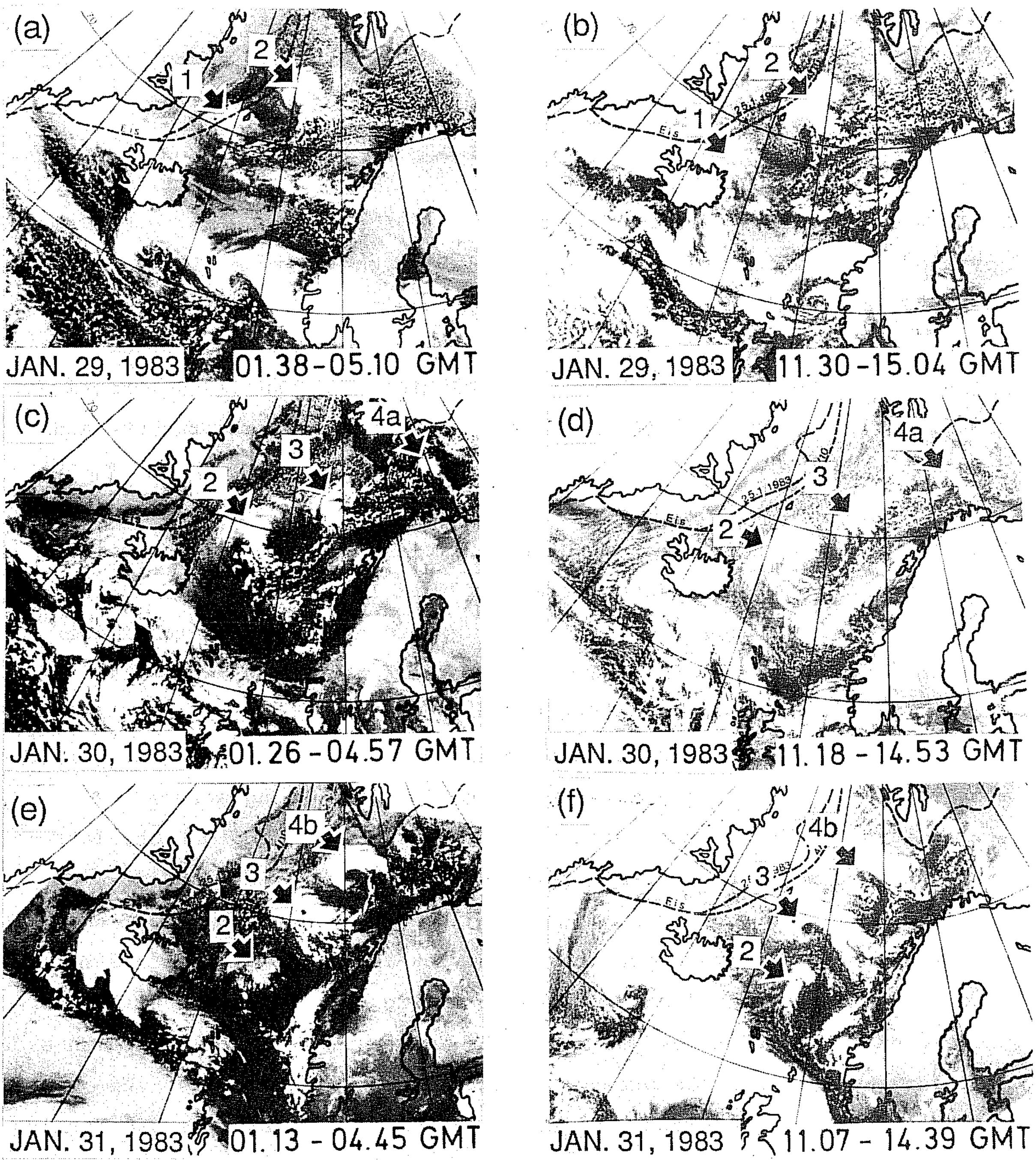



Fig. 5. NOAA satellite images of a series of polar lows. Arrows indicate positions of polar lows 1-4. (Courtesy of M. Eckardt, Free University of Berlin)

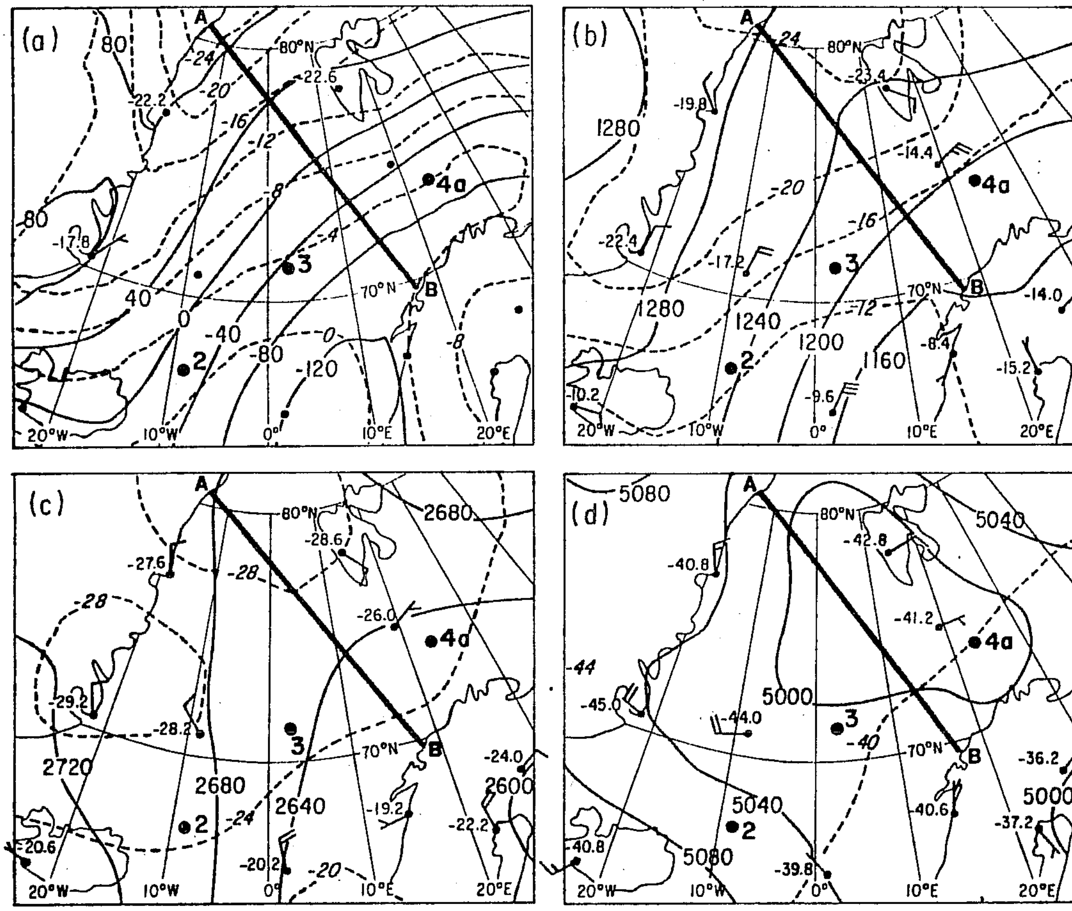



Fig. 6. (a) 1000 mb, (b) 850 mb, (c) 700 mb and (d) 500 mb charts for 1200 GMT, 30 January 1983. Solid lines contour at 40 m intervals; dashed lines isotherms at 4° C intervals. Dots indicate positions of polar lows. (From Reed and Duncan, 1987).

The reversed shear case is further illustrated in Fig. 8 where it is contrasted with the forward shear type represented by the short wave/jet streak systems. In both cases the upward motion and comma-shaped cloud pattern are located, in conformity with the Sutcliffe development principle, where the thermal wind advects positive vorticity, i.e. down-shear of the trough. However, because of the opposite relationships between thermal winds and steering level winds, in one case the cloud system lies ahead of the trough and in the other case to its rear. In some cases (Grønas, et al., 1986b) the reversed shear disturbances appear to initiate in a tongue of warm air that protrudes northward over the open sea to the west of Spitzbergen and Bear Island.

### 2.2.3 Combined type

The foregoing examples highlight two quite distinct flow patterns that are associated with polar low development, one characterized by upper-level

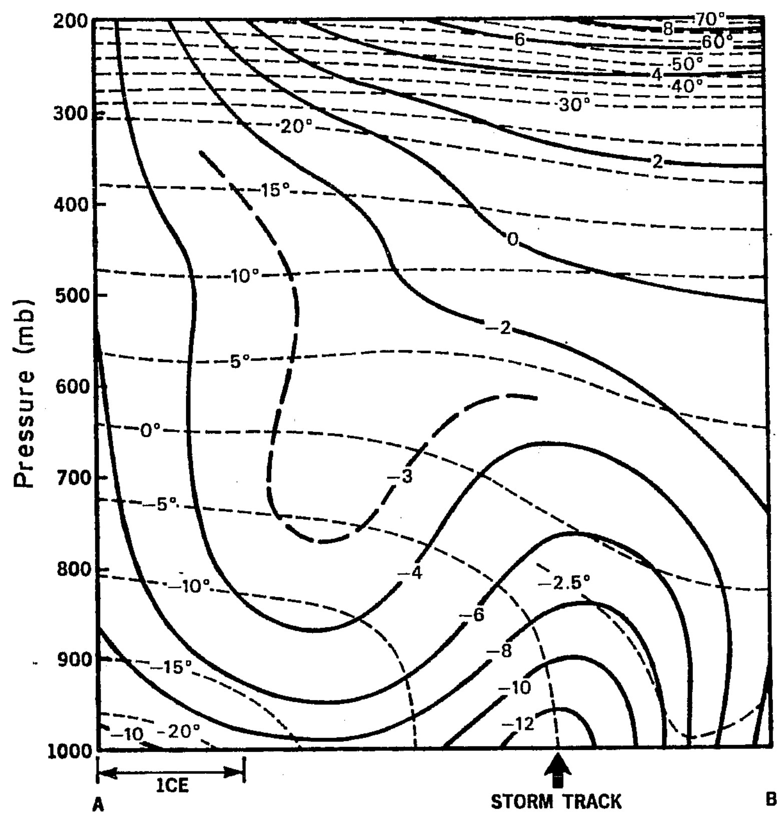



Fig. 7. Cross section along line AB in Fig. 6. Solid lines are isotachs (m $s^{-1}$). Dashed lines are potential isotherms (°C). (From Reed and Duncan, 1987)

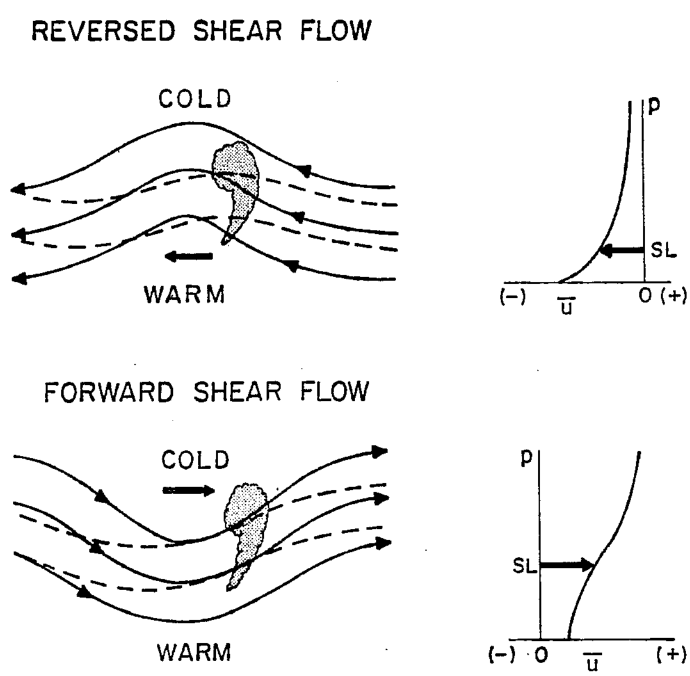



Fig. 8. Comparison of structures of disturbances in reversed shear flow (top) and forward shear flow (bottom). Solid lines, streamlines; dashed lines, isotherms. Heavy arrows, phase propagation vector and steering level (SL) wind. Stippling, comma cloud.

PVA and the other by shallow baroclinity. When an upper-level short wave traverses the marginal ice zone, it is possible for a system to develop that combines both features. Cases presented by Rasmussen (1985) and Businger (1985) are perhaps good examples of such mixed developments. The Rasmussen case will be further discussed and illustrated in the next section.

### 2.2.4 Inner occlusion type

Sometimes small comma or spiral-shaped cloud patterns of convective character are observed to flair up within the inner cores of old occlusions or cold lows without any obvious association with upper-level short waves or low level baroclinic features. An example of an extreme case of this type will also be discussed and illustrated in the next section.

## 2.3 Hurricane-like cores

Sustained maximum winds in polar lows are generally weaker than 20 m $s^{-1}$, but cases exist in which the winds exceed this limit, sometimes reaching speeds as high as 30 to 35 m $s^{-1}$. In some cases the extreme winds can be attributed to a strong background current superimposed on a cyclonic circulation of normal intensity. However, in other cases they are associated with small, hurricane-like vortices embedded within a larger polar low or synoptic-scale low. It is not clear at this stage whether such systems should be regarded as a distinct class of polar low or as embedded sub-structure within a larger system. In any case they are of sufficient importance to warrant separate discussion.

A particularly illuminating example of such a system that developed over the Barents Sea has been documented by Rasmussen (1985). Satellite images of the system taken at 0250 GMT and 1345 GMT 13 December 1982 are shown in Fig. 9. By this time the cloud pattern of the system was already fully developed. Antecedent conditions at 500 mb are displayed in Fig. 10, and a sequence of surface maps commencing at about the time of the satellite picture appear in Fig. 11. A geographical map showing land and ice boundaries and sea surface temperatures is presented in Fig. 12.

The upper level chart for 1200 GMT 12 December (Fig. 10b) shows a sharp trough and closed low west of Bear Island. The path of this short wave

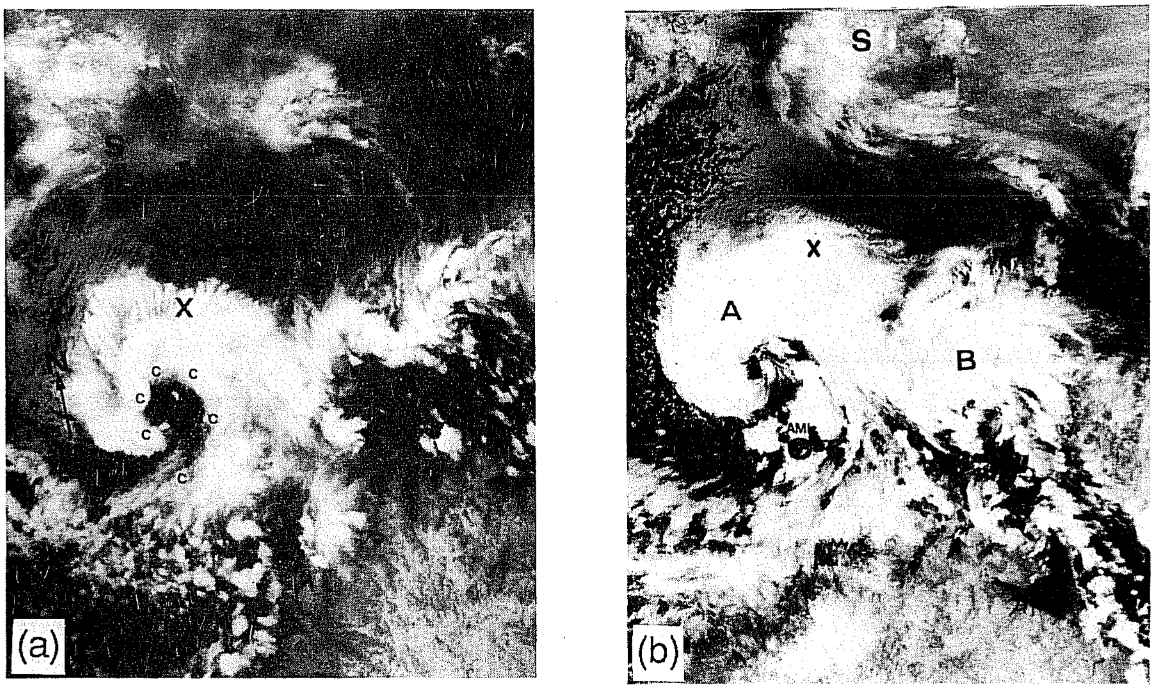



Fig. 9. NOAA-7 infrared images for (a) 0250 GMT, and (b) 1345 GMT December 13, 1982. The southern part of Svalbard is marked by "S" and the position of Bear Island by "X". (From Rasmussen, 1985)

system is indicated by the broken line. It appears from the evolution at 500 mb that upper-level vorticity advection played a role in the development. The surface chart for 0000 GMT 13 December (Fig. 11a) shows only a trough in the vicinity of the incipient low. This trough, located within the region of strong low level thermal contrast, strengthens during the ensuing 12 h, while a well formed, comma or spiral-shaped cloud remains on the satellite picture (not shown). The later sequence of surface charts (Figs. 11 d-f) reveals that a dramatic new development took place between 1200 GMT on the 13th and 0000 GMT on the 14th. A small, tight surface low is seen to cross weather ship AMI, bringing a pressure fall of 5.9 mb during a 3 h period and winds of 20 m $s^{-1}$ within a distance of 50-100 km of the low center. It is perhaps of some significance that the hurricane-like core formed as the low passed over the warmest waters (Fig. 12). Because of the upper-level vorticity advection and enhanced low-level baroclinity, this system can be classified as a combined type, but it had the added ingredient of a hurricane-like core.

The best available documentation of the structure of a small, intense polar low was achieved during the Arctic Cyclone Expedition of 1984 when a research aircraft successfully penetrated a mature mesoscale vortex

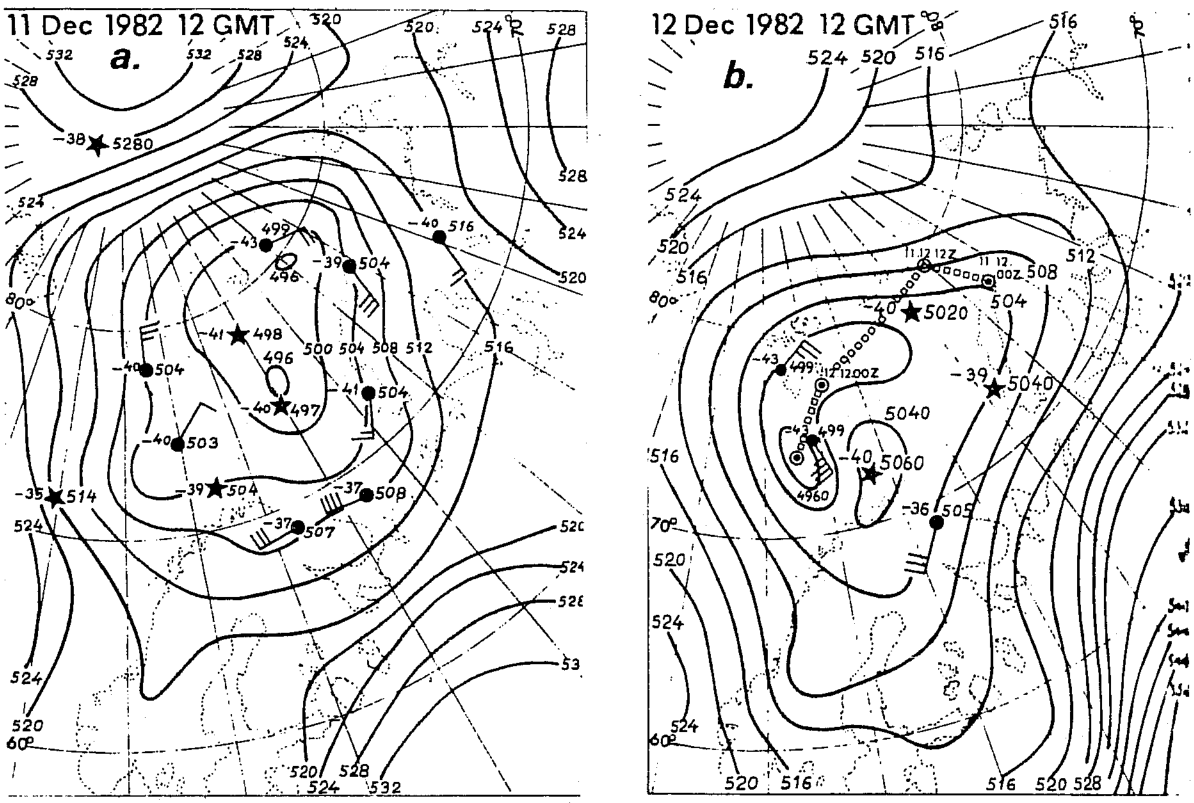



Fig. 10. 500 mb charts for (a) 11 December 1982, 1200 GMT and (b) 12 December 1982, 1200 GMT. Contours in decameters. Track of upper low is shown by broken line. (From Rasmussen, 1985).

(Shapiro et al., 1987). The ECMWF 1000 mb analysis for this case is shown in Fig. 13. The circled cross marks the position of the polar low. Lacking the flight data, the 1000 mb analysis gives no hint of the low. The surface pressure and 300 m winds determined from the aircraft observations appear in Fig. 14. It is seen that a small cyclone with central pressure of about 980 mb and winds near the surface in the 25-35 m $s^{-1}$ range at radial distances of 50-100 km was present in the rear part of the synoptic-scale low. Aircraft soundings revealed that the low possessed a warm core. The satellite picture for the time in question (Fig. 15) shows a comma-shaped cloud pattern with the suggestion of an eye-like feature in the head. The polar low was the most intense of five mesoscale vortical circulations that were observed within the general cloud shield during a period of about 12 hours. Scales ranging from the synoptic scale down to the small mesoscale appeared to be involved in this notable case. Synoptic-scale lapse rates based on ECMWF analyses (Fig. 16) reveal the destabilization that occurred at the 1200 GMT 27 February position of the polar low (marked by the cross in Fig. 13) as the parent low approached and passed the point.

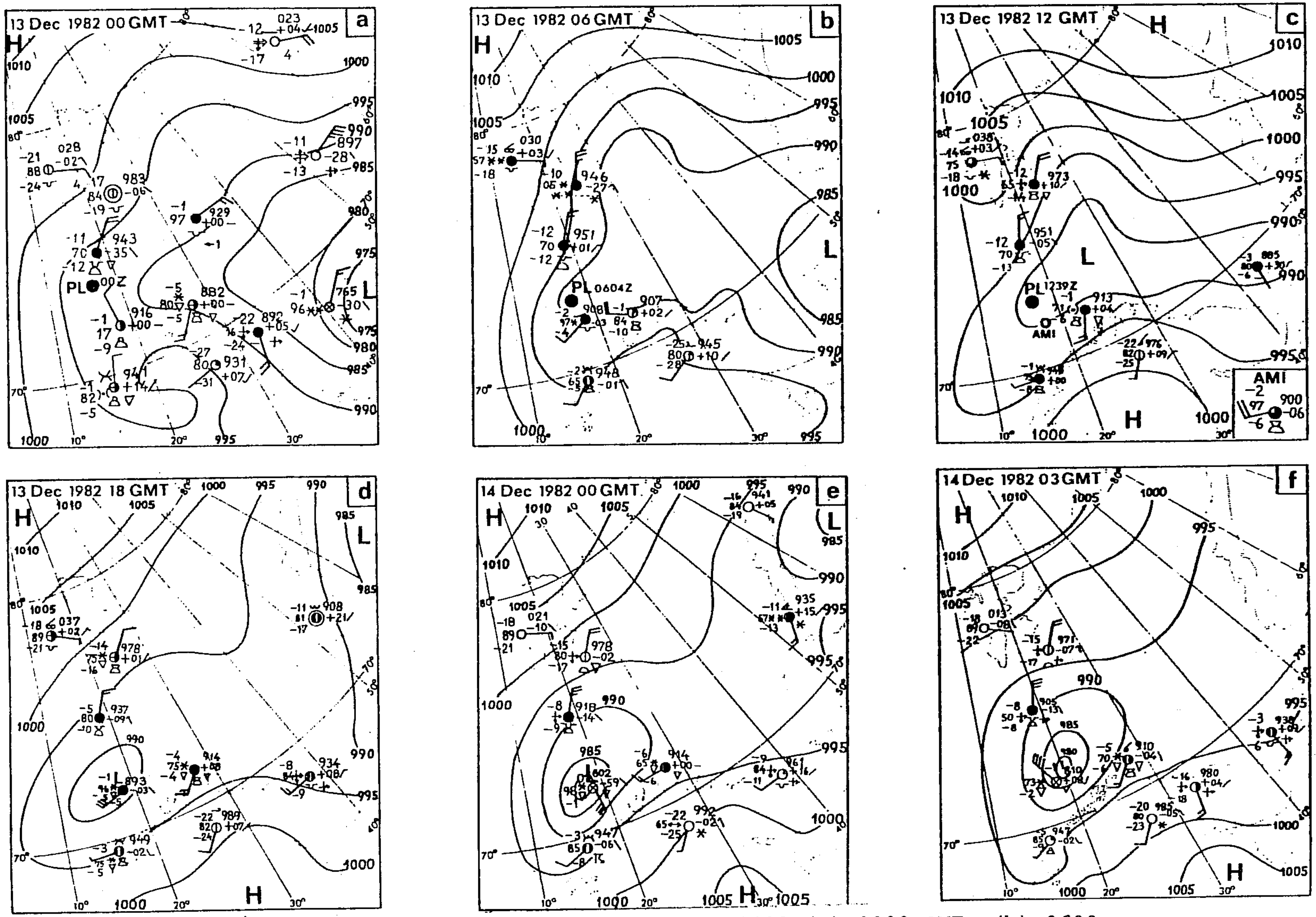



Fig. 11. Surface maps for 13 December, 1982 (a) 0000 GMT, (b) 0600 GMT, (c) 1200 GMT, (d) 1800 GMT and 14 December, 1982 (e) 0000 GMT and (f) 0300 GMT. PL indicates position of polar low. (From Rasmussen, 1985).

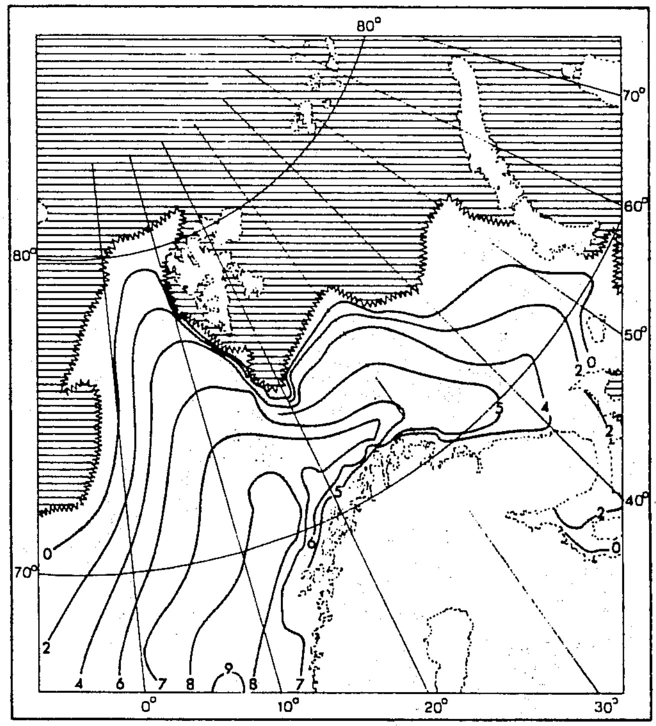
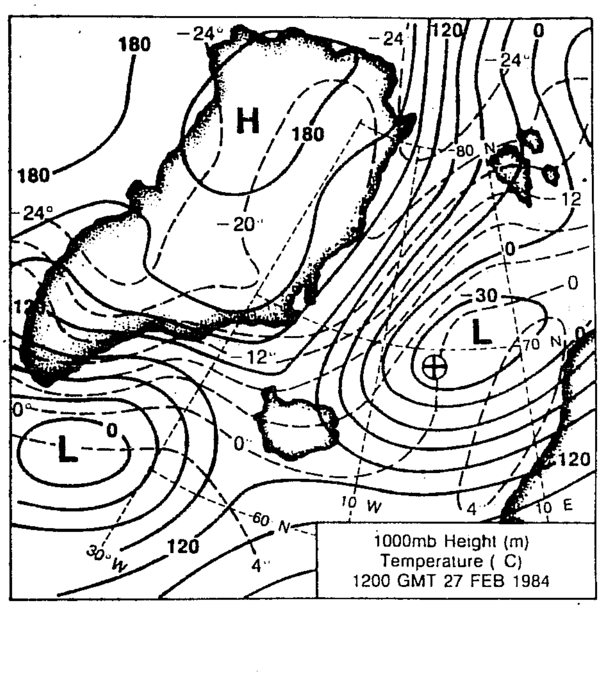



Fig. 12. Map showing extent of sea ice and sea surface temperature (°C), December 10-12, 1982. (From Rasmussen, 1985).



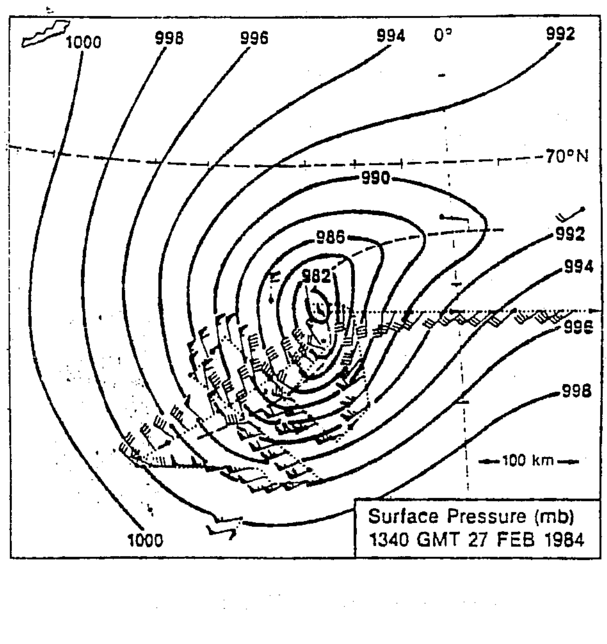




Fig. 13. ECMWF 1000 mb height analysis, 1200 GMT February 27, 1984. Solid lines, contours (m); dashed lines isotherms (°C). circled cross marks position of polar low. (From Shapiro et al., 1987)

Fig. 14. Surface pressure (mb) and 300 m winds at 1340 GMT 27 February, 1984. Full barb 5 m $s^{-1}$; pennant 25 m $s^{-1}$. (From Shapiro et al., 1987)


Fig. 15. NOAA satellite infrared image for 1340 GMT 27 February 1987. (From Shapiro et al., 1987)

Another case in which a hurricane-like feature formed within a synoptic-scale low -- in this case a decaying, old occlusion beneath an upper-level cold trough -- has been described by Ernst and Matson (1983). This is the case referred to in Section 2.2.4. The event occurred over the Mediterranean Sea, an unusual location for a polar low type of development. Satellite visible and infrared images (Fig. 17) show an eye-like feature and an in-spiralling convective band. The upper-level cold trough is depicted in Fig. 18. Surface maps appear in Fig. 19. It is evident that an intense mesoscale vortex formed within the synoptic low as the latter decayed. A ship caught in the storm recorded a sustained wind of 25 m $s^{-1}$ so that the system well exceeded tropical storm intensity.

## 3. THEORETICAL IDEAS AND STUDIES

Most early writings on polar lows attributed their origin to thermal instability within cold air masses flowing over warm seas (e.g., Meteorological Office, 1962). The exact mechanism by which the heating produced the lows and their vortical circulations was not specified. Harley (1960) appears to have been the first to raise the question of whether at least some polar lows are of baroclinic origin, citing the case

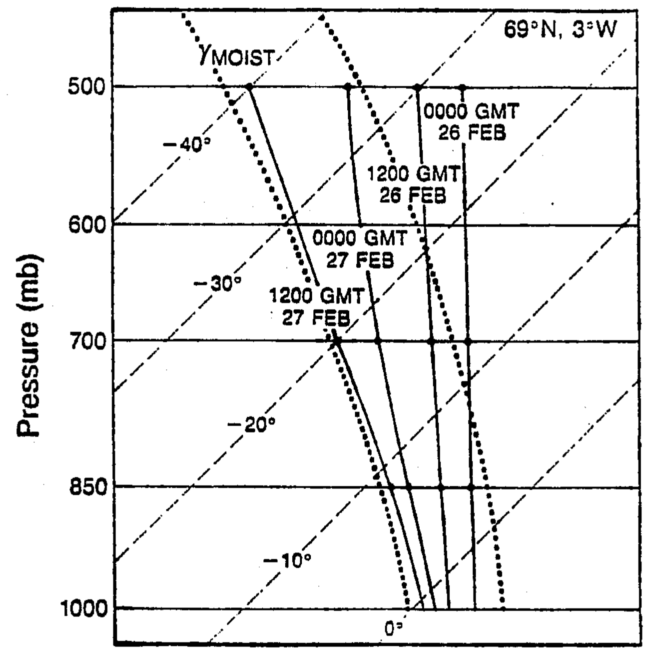



Fig. 16. Temperature profiles (heavy solid lines) over the region of polar low development (69° N, 3° W) for period 0000 GMT 26 February through 1200 GMT 27 February 1984. (From Shapiro et al., 1987)

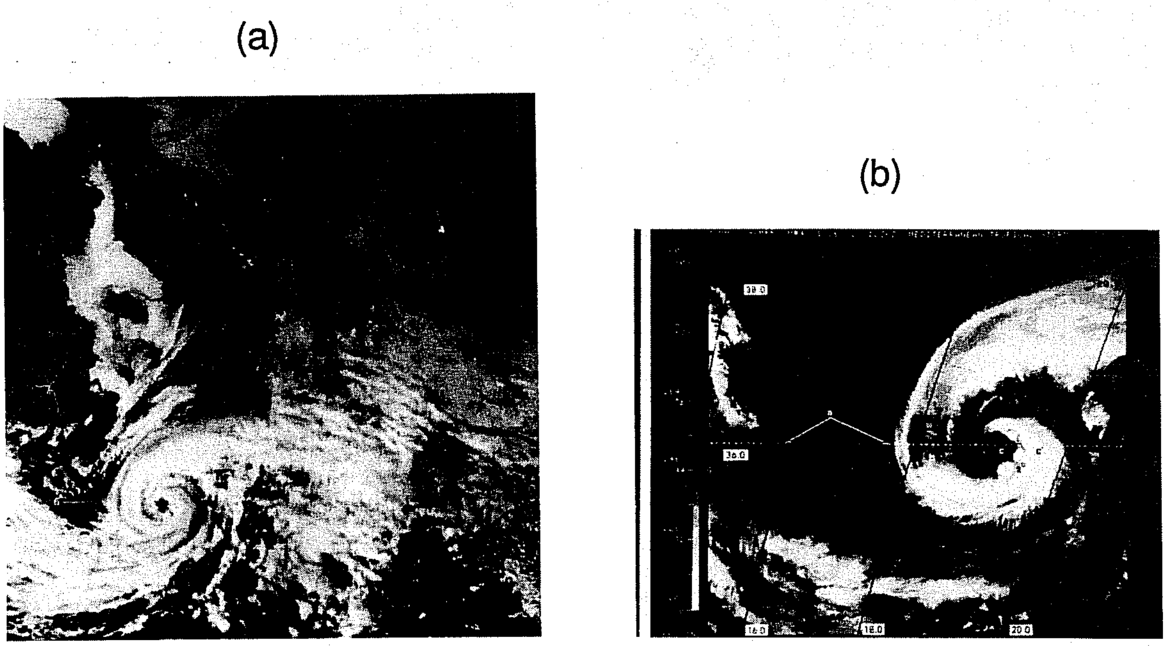



Fig. 17. (a) NOAA-7 visible image 1236 GMT 26 January 1982, (b) NOAA-7 enhanced infrared image for same time. (From Ernst and Matson, 1983)

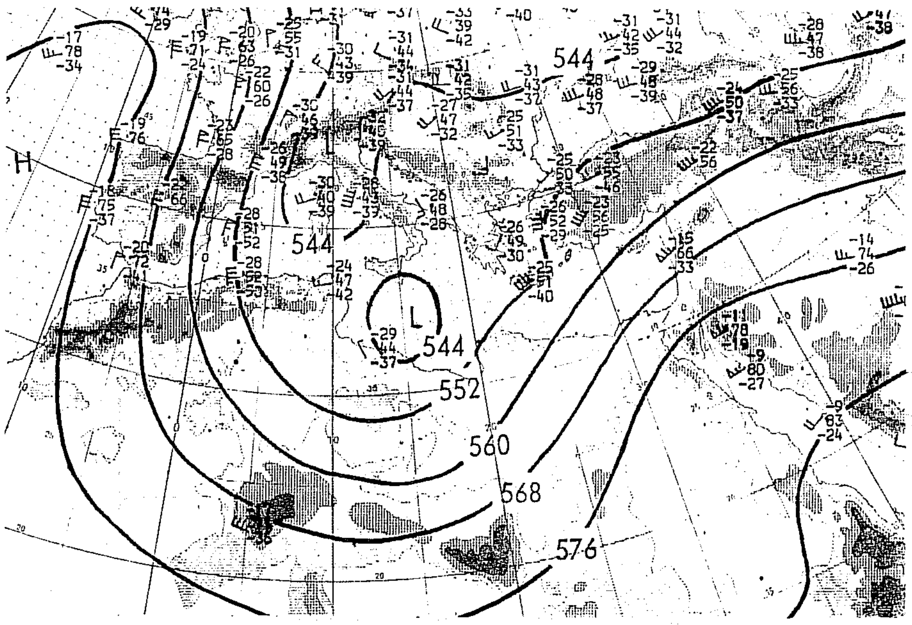



Fig. 18. 500 mb chart, 0000 GMT 25 January 1982. (From European Meteorological Bulletin)

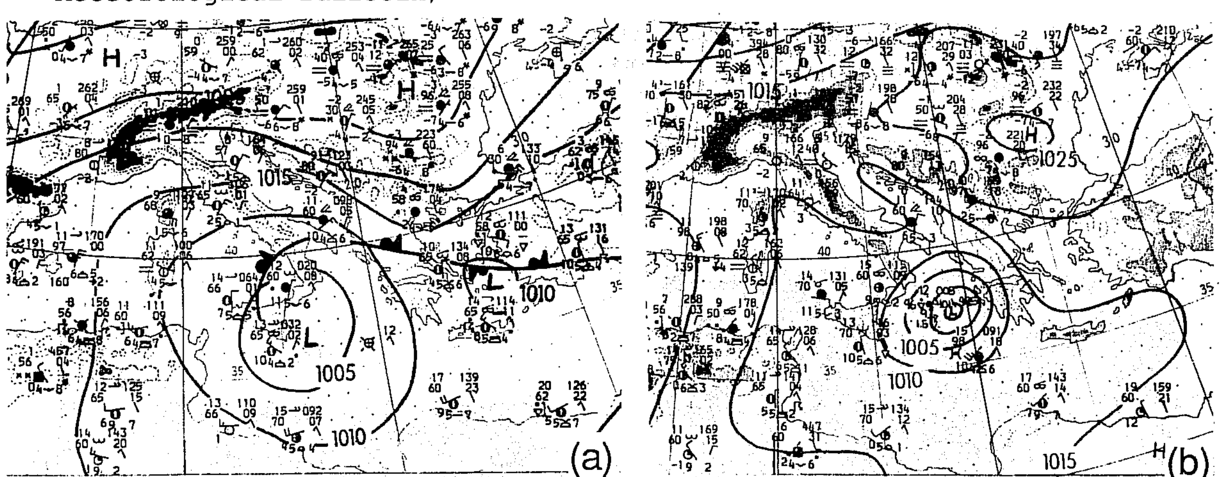



Fig. 19. Surface maps: (a) 1200 GMT 25 January 1982, (b) 1200 GMT 26 January 1982. (From European Meteorological Bulletin)

of a wavelike, upper-level frontal perturbation that progressed southeastward from Greenland and spawned a non-frontal surface low in the North Sea. It appears from his maps that the upper-level system in question would today be termed a short wave or secondary vorticity maximum.

Interest in baroclinic instability as a factor in polar low formation was much stimulated by Harrold and Browning's well known paper (1969). With the use of radar these authors showed that in the case of a polar low passing over England the precipitation occurred mainly in slantwise ascent as in a typical baroclinic disturbance. They proposed that the low formed in the characteristic shallow frontal zone found near Iceland and, citing Eady's theory, attributed the small horizontal size to the shallow depth. They also called attention to the existence of deep baroclinity and a jet stream in the vicinity of the low but argued that these were unlikely to have affected the development, since the propagation speed was indicative of steering by lower level winds. In any event it should be noted that the case bore some resemblance to that cited by Harley and to the typical comma cloud case described in the previous section.

A succession of papers dealing with baroclinic instability as a mechanism of polar low formation have followed Harrold and Browning's work.

Mansfield (1974) applied the Eady linear perturbation model to a shallow (1.6 km) rigidly bounded layer, using the observed mean state in the Harrold and Browning case. Despite the neglect of moist convection, he obtained realistic growth rates ( e-folding times of 1-2 days) and realistic sizes (6-800 km) for the most unstable disturbances. Friction and sensible heat flux were found to inhibit the development. Though it may be questioned whether the basic state employed by Mansfield adequately represented the true state, his results provided the first quantitative evidence that baroclinity could play an important role in at least some polar low developments.

Duncan (1977) employed a linear semi-geostrophic inviscid model to find normal mode solutions for unstable disturbances with small static stability near the earth's surface. Three observed cases of polar lows were used to specify the basic state wind and temperature distributions in vertical sections normal to the flow and the vertical profiles of static stability. Sensible and latent heating and friction were neglected. The presence of small static stability at low levels in conjunction with the existence of low-level baroclinity resulted in the formation of shallow disturbances that in two out of three cases investigated resembled the observed disturbances in size, growth rate and propagation speed. In a later paper Duncan (1978) applied his model to a case of baroclinic instability in a reversed shear flow and elucidated the structure of the reversed shear disturbance.

Blumen (1979) studied the non-linear evolution of unstable two-dimensional Eady waves in a two layer model characterized by smaller static stability in the lower layer than in the upper. Two types of unstable disturbances were found, one being a short wave solution confined to the lower layer. His results may be relevant to cases in which there is evidence of different wave scales at upper and lower levels.

On the basis of a cursory inspection of several small comma cloud developments in the Pacific, Reed (1979) stated that these systems invariably form in the cyclonic shear zone poleward of the jet stream and that this zone is marked by conditional instability and weak to moderate baroclinity. Taking note of the ideas of Harrold and Browning (1969) and Duncan (1977), he proposed that this type of polar low is primarily a baroclinic disturbance that owes its small size to the effect that small static stability at lower levels has in reducing the wave length of maximum instability. A significant enhancing effect by condensation heating was also considered to be a possibility. Mullen (1979) obtained a composite picture of the large-scale environment of 22 small comma clouds in the Pacific that reinforced the foregoing description and interpretation.

Reed and Duncan (1987) have recently applied the aforementioned baroclinic model of Duncan (1977) to the observed background state in the case of the train of four, more or less evenly spaced polar lows described in Section 2.2.2. Their computations yielded a wavelength of maximum instability that was consistent with the observed wavelength of 5-600 km, suggesting a possible baroclinic origin for the wave train. However, these authors pointed out that some factor other than baroclinity - presumably latent heat release in deep convection - must have been an important factor in the development, since the observed lows moved at significantly slower speeds than predicted by the dry baroclinic model and the growth rates given by the model, though substantial, were not sufficiently large, especially in view of the neglect of friction.

Paralleling the studies of the role of baroclinic instability in polar low development have been a number of studies that have examined quantitatively the role of diabatic heating. The underlying concept in most of these studies has been the concept of Conditional Instability of the Second Kind (CISK) introduced by Charney and Eliassen (1964) to explain the growth of the hurricane depression. Økland (1977) formulated an analytical model that examined the effects of surface fluxes and latent heat release in clouds in intensifying small cyclones in cold air masses over the ocean. His results showed that release of latent heat, although comparatively small under the specified conditions, may be a sufficient energy source to account for the spin-up. The results also indicated that sensible heat flux can modify the dynamics of the vortex considerably and that the static stability is an important parameter that must be below a certain limit for intensification to occur.

Using a three-layer, linear, quasi-geostrophic model, Rasmussen (1977, 1979) obtained normal mode solutions for CISK-driven disturbances under typical polar low conditions. His results showed that provided the heating in the upper layer of the model was sufficiently strong relative to that in the lower layer, a short wave cut-off to the instability could be obtained. The maximum growth rate for disturbances larger than the cut-off size occurred at wave lengths comparable in size to polar lows. Computed growth rates of 2-3 x $10^{-5}$ $s^{-1}$ (e-folding times of approximately one-half day) were easily large enough to account for the rapidity of polar low development.

Bratseth (1985), employing a linear analytic model, found that CISK may be important in polar air if heating takes place in a shallow layer at low levels. The layer must be elevated above the surface in order for a short-wave cut-off to exist. Another finding of Bratseth was that the artificial unconditional heating used by Rasmussen (and others), i.e., a CISK formulation in which the heating in regions of ascent is matched by cooling in regions of descent, greatly overestimates the growth rates. Even so, it seems apparent that the CISK mechanism can be a vital factor in polar low development.

A somewhat different idea for the role of CISK in polar low development has been proposed in a later paper by Økland (1986). In this paper he develops a new CISK formulation that lacks a short-wave cut-off. He then proposes that the small dimension of the polar low is due to the presence of local regions of deep convection within the large-scale environment. For instance, baroclinic development may produce isolated regions of less stable air aloft. When boundary layer heating causes the layer to reach the base of the overlying less stable layer convection grows rapidly to great height and precipitation ensues. In this paper Økland also shows that a small vortex may have a greater amplification rate if it develops inside a larger disturbance. His remarks obviously have relevance to the problem of the hurricane-like inner core of systems discussed earlier, and indeed Økland presents an example of such a system.

A final theoretical study deserving mention is that of Sardie and Warner (1983) who developed a three-layer, two-dimensional, quasi-geostrophic model, which included both the effects of latent heating and baroclinity. They found that in general both moist baroclinity and CISK were of importance in polar low formation, though moist baroclinic processes alone were sufficient to account for the comma cloud type of development. Prior to Sardie and Warner's work most investigators emphasized either baroclinic instability or diabatic heating as the primary cause of polar low development. Lately there seems to be greater recognition that both mechanisms need to be taken into account (Craig and Cho, 1987).

## 4. NUMERICAL PREDICTION

We review here briefly the few prediction experiments that have been carried out using real initial data and mesoscale models of sufficiently fine resolution to at least roughly represent systems of the dimensions of polar lows. Information concerning the models, the cases investigated and the data sources is given in Table 1 for simulations conducted by Seaman (1983), by Sardie and Warner (1985) and by Grønas, Foss and Lystad (1986 a,b). The two models utilized thus far, the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) and the Norwegian Meteorological Institute (NMI) mesoscale models, are advanced models that represent the basic physical processes believed to be of importance in polar development. The processes include surface and boundary layer fluxes and release of latent heat by resolvable motions (explicit convection) and by parameterized, subgrid scale convection.

Short range (12 h) forecasts obtained by Seaman were moderately successful, though they consistently underestimated the intensity of the disturbance. Surface fluxes, convection and forcing by an upper-level short-wave all proved necessary for the maintenance of the storm. The

TABLE 1. Polar low simulations using full physics mesoscale models and real data.

| Investigators | Model | Resolution | Layers | Cases | Area | Sources |
|---|---|---|---|---|---|---|
| Seaman (1983) | PSU/ NCAR | 50 km | 10 | 1 | North Sea | NMC grid data |
| Sardie & Warner (1985) | PSU/ NCAR | 80 km | 10 | 1<br>1 | Atlantic<br>Pacific | NMC grid data, Manual Analysis |
| Grønas, Foss & Lystad (1986) | NMI meso-scale | Nested grids: 150,50 25 km | 10 | 7 | Norwegian Sea | ECMWF grid data |

Atlantic low investigated by Sardie and Warner developed baroclinically at first, but latent heat release and surface fluxes were required for its subsequent maintenance. The Pacific low was well predicted in the control experiment that employed parameterized convection. However, baroclinity was identified as the major factor in the deepening; latent heat release accounted for only 5 mb of 14 mb deepening. An experiment using explicit convection produced a significant over-intensification, a common feature of the explicit scheme.

In all cases studied by Grønas et al. disturbances were predicted that could be associated with the observed polar lows. A failing of the forecasts was their inability to predict the strength of the disturbances when the scale was small. The low investigated by Shapiro et al. (1987) was a case in point. The failing may arise from a lack of sufficient resolution in the model to capture essential features of the initial state or to represent essential physical processes.

The mesoscale models hold great promise for the future. While simple theoretical models may continue to yield valuable insights, the greater versatility of the sophisticated prediction models would seem to make them the prime tool for future research.

## 5. CONCLUSION

This brief overview has looked at polar lows from the standpoints of observation, theory and numerical modelling. From the observational standpoint it is clear that a variety of systems fall under the general heading of polar lows. Work is still needed to develop a meaningful classification of the systems and to resolve the issue of whether the small, intense vortices that are sometimes termed "real" polar lows should be regarded as a distinct phenomenon or as a substructure embedded within a larger, subsynoptic system. Urgently required if the subject is to advance are far more observations of the type taken during the Arctic Cyclone Experiment. As maritime phenomena that cannot be resolved with current observational networks, they require special observations of the type that can only be supplied by aircraft.

Theoretical investigators in the past have tended to divide into two schools of thought, one school emphasizing baroclinic effects and the other championing CISK or other heating mechanisms. Lately there has been widespread recognition that both mechanisms are important. Accordingly, the problem has become more complex, and it has become increasingly difficult to advance theoretical understanding using only simple models, though these still have a place. Particularly promising for future advancement are the mesoscale models that are now under development at a number of research centers and that are coming into operational use at some forecast centers. These offer the opportunity for a wide variety of experimentation on the polar low problem.

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