Polar Lows

Mesoscale Weather Systems in the Polar Regions

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Introduction

1.1 Polar lows and other mesoscale lows in the polar regions

In this volume we are concerned with the whole range of mesoscale lows with a horizontal length scale of less than *c.* 1000 km that occur in the Arctic and Antarctic poleward of the main polar front or other major frontal zones. However, much of the interest will be focused on the more intense systems, the so-called polar lows. The term mesocyclone covers a very wide range of weather systems from insignificant, minor vortices with only a weak cloud signature and no surface circulation, to the very active maritime disturbances known as polar lows, which in extreme cases may have winds of hurricane force and bring heavy snowfall to some areas. Clearly it is very important to be able to forecast these more active systems since they can pose a serious threat to marine operations and coastal communities when they make landfall.

Although it has been known for many years in high latitude coastal communities that violent small storms could arrive with little warning, it was only with the general availability of imagery from the polar orbiting weather satellites in the 1960s that it was realized that these phenomena were quite common. The imagery indicated that the storms developed over the high latitude ocean areas (generally during the winter months) and tended to decline rapidly once they made landfall. Much of the early interest in polar lows came from meteorologists in the Scandinavian countries and the British Isles, since coastal districts in these areas were particularly prone to being affected by polar lows during the winter months. The early satellite imagery provided a means of forecasting the arrival of the storms at least a few hours ahead and also initiated investigations into the climatological occurrence of the lows.

During the 1970s it was realized that intense polar lows tended to develop over ocean areas where the sea surface temperatures were relatively high during outbreaks of cold, Arctic air. Such conditions promote strong, deep convection and the satellite imagery almost always shows cumulonimbus clouds associated with the more active systems. In fact, meteorologists noted the similarity between some polar lows and tropical cyclones. However, other polar lows appeared more like small frontal depressions, so prompting a long debate in the scientific literature (which, as later chapters will make clear, is still ongoing) regarding the mechanisms that are behind the various types of development observed.

While the early studies of polar lows were concerned with systems over the northeast Atlantic and the Barents and Norwegian Seas, meteorologists soon noted that similar vortices were to be found in other parts of the world, including the North Pacific, the Sea of Japan and the Labrador Sea. Mesoscale lows in these areas varied in intensity, but they were clearly very similar to the polar lows that had been observed over the northeast Atlantic and in the Scandinavian region. In most of these areas there is a large difference between the sea surface temperature and near-surface air temperature, pointing to the importance of air–sea interactions in the development and maintenance of the vortices.

During the 1970s and 1980s there was interest in whether polar low-like systems were to be found in the high latitude areas of the Southern Hemisphere and a number of studies based on satellite imagery were carried out. It was found that there were indeed many mesoscale vortices over the Southern Ocean and also over the sea ice near to the coast of the Antarctic, but the lows at more southerly latitudes appeared to be generally weaker than their Northern Hemisphere counterparts. However, in the area around New Zealand and probably in other regions as well there were more active systems with deep convection that appeared more like the active northern systems. The term 'mesocyclone' then came into use to describe the ubiquitous rather weak mesoscale lows of the Southern Hemisphere. The difference between Northern Hemisphere and Southern Hemisphere mesoscale lows is examined in later chapters, but is felt to be a result of the different oceanic conditions in the two polar regions where the flow is much more zonal in the south and does not promote the large air–sea temperature differences that are found in the Arctic.

Early Northern Hemisphere studies were concerned mainly with the very active polar lows, but recent investigations in the Arctic have also documented the very large number of minor vortices that seem to be a year-round feature of the ocean areas of the Arctic. Minor mesoscale vortices therefore seem to be a feature of both polar regions.

While most of the early research into polar lows consisted of observational studies, attempts were made during the 1980s to represent these lows in atmospheric models. The first results were generally poor because the models did not have a resolution high enough to resolve these systems, which often have a diameter of only a few hundred kilometres. There were also difficulties because of the poor representation of convection in many of the early models, and theoretical and observational considerations suggested that convection was a very important factor in many of the developments. However, throughout the 1990s there have been many advances in modelling and the latest generation of models with resolutions of 50 km and higher, and a good representation of physical processes, are having more success in simulating some polar mesoscale weather systems. Forecasting polar lows and the weaker mesoscale vortices still presents many challenges, but the indications are that improvements in modelling will give further advances in the coming years.

This brief introduction to polar lows and other high latitude mesoscale weather systems has put forward various ideas that are covered in much more detail in the following chapters. The study of polar lows is still relatively new and there remain many gaps in our theoretical understanding of the development of the lows and aspects of the observational data that cannot be explained. In a summary in the *Bulletin of the American Meteorological Society* of a workshop on 'Arctic lows', William W. Kellogg and Paul F. Twitchell (Kellogg and Twitchell, 1986) wrote:

> The history of meteorology is replete with instances of some phenomenon in the atmosphere that defies an adequate description. We know that something exists, sometimes with disastrous consequences to people and their possessions, but its origins and evolution and characteristics are only vaguely understood. Furthermore, it may even be hard for meteorologists to agree what to call it.

Kellogg and Twitchell were describing the situation facing meteorologists around 1980 concerning the meteorological phenomenon known as polar lows (occasionally called 'Arctic lows' by Kellogg and Twitchell). Their statement was very precise and actually it was not until 1994 that some meteorologists, after a considerable debate, agreed upon a definition of polar lows (see editorial comment by A. Carleton in the *Global Atmosphere Ocean System* special issue on cold air mesoscale cyclones in the Arctic and Antarctic, Vol. 4, Nos. 2–4, 1996) and even this definition could be developed further. However, it is hoped that the following chapters will provide a comprehensive description of our current understanding of these fascinating weather systems and shed a little light on their relationship to other depressions.

1.2 A brief historical review

Our knowledge of polar lows and mesocyclones has come almost entirely during the period for which we have data from satellites since, by virtue of their small horizontal scale, it was rarely possible to analyse these lows on conventional weather charts using only the data from the synoptic observing network. However, the effects of intense polar lows have been felt by coastal communities and seafarers since the earliest times and there are many tales in the Scandinavian countries of sailors encountering small violent storms. These weather systems were thought to be responsible for the loss of many small vessels over the centuries, although the nature of the storms was not understood and their arrival could not be predicted. The effects of many of the polar lows were also felt during the winter months in coastal areas, such as along the northern coast of Norway where the weather could deteriorate very rapidly with winds increasing to gale force and heavy snow occurring in relatively limited areas. While Norwegian weather forecasters were aware of the existence of these lows, it was nearly impossible to forecast them.

Without specifically mentioning polar lows, Sumner (1950) in a study of the role of vertical stability for synoptic developments, concluded that '… there is every justification for supposing that tropical cyclones and a number of small hurricane-like centres, which develop in higher latitudes, are the result of the instability in depth i.e. saturation with a lapse greater than the saturated adiabatic through a deep layer.' The type of 'hurricane-like centre' envisaged by Sumner is illustrated in Figure 1.1. One of the earliest references to what became known as polar lows was made by Peter Dannevig, who wrote about 'instability lows' over the sea areas around Norway in a book for pilots (Dannevig, 1954). Dannevig produced a schematic weather chart showing the relationship of these vortices to the typical airflow around Norway during a polar outbreak (Figure 1.2). A satellite image of such an outbreak of polar lows is shown in Figure 1.3. He also considered the possible mechanisms behind their formation and suggested that these lows could develop in the same way as tropical cyclones.

Another early (German) reference to polar lows is given by Scherhag and Klauser (1962). Sherhag and Klauser described '*das polartief*' as a young, active and, mainly in height, well-developed cyclone with a marked pressure and temperature minimum. According to Sherhag and Klauser, the lows were best developed over warm sea surfaces. The surface circulations were thought to form because of vertical exchange of momentum in the strongly unstable air masses within which the lows formed. '*Das polartief*' was described as following the general flow in the region where it formed, initially containing no fronts. Fronts, however, could eventually form as the low passed surfaces with a varying temperature.

'Arctic instability low' was the name used for polar lows in Norway up to the 1980s. Concerning the motivation for the application of this name to the

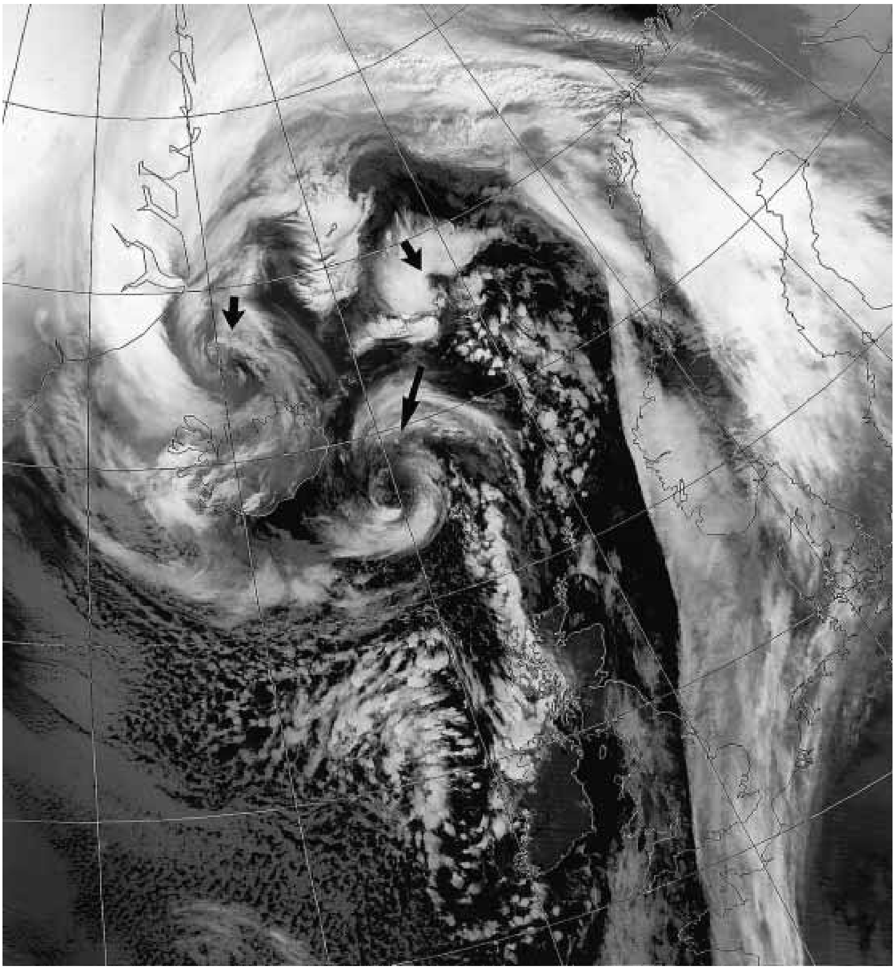

Figure 1.1. An infra-red satellite image for 0853 GMT 18 December 1994 showing a large, synoptic-scale low with a 'merry-go-round' structure, including a central 'hurricane-like' mesoscale vortex (indicated by the long arrow) of the type alluded to by Sumner (1950). Minor vortices (indicated by short arrows) circulate around the central vortex. (Image courtesy of the NERC Satellite Receiving Station, University of Dundee.)

small-scale lows in question, Rabbe (1975) explained that 'since the lows occur in cold unstable air masses they lend themselves to be called "Arctic instability lows".' In this early paper Rabbe presented several examples of polar lows around Norway and discussed their formation using the vorticity equation. Concerning the energy source for the lows, Rabbe pointed towards heating of the atmosphere by the ocean, noting that the energy transfer from the sea to the atmosphere reached extremely high values in connection with such

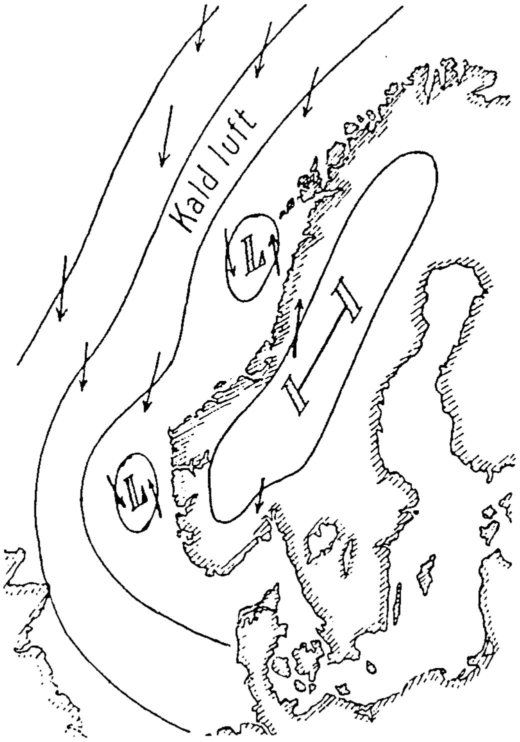

Figure 1.2. Dannevig's 1954 schematic surface chart showing two polar lows (called 'instability lows' by Dannevig) within a northerly outbreak of polar air near the Norwegian coast.

developments. Rabbe also included a number of examples of the near impossibility at that time of forecasting these dangerous, small-scale lows.

Since the 1960s British meteorologists have taken a keen interest in mesoscale weather systems in polar airstreams since such systems could give extensive snowfall across the British Isles, especially in Scotland. In Britain such systems were called 'cold air depressions' (Meteorological Office, 1962) and forecasters were clearly aware of their existence and importance. This interest resulted in a number of preliminary descriptive accounts of these lows in the literature. The earliest known case studies of polar lows by British meteorologists were published in the British magazine *Weather* in the 1960s and 1970s (Harley, 1960; Stevenson, 1968; Lyall, 1972), based mainly on routine surface observations. Lyall showed a Nimbus 3 satellite picture of the clouds associated with a polar low that occurred on 5 January 1970. The picture, which is probably the first published satellite image of a polar low, showed that the very active polar low (Suttie, 1970) was associated with a small, comma-shaped cloud. While these early studies were true observational studies, many

Figure 1.3. A visible wavelength satellite image of an outbreak of polar lows down the coast of Norway and Denmark. Three polar lows (indicated by arrows) have formed within the outbreak at, respectively, North Cape, the Norwegian Sea at 65° N, and over Denmark. The image was taken by NOAA 9 at 1308 GMT 27 April 1985. (Image courtesy of the NERC Satellite Receiving Station, University of Dundee.)

recent studies combine the observational aspect with results from numerical models.

The Stevenson (1968) study described a polar low that crossed southern England, giving 11 inches of snow around Brighton and causing major traffic disruption. However, no attempt was made to account for the development of the low. Nevertheless, this case formed the basis for the much more detailed investigation carried out by Harrold and Browning (1969) who studied the structure of the low using frequent radiosonde ascents and surface synoptic observations. This paper was the first full account of a polar low in the refereed scientific literature.

The arrival of imagery from the polar orbiting satellites during the 1960s provided a major advance in the study of polar lows. In the early years of meteorological satellites the only data available were infra-red and sometimes visible, hard copy images. Since then a variety of satellite data have been available, including satellite sounder measurements, scatterometer data for estimation of surface winds over the sea, and microwave data.

The imagery available from high latitudes indicated the high frequency with which polar lows developed and the wide range of cloud signatures associated with these lows. The imagery for the Arctic showed many minor mesoscale vortices well north of the main polar front, as well as the less common, intense vortices that became known as polar lows. Anderson *et al.* (1969), in their early manual on interpreting satellite imagery, referred to comma clouds, a special class of polar low, which is discussed in detail in Section 3.1.3.

In parallel with the early observational studies of polar lows, consideration was also being given to the mechanisms responsible for the development of the vortices. Early theoretical studies considered two possible mechanisms. Harrold and Browning (1969) suggested that the lows formed as a result of baroclinic instability, with Mansfield (1974) and Duncan (1977) further developing these ideas during the 1970s. In contrast, Økland (1977) and Rasmussen (1977, 1979) proposed that these polar lows developed as a result of Conditional Instability of the Second Kind (CISK) (see Section 4.5). Since the 1970s it has become clear that a very wide range of polar lows and mesocyclones develop in the polar regions and that both baroclinic and convective processes are involved in the development of these lows or can both be involved during the lifetime of a single polar low. A full discussion of the theories that have been proposed for the development of polar lows and other vortices is presented in Chapter 4.

A major handicap to research on polar lows has always been the lack of data in the high latitude areas, both for investigation of the structure of the lows and for the preparation of numerical analyses from which models could be run. A significant advance came with the Norwegian Polar Lows Project (Lystad, 1986; Rasmussen and Lystad, 1987), which took place between 1983 and 1985. Driven by the possible destructive effects of polar lows on the gas and oil drilling activities in the northern North Sea, this international project had observational and modelling elements that sought to improve our understanding and capability to forecast these vigorous storms. Within the project, the first aircraft observations were collected within a polar low (Shapiro *et al.*, 1987), a climatology of polar lows was prepared (Wilhelmsen, 1985), and advanced modelling studies were carried out (Nordeng, 1987).

During the 1980s attention turned also to the polar lows that occurred in areas other than the Atlantic sector of the Arctic. Inspection of satellite imagery showed that many polar lows were also to be found in the North Pacific (Businger, 1987; Douglas *et al.*, 1991) and in the Sea of Japan (Ninomiya, 1989). A number of these lows were quite intense and similar to the polar lows of the Norwegian/Barents Seas that had been studied for more than a decade.

In the 1980s researchers also considered the mesocyclones that were to be found around the Antarctic continent. In probably the first paper on polar lows over the Southern Hemisphere, 'An observational study of polar air depressions in the Australian region', Auer (1986) discussed the occurrence, evolution and maintenance of polar air depressions (polar lows) in the Australian region. Since the availability of routine satellite imagery, Australian meteorologists had, according to Auer, long been aware of subsynoptic-scale storms that develop rapidly over the Tasman Sea. As a useful forecasting tool Auer recommended the use of a temperature index called the Polar Depression Index (PDI), simply defined as the temperature surplus (or deficit) of a saturated parcel of air warmed to the sea surface temperature and lifted moist adiabatically to 500 hPa and compared to the environmental temperature at that level. Auer also stressed the importance of the upper-air flow geometry, noting amongst other things that 86% of the moderate to strong polar air depressions found by him were identified with medium amplitude short-waves or closed circulations.

With the availability of high resolution satellite imagery it had become clear that many mesoscale vortices were present over the Southern Ocean (Turner and Row, 1989; Heinemann, 1990), although, as in the Northern Hemisphere, very few systems were found over the land areas and the high ice cap of the Antarctic continent. However, many vortices were found on the low-lying ice shelves (Carrasco and Bromwich, 1991) as a result of the baroclinic conditions that exist in these areas. Although conventional synoptic data are rather limited around the Antarctic, the observations collected when vortices crossed observing stations suggested that most Southern Hemisphere mesocyclones were rather weak. Some systems had surface wind speeds of more than gale force but few vortices have been discovered with deep convective cloud and winds of up to around 30 m s^{-1}, such as are occasionally found in parts of the Arctic. As is discussed in later chapters, this is probably a result of the generally more stable atmospheric conditions found around the Antarctic compared to the Arctic.

In the 1990s the availability of large amounts of satellite imagery for both polar regions had allowed the production of mesocyclone climatologies describing the frequency and form of vortices found in many areas, although consistent broad-scale climatologies are not yet available for either polar region. Our understanding of the structure of mesocyclones was further advanced by the first instrumented aircraft flights through a mesocyclone in the Antarctic (Heinemann, 1996b) and the use of new forms of satellite data, such as the surface wind vectors available from scatterometers (Claud *et al.*, 1993; Marshall and Turner, 1997a). Further advances in our understanding of mesocyclone formation and development have also come about through the use of sophisticated numerical models simulating individual lows (see Chapter 5), as well as new theoretical investigations based on the use of simple models (Craig and Cho, 1989).

At the time of writing, there is still a great deal of research taking place into mesoscale weather systems in the polar regions. The European Geophysical Society's Polar Lows Working Group is a major focus for research and has been instrumental in organizing international, combined modelling/observational studies into selected cases. As will be apparent in the following chapters, we have made many advances in our understanding of these systems over the last three decades, but there are still many outstanding questions that require continued research.

1.3 Definition

Mesoscale vortices at high latitudes have been known by a variety of different names, among which the term 'polar low' is the most common. Other terms used include Arctic instability low, polar air depression, mesocyclone, mesoscale vortex, mesoscale cyclone, Arctic hurricane and polar airstream cyclone.

Polar lows are generally characterized by severe weather in the form of strong winds, showers and occasionally heavy snow, which have sometimes resulted in the loss of life, especially at sea. The severity of these systems is reflected in the term 'Arctic hurricane', which has been used for especially intense polar lows.

The difficulty of formulating a brief, unambiguous polar low definition is partly due to the fact that a variety of forcing mechanisms can play a role and may all be important for the development of these systems. Depending upon the relative importance of the forcing mechanism, different types of polar lows may form, leading to the idea of a 'spectrum' of mesoscale cyclones including both purely baroclinic as well as purely 'convective' systems, i.e. systems for which the main energy source is latent heat released in deep convection. A practical definition must include all the different types and also reflect the fact that the polar low traditionally is considered as an intense and vigorous phenomenon.

Dannevig (see Section 1.2) defined instability lows (polar lows) as small but intense vortices which form in cold air outbreaks over the sea, occasionally accompanied by strong winds (of gale or storm force) and strong precipitation.

In *The Handbook of Weather Forecasting* (Meteorological Office, 1964) the term polar low was taken to refer to 'fairly small-scale cyclones or troughs embedded in a deep northerly current which has recently left northerly latitudes'. However, the 1972 edition of *The Meteorological Glossary* (Meteorological Office, 1972) referred only to a polar-air depression, which was considered to be 'A secondary depression of a non-frontal character which forms, more especially in winter, within an apparently homogeneous polar air mass'. Following this idea, Carlson (1991) defined a polar low as being 'usually a *non-frontal low* that occurs to the rear of the cold front . . .'.

Reed (1979) identified the polar low with the so-called comma cloud (see Section 3.1.3), which typically develops in baroclinic regions, poleward, but relatively near the polar front. Reed's paper started a debate on whether comma clouds should be considered as 'real' or 'true' polar lows and highlighted the need for a more precise definition. Businger and Reed (1989a, b) suggested 'a broad definition' in order to group the various cases reported in the literature together, defining the polar low as 'any type of small synoptic- or subsynoptic-scale cyclone 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'. It should be noted that some significant polar low developments can be found that do not have convective cloud associated with them (see the case of the polar low that occurred on 2 March 1989 discussed in Section 4.2).

A slightly different definition was suggested by Rasmussen *et al.* (1993), defining the polar low as 'a small, but fairly intense maritime cyclone that forms poleward of the main baroclinic zone (the polar front). The horizontal scale of the polar low is approximately between 200 and 800 km and the winds around it of gale force or above'. This latter definition specifically points out that polar lows are maritime systems. Also, it takes into account that polar lows traditionally have been associated with the occurrence of relatively strong surface winds, around or above gale force. Small vortices ('cloud vortices') have a tendency to form in regions where cyclonic vorticity is maximized, such as along troughs or around cyclonic shear lines within the low-level flow. Such vortices are not necessarily accompanied by a significant pressure perturbation in the form of a trough or a closed circulation and/or any significant wind. Omitting the wind force requirement means that in principle *any*, however insignificant, cyclonic disturbance (cloud vortex) within cold air masses, should be called a polar low, including the type of cloud vortices mentioned earlier for which the term polar low is clearly inappropriate. The requirement of a relatively strong wind speed excludes the small and frequently very weak cyclones that often can be observed close to the Arctic and Antarctic coasts/sea ice edges, and also, to a large extent, the comma clouds, which are often associated with relatively weak surface circulations.

A definition endorsed by the European Geophysical Society's Polar Lows Working Group (Paris 1994), states: 'The term "*polar mesoscale cyclone*" (polar mesocyclone) is the generic term for all meso-α and meso-β cyclonic vortices poleward of the main polar front (scale definition according to Orlanski, 1975). The term "*polar low*" should be used for intense maritime polar mesoscale cyclones with scales up to 1000 km with a near-surface wind speed exceeding 15 m s^{-1}'. An advantage of the Paris definition is that it distinguishes clearly between weak vortices such as, for example, those often observed along the Antarctic coast, and the more vigorous polar lows from the Northern Hemisphere. A drawback is the rather cumbersome formulation and the fact that the wind speed requirement is probably *too* severe. On the other hand, Fett *et al.* (1993), referring to the distinction made in tropical meteorology between an easterly wave and a tropical depression, used an even more restrictive definition defining a cold air vortex as a polar low only when the wind speed was 18 m s^{-1} or above.

As a useful compromise between the different definitions mentioned above we will use the following definition of a polar low in this volume:

> *A polar low is a small, but fairly intense maritime cyclone that forms poleward of the main baroclinic zone (the polar front or other major baroclinic zone). The horizontal scale of the polar low is approximately between 200 and 1000 kilometres and surface winds near or above gale force.*

The definition is fairly general, and there are no requirements about the existence (or rather non-existence) of fronts or the prevailing cloud type, as in Businger and Reed's definition from 1989. The definition above can be extended if necessary by specifying the dominant physical mechanism responsible for the development of the low, such as, for example a 'baroclinic polar low' or a 'convective polar low', the latter being driven primarily by organized convection.

1.4 Nomenclature

Closely connected to the definition problem is the difficulty of nomenclature. As mentioned in the preceding sections, one of the pioneers of polar low research, Peter Dannevig, used the term 'instability low' reflecting his point of view that the small-scale lows were the result of organized release of convective instability. This term, however, had to yield to the expression 'polar low' used by British meteorologists for the small-scale systems in question.

In order to stress the rapid development and the similarity between some polar lows and tropical systems (hurricanes), Rasmussen (1983) used the term 'extra-tropical hurricane' and 'Arctic bomb' for an impressive polar low development around 27 January 1982 (see the discussion in Section 3.1.4, The 'polar low spectrum'). Emanuel and Rotunno (1989) argued that 'at least some polar lows are indeed Arctic hurricanes', and also Businger and Baik (1991) used the term 'Arctic hurricane' for intense polar lows. In Businger and Baik the Arctic hurricane was defined as 'a polar low with symmetric signature and threshold winds greater than or equal to 25 m s^{-1}, in which surface fluxes play the dominant role in the structure and sustenance of the mature storm'. Reed (1992), on the other hand, raised objections to the use of the term 'Arctic hurricane' arguing that in no cases had the surface winds exceeded the 33 m s^{-1} speed required of a hurricane, and, referring to the fact that similar systems have been observed over the Mediterranean (e.g. Rasmussen and Zick, 1987), that these systems are not peculiar to the polar regions. Reed's criticism, however, seems a little misplaced since none of the authors cited above have claimed that a complete similarity existed between hurricane-like systems in the Arctic and in the tropics, but rather have pointed out certain basic similarities, such as the existence of a warm core, the role of deep convection in the dynamics of the system, etc. Also, at least on two occasions, surface winds associated with a polar low have exceeded the 33 m s^{-1} threshold for hurricane force winds (the polar low on 25 April 1985 described by Lystad, 1986, p. 38, and the case discussed in Section 6.2.6).

Reed's 1979 paper, 'Cyclogenesis in polar airstreams', marked the starting point of a debate over whether comma clouds were 'true' polar lows, the latter being defined as the systems observed further poleward near the ice edge and often associated with a spiraliform cloud signature. This sometimes heated debate has been resolved through the general acceptance of the definitions discussed earlier through which a polar low is defined by some objective characteristic independent of the basic dynamics of the system and/or of their cloud field structure as seen from a satellite perspective.

Polar low research during the early 1980s was almost exclusively focused on the Northern Hemisphere systems. During the late 1980s and the 1990s, however, increasing interest was focused on Southern Hemisphere phenomena (see Section 1.2). While Southern Hemisphere systems just north of the polar front resemble their Northern Hemisphere counterparts, higher latitude systems near the Antarctic sea ice/coast line, differ in important respects from Northern Hemisphere polar lows. Most significantly, most of the vortices observed near the Antarctic ice edge are much weaker and of small horizontal scale compared to the Northern Hemisphere polar lows. Further, the small, weak cyclonic systems observed near Antarctica are generally characterized by low-level, stratiform cloud and not by the deep convection characteristic of Northern Hemisphere polar lows. In order to avoid confusion between the weak Southern Hemisphere systems and the generally much more vigorous Northern Hemisphere polar lows it soon became customary to denote the Southern Hemisphere systems by terms such as mesocyclone, Antarctic mesocyclone, mesoscale vortex etc. This way of distinguishing between the different systems was formalized through the 'Paris definition' mentioned above.

1.5 Classification

The problem of nomenclature of polar low and other cold air mass, small-scale disturbances is closely connected to the problem of *classification* of these systems.

Troup and Streten (1972) and Streten and Troup (1973) carried out one of the first investigations into the relationship between cloud patterns in satellite imagery and the synoptic environment and proposed a number of vortex types based on their appearance in the imagery. Their type 'A' signature was essentially a cold air development/polar low occurring in southerly flow around the Southern Ocean.

A further early morphological classification based on the appearance of the polar low as seen from a satellite perspective (Rasmussen, 1981, 1983), distinguished between 'real' or 'true' polar lows and comma clouds, the first terms denoting high latitude systems characterized by deep convection and spiraliform cloud systems, in contrast to the comma-shaped systems closer to the main baroclinic zones (see Section 1.6, Cloud signatures).

Forbes and Lottes (1985) presented a detailed morphological scheme for classification of mesoscale vortices, based on a systematic study of organized cloud systems in satellite imagery for the northeast Atlantic, the Norwegian Sea and the North Sea covering the winter 1981–82. Cloud configurations accompanying polar vortices were classified into nine categories, and only vortices with a pressure perturbation estimated to be of about 6 hPa were considered sufficiently intense to 'merit the title of a polar low'. It was concluded that satellite imagery can be used to identify and distinguish between polar lows and insignificant polar vortices and that the cloud configurations in early stages of the vortex lifetime give some clues regarding which vortices will subsequently develop.

A widely used classification system differentiating between three elementary types of polar low development based on associated distinctive synoptic patterns was suggested by Businger and Reed (1989a, b). The classification comprised three basic types: (1) the short-wave/jet-streak type, characterized by a secondary vorticity maximum and PVA (positive vorticity advection) aloft, deep, moderate baroclinicity, and modest surface fluxes; (2) the Arctic-front type, associated with ice boundaries and characterized by shallow baroclinicity and strong surface fluxes; and (3) the cold-low type, characterized by shallow baroclinicity, strong surface fluxes, and deep convection. The first type is identical with the so-called comma clouds (Section 3.1.3) and characterized by PVA aloft. Actually, upper-level PVA (and the cold upper-level temperatures within the region of the short wave trough) seems essential for a large number of significant polar low developments, including the systems placed by Businger and Reed in the second category or group, the Arctic front type.

Concerning the classification proposed by Businger and Reed (1989a, b), Grønås and Kvamstø (1995) argued the following: 'Our findings suggest a modification of the definition of the *Arctic front polar low* class in the classification of polar lows proposed by Businger and Reed (1989a). They found that this type is characterized by shallow baroclinicity and strong surface fluxes. We chose to call this class *Arctic outbreak polar lows* since they do not form at the leading edge of the Arctic front. It seems evident that a mobile upper disturbance is also active.' And, they continue: 'The presence of an upper disturbance, using the potential vorticity concept, should therefore be included in the definition.'

Rasmussen *et al.* (1993) proposed a basic classification of *primary* and *secondary polar lows* resembling the earlier mentioned classification of real (true) polar lows and comma clouds, but based on physical/dynamical considerations rather than on the cloud field structure. According to this classification, a polar low that forms as the result of a southward migration of an upper-level cold core vortex, originating within the large-scale circumpolar vortex, should be called a 'primary polar low' (a corresponding definition can of course most likely be used in the Southern Hemisphere). Primary polar lows associated with upper-level cold core disturbances will generally be characterized by deep convection and 'real' or 'true' polar lows can indeed be defined as being primary polar lows.

An attempt is presented in Section 3.1.4 to extend and improve the Businger–Reed classification scheme based on a study of a number of polar lows examined by Wilhelmsen (1985). According to this scheme most (nearly all) polar lows can be placed within one of the seven categories shown in Table 3.1 (p. 159). The 'classification' should not be considered as a 'dynamical classification' based on the mechanisms involved in the formation of the lows, but rather as *a convenient way to group polar lows within a relatively small number of categories.*

1.6 Cloud signatures

1.6.1 Introduction

Satellite data can provide a great deal of information about the form and composition of the cloud associated with mesoscale cyclones/polar lows from which information can be inferred about the air masses and physical processes involved in the formation of the systems. The visible and infra-red imagery shows the locations of the lows and provides data on the cloud-top temperatures. If a nearby radiosonde profile is available or an estimate of the atmospheric profile is obtained from a numerical model, then the actual height of the cloud tops can be estimated. Passive microwave data from satellites allow the estimation of integrated water vapour (IWV) across the system and integrated cloud liquid water (CLW) in the cloudy regions. These two quantities are particularly valuable since they provide information on the whole atmospheric column and not just for the top of the cloud. For example, the CLW data can provide information on the frontal structure not apparent in the conventional imagery (Lieder and Heinemann, 1999).

All these types of data allow an estimation of the diameter of the lows to be determined, although these cannot easily be related to the surface pressure pattern without other data being available. The imagery shows that mesoscale cyclones at high latitudes have a very wide range of diameters from a few tens of kilometres up to the maximum of the mesoscale taken here as 1000 km.

The imagery is also very useful for determining the lifetime of mesoscale cyclones, which although often existing for less than 24 h, can be observed to remain as distinct features for two or three days if the large-scale synoptic activity in the area is limited (Turner *et al.*, 1993b, 1996a). Over the southwestern Ross Sea, Bromwich (1991) found that the mesoscale cyclones observed over a two-year period existed for an average of 29 h, a much longer period than found for systems around the Antarctic Peninsula (6–12 h) in the study by Turner *et al.* (1996a). The vortices over the Ross Sea probably exist for such a long period because of the relatively quiet synoptic conditions at this location well south of the circumpolar trough. The mesoscale cyclones that were classified as 'significant' with winds of at least 7.5 $\mathrm{m\,s^{-1}}$ had a longer mean lifetime of 35 h. In the Northern Hemisphere, early case studies (Rasmussen, 1985a) showed that occasionally polar lows could exist for around two days provided they remained over the sea.

The work of Harold *et al.* (1999a) examining mesoscale cyclones in the North Atlantic section of the Arctic via AVHRR (Advanced Very High Resolution Radiometer) satellite imagery, has shown that many vortices can be observed year-round, but with a maximum in the winter. Eighty-six per cent had a diameter of less than 400 km and most had a lifetime of less than one day (see Section 2.1).

Mesoscale cyclones and polar lows owe their existence to specific physical forcing mechanisms. Depending on the nature of these mechanisms, the cloud fields of the different types of vortices will show certain basic, characteristic features through which the cyclones can be identified.

Examination of visible and infra-red satellite images has shown the existence of several characteristic cloud signatures of mesoscale vortices at higher latitudes. Two of these, the 'comma cloud' and the 'spiraliform vortex', are the most commonly observed types (Carleton *et al.*, 1995). In the following we consider the most important, characteristic cloud signatures for mesoscale cyclones/polar lows seen on satellite imagery.

1.6.2 The comma cloud

The majority of comma clouds are caused by a region of upper-level PVA ahead of a short-wave trough (see Section 3.1.3), the tail of the comma cloud being aligned along the trough axis. Comma clouds, such as the one illustrated in Figure 1.4 showing a typical signature over Iceland around 1000 km west of the polar front, are usually found at middle latitudes close to the main baroclinic zone. Occasionally, though, they may also be seen over higher latitudes, as illustrated on Figure 1.5 showing a characteristic comma cloud over the Barents Sea. Comma clouds are not limited to the Northern Hemisphere, and Figure 1.6 shows an example from the Southern Hemisphere. The comma cloud tail often marks the leading edge of a cold air outbreak with cumulus cloud, sometimes in the form of cloud streets, behind it (see Figure 1.4), and is often represented on synoptic charts as a short 'secondary' cold front. This mesoscale cloud vortex type is the most frequently observed mesocyclone signature over the Southern Hemisphere extratropics (Zillman and Price, 1972; Carleton and Carpenter, 1990), although in satellite climatologies that use relatively coarse resolution imagery (Streten and Troup, 1973; Carleton, 1979) this dominance is partly a function of the larger mean size of this vortex type compared with other mesocyclone signatures. For a detailed discussion of comma clouds see Section 3.1.3, Comma clouds.

1.6.3 The 'Spiraliform' signature

The second major cloud form seen on satellite imagery is the 'spiraliform' signature first described for the northeast North Atlantic by Rasmussen

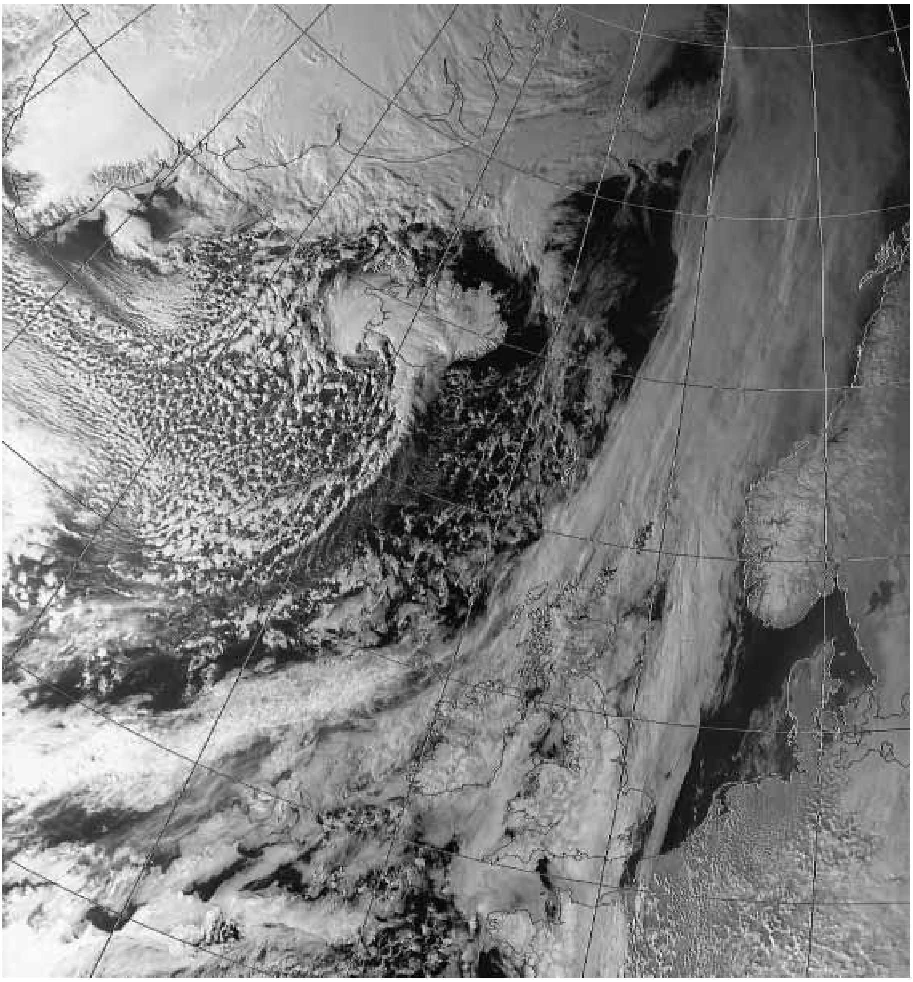

Figure 1.4. A visible wavelength satellite image showing a comma cloud over Iceland around 1000 km west of a synoptic-scale cloud band associated with the polar front. The comma tail was leading an outbreak of cold polar air characterized by cellular, rather shallow convection within the region of subsiding air behind an upper-level trough. Taken by NOAA 9 at 1528 GMT 8 March 1988. (Image courtesy of the NERC Satellite Receiving Station, University of Dundee.)

(1981). Figure 1.7 taken from his paper shows a spiraliform mesoscale cyclone over the sea between Iceland and the Faeroe Isles. Interestingly, a comma cloud situated over the northwestern part of the British Isles can be seen on the same image, which illustrates the striking difference between the two types of disturbance. The spiraliform system seen on Figure 1.7 initially formed south of Iceland and from there moved across the northeastern Atlantic into the North Sea, where it dissipated after making landfall on the German coast. The low,

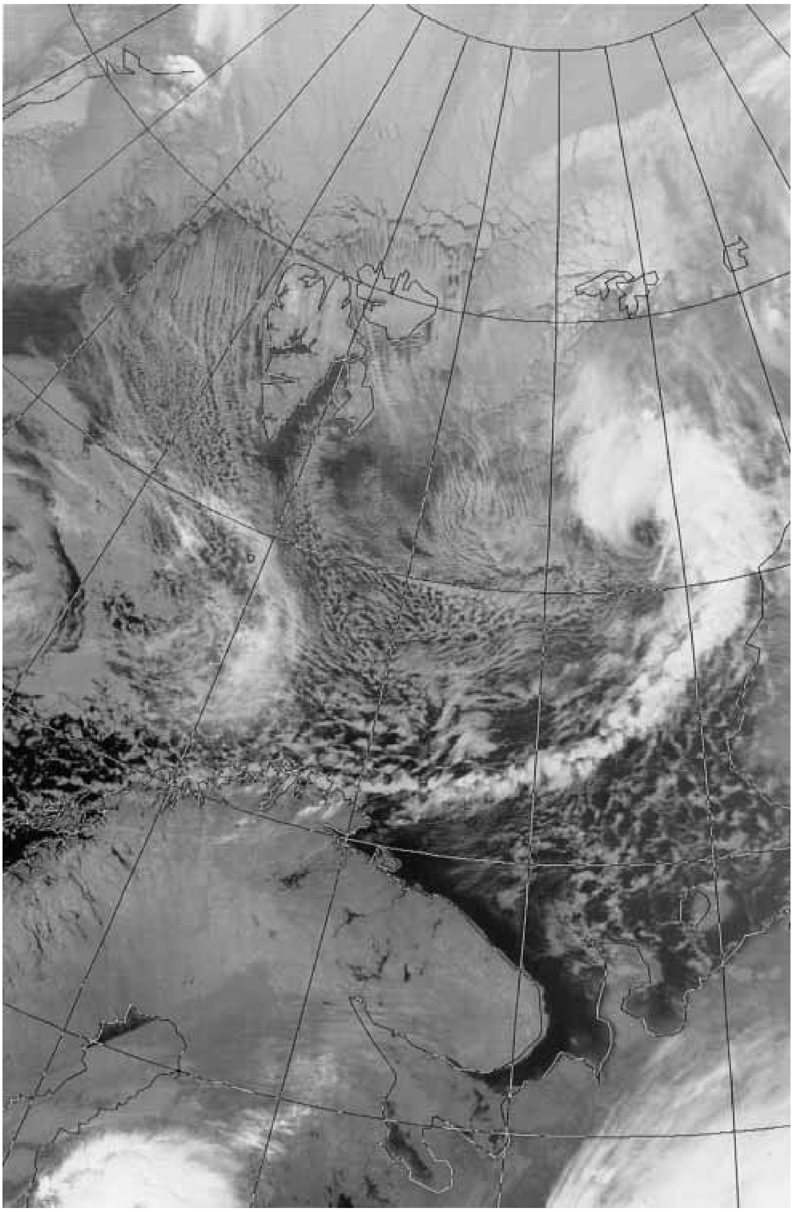

Figure 1.5. An infra-red satellite image showing a rare high latitude comma cloud over the Barents Sea close to Novaya Zemlya. The image was taken by NOAA 11 at 1244 GMT 20 October 1992. (Image courtesy of the NERC Satellite Receiving Station, University of Dundee.)

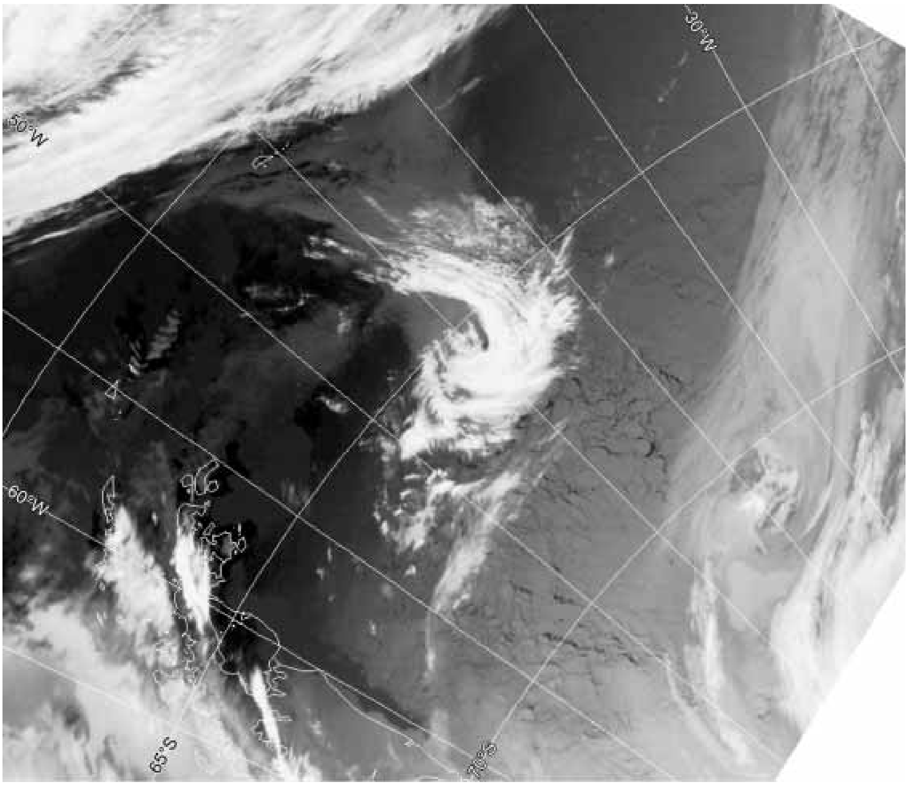

Figure 1.6. An infra-red satellite image of a Southern Hemisphere comma cloud over the northern Weddell Sea at 1726 GMT 6 October 1995.

which developed a warm core, could be followed on the synoptic charts for about two days over a distance around 2000 km.

Spiraliform systems are characterized by one or more spiral bands of convective cloud around the circulation centre, as illustrated in Figures 1.7 and 1.8, the latter figure showing a spiraliform polar low over one of the major genesis regions for such systems over the northern part of the Norwegian Sea. Spiraliform mesoscale cyclones occasionally have an 'eye-like' cloud-free or nearly cloud-free area at the centre of the low, as seen on Figures 1.7 and 1.8 (see also Figure 5.4, 'the most beautiful polar low'). On Figure 1.8 two major spiral arms can be seen, one being the southern extension of the Svalbard boundary layer front (BLF) (indicated by small arrows) entering the central part of the low from the west (BLFs play an important role in the development of many mesoscale cyclones and polar lows in the region and will be further discussed in Section 3.1.4). The other cloud band forms an arc north of the centre marking the boundary between an outbreak of unmodified Arctic air flowing towards the