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1 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

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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

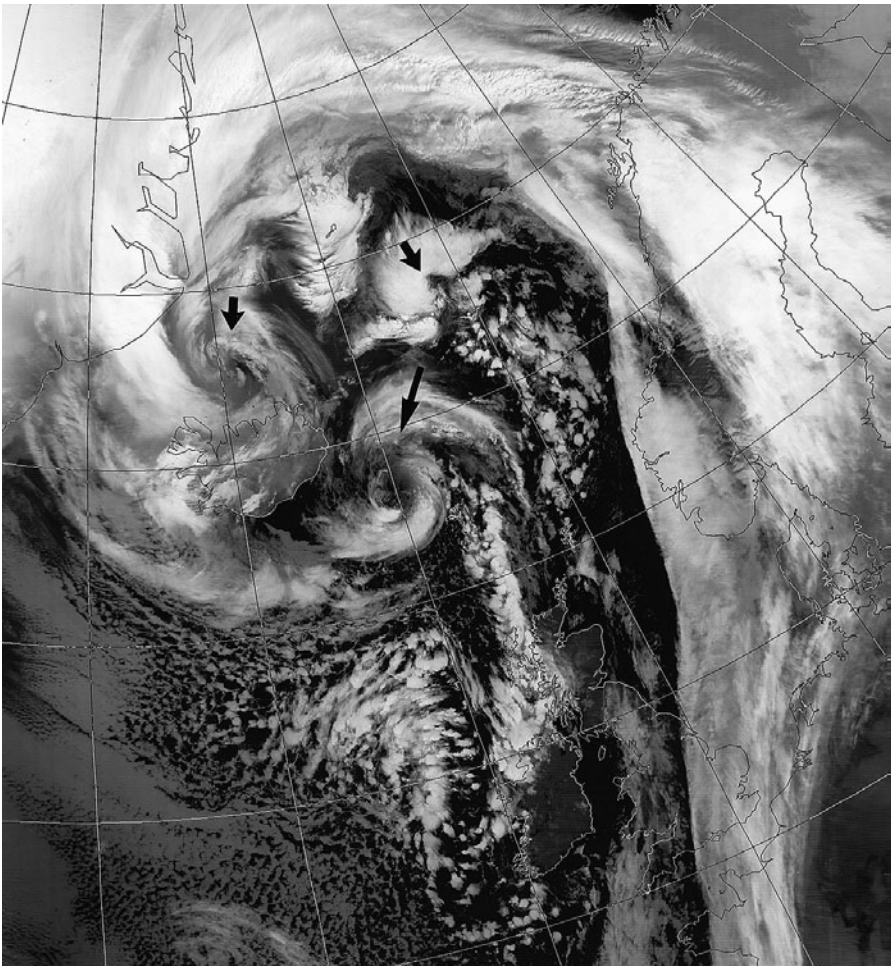

Figure 1.1. An infra-red satellite image for 0853 GMT 18 December 1994 showing a large, synoptic-scale low with a 'merry-go-round' structure, including a central 'hurricane-like' mesoscale vortex (indicated by the long arrow) of the type alluded to by Sumner (1950). Minor vortices (indicated by short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

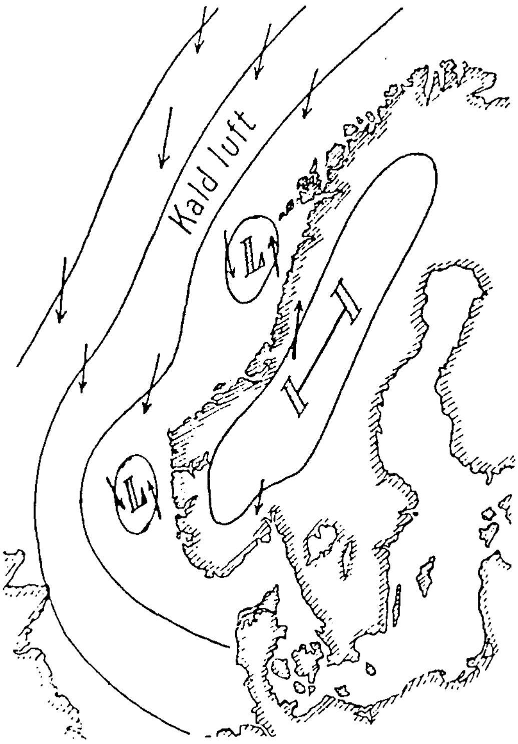

Figure 1.2. Dannevig's 1954 schematic surface chart showing two polar lows (called 'instability lows' by Dannevig) within a northerly outbreak of polar air near the Norwegian coast.

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