Extreme winds in the Nordic Seas: polar lows and Arctic fronts in a changing climate

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Contents

Chapter 1

Introduction

Along the coast of Northern Norway, the weather has taken many lives up through the years. In what is probably one of the first historical references to extreme weather in this region, the poet priest Petter Dass (1647-1707) wrote about how fishing villages were devastated when most of the male population perished in the same storms. He recalls one particular event, when up to 500 men drowned as they were surprised by a sudden outbreak of ferocious northerly winds. The small spatial scale of the weather is also emphasised - ships were known to have gone down within speaking distance of other ships that took no harm from the rough seas. Often, the fishermen would go out to sea when the weather cleared after days of strong southerly winds, only to be surprised by strong winds and massive snowfall coming from the north.

Shipwrecks in the Nordic Seas (Figure 1.1) are not a thing of the past; according to Kari Wilhelmsen in Grønås and Skeie (1999), 56 vessels were lost and 342 people lost their lives in accidents in the 20^{th} century alone. Grønås and Skeie (1999) provides a list of the mesoscale phenomena that are known to produce strong winds, and thereby indirectly large surface waves, icing and packing of the sea-ice in the Nordic Seas:

Polar lows are mesoscale cyclones that form in cold air masses over relatively warm, open ocean. There are many different types of polar lows, ranging from strongly baroclinic comma cloud developments to almost barotropic, hurricane-like systems that are driven by strong heating from below. Polar lows have been

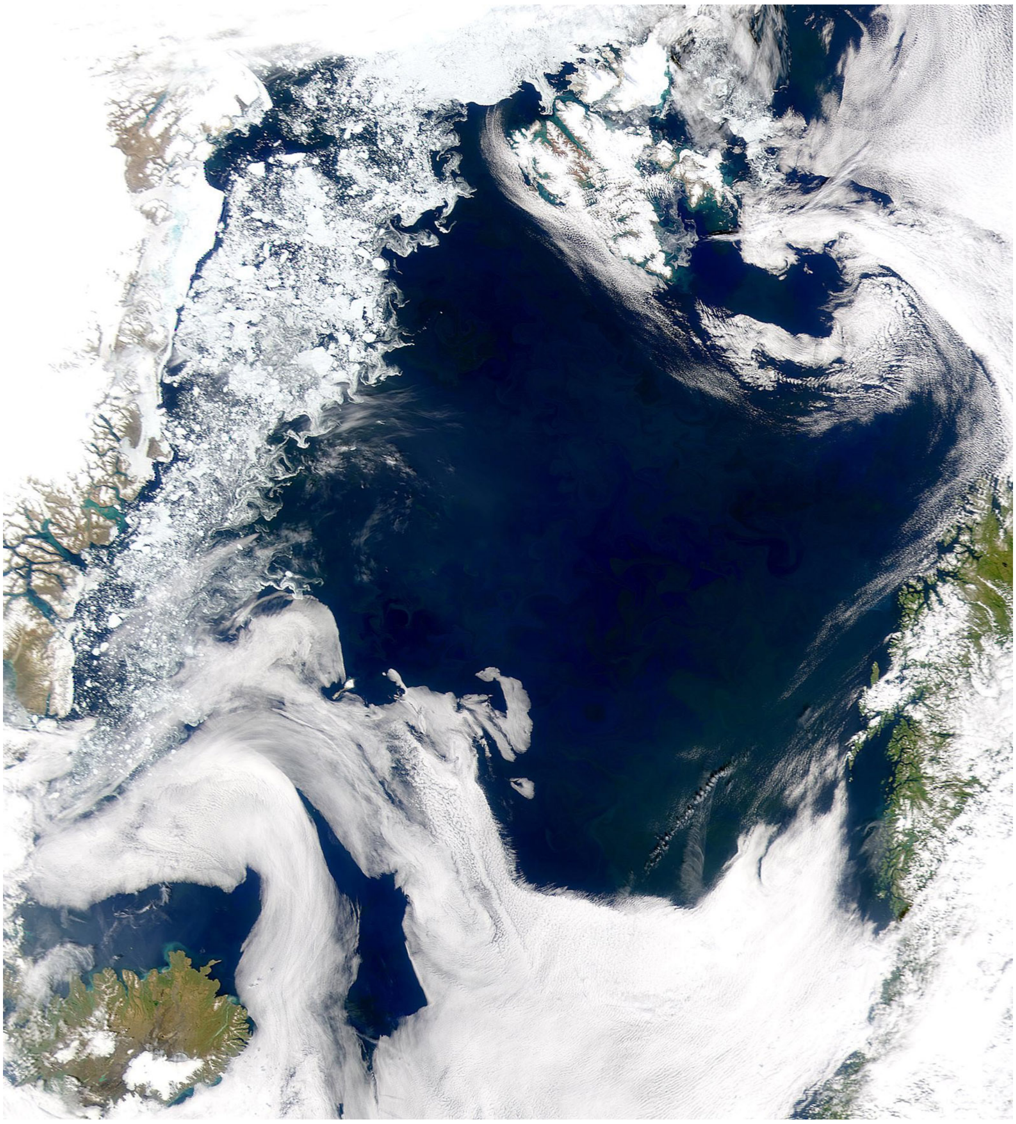

Figure 1.1: The Nordic Seas.

known to produce surface winds of hurricane force and tremendous amounts of precipitation. They are the subject of Papers I and II and will be discussed in section 1.2.

Orography-induced winds also pose a grave danger to ships, and include: the northeasterly jet near the southern tip of Spitsbergen (Skeie and Grønås, 2000); the tip jet (and reverse tip jet) near Cape Farewell at the southern extremity of Greenland (Doyle and Shapiro, 1999; Moore and Renfrew, 2005); the barrier winds at either end of the Denmark Strait between Iceland and Greenland (Moore and Renfrew, 2005); the left-side jet off the west coast of Norway (Barstad and Grønås, 2005, 2006); and the left-side jet in southerly flow on the east coast of Novaya Zemlya in the Barents Sea (Paper III).

Although it is a phenomenon that has not received much attention in the literature, Arctic fronts are thought to be the direct cause of at least two terrible accidents. Numerical simulations with very high horizontal resolution (3 km) performed at the Geophysical Institute in Bergen (Norhagen, 2004) strongly suggest that the British trawler Gaul, which went down south of Bjørnøya in 1974 with 36 men, was surprised by high seas induced by a mesoscale Arctic front. This disaster sparked much controversy, and two formal investigations were held, both of which concluded that the trawler was "overwhelmed by a succession of heavy seas". An earlier episode which received much attention in Norway, was the storm in which seven ships went down off the coast of Eastern Greenland in 1954, killing 78. Økland (1998) suggested that an Arctic front lead to cross-frontal frontogenetic vertical circulation and strong amplification of the winds parallel to the ice edge. Arctic fronts and winds near the sea-ice edge in the Nordic Seas are the subject of Paper III.

It is important to investigate the nature of extreme weather in this region. There is more human activity in these seas than ever before, and the size of the visiting ships and resident installations has increased and is projected to increase further with the rapidly developing oil and gas industries. An inherent problem with forecasting the weather in the Nordic Seas is the lack of observational data. Although this has been ameliorated with the dawn of satellite-derived data such as QuikSCAT (Chelton et al., 2006), which are used in Paper III, the infrastructure is very different from more inhabited regions. In addition, the most potent weather is highly localised and beyond the reach of relatively coarse-resolution numerical weather prediction models.

This thesis is a survey of different aspects of small-scale severe weather in the Nordic Seas, in the form of three scientific papers. One of these was published in Tellus A in 2006 (Paper I), one has been submitted to Climate Dynamics (Paper II), while Paper III will be submitted to Journal of Geophysical Research–Atmospheres shortly. The remaining sections of this introduction are meant to be a brief introduction to the subjects which are addressed in the papers.

1.1 Large-scale conditions

Synoptic lows moving into the Nordic Seas lead to large amounts of precipitation along the western coast of Norway. They usually move into the region along the North Atlantic storm track. The Bergen school of Meteorology was initiated by Vilhelm Bjerknes in 1917, and refined by various now famous members such as his son Jacob Bjerknes, Sverre Petterssen, and Harald Sverdrup, to mention a few. These were the first to formulate the theory of fronts and its importance to understand cyclogenesis in the mid-latitudes, and their work is of tremendous importance in the early history of meteorology.

The choice of Bergen as a laboratory for weather was both ingenious and fortuitous. It is the wettest city in Norway (and probably in Northern Europe), partly because of its surrounding mountains, but also because it is situated in the dead center of the highway of Northeast Atlantic cyclones. Since the dawn of modern meteorology, a sound theoretical understanding of synoptic baroclinic waves and their large-scale background flow has been a key issue in the atmospheric sciences.

Although synoptic low-pressure systems are hugely important for the climate in the Nordic Seas, we now know that this region is prone to mesoscale severe weather phenomena of different flavours. Common to most of them is that they are formed during outbreaks of cold, stable, dry Arctic air masses over the warm waters of the region. In the marginal ice zone near the edge of the sea-ice, the local horizontal and vertical temperature gradients can be astonishingly large, leading to fierce baroclinic frontal systems and strong air-sea heat interactions. Sometimes, when the northerly winds persist over a longer period (a few days), the polar air masses can reach far south in the North Atlantic, and may lead to severe snowfall and surface winds as far south as the European continent and the British Isles. Such situations are defined in Paper II as Marine Cold-Air Outbreaks (MCAOs). A typical outbreak from the ice sheet over the northern Greenland Sea near Spitsbergen is shown in Figure 1.2. This thesis is an investigation of the climatology of weather systems that form under such conditions in the Nordic Seas.

A statistical indication of the significance of MCAOs in a climatic sense was provided by Skeie (2000). He found that the second EOF of monthly sea level

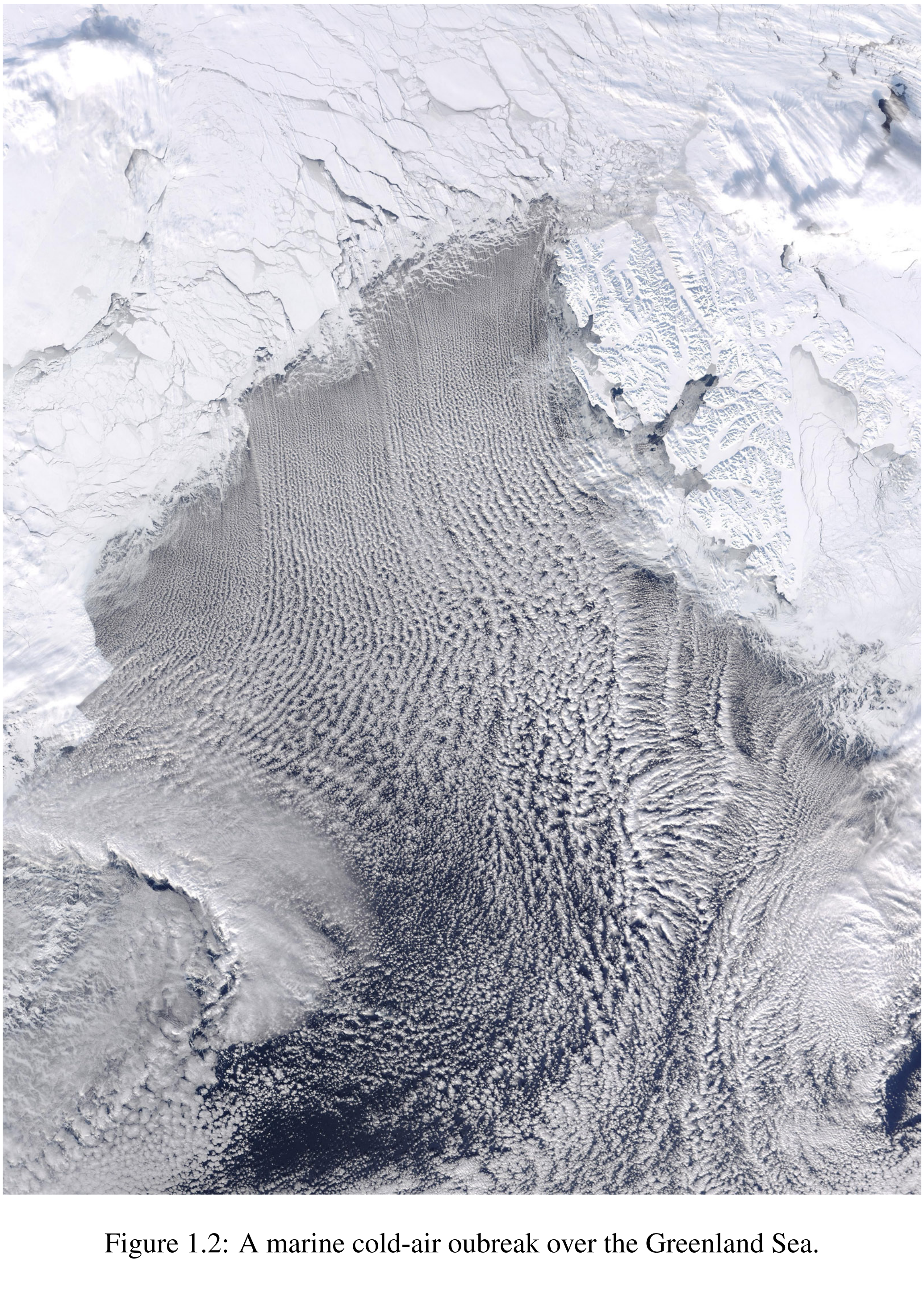

Figure 1.2: A marine cold-air oubreak over the Greenland Sea.

pressure poleward of 30°N described a distinct meridional flow in the Nordic Seas (the first EOF is the Northern Annular Mode or Arctic Oscillation; e.g. Thompson and Wallace, 2000). A strong correlation with sensible heat loss over the region was also found. Wu et al. (2006), using a different approach by only considering the region north of 70°N, found a similar pressure dipole which accounted for 13 % of the variability.

1.2 Polar lows

'Polar low' is the denomination of a wide range of weather phenomena at high latitudes. Although many definitions have been proposed, the following one by Rasmussen and Turner (2003) is adopted in this study:

> 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.

Although we now know that polar lows can occur in both hemispheres (a polar low-like feature has even been observed over the Mediterranean; Rasmussen and Zick, 1987), they were first noticed in the Nordic Seas, or more specifically along the coast of Norway. Papers I and II provide climatologies of favourable conditions for polar lows in the northern Northern Hemisphere both for the past and the projected future, but the focus is on the Nordic Seas. This has also been the case of much of the published polar lows research, and this region is undoubtedly the best-documented with respect to climatology in the literature.

1.2.1 Nordic Seas climatology of polar lows

The first statistical treatment of polar low climatology was performed by Businger (1985). With ten years of data, he calculated the composite 500-hPa geopotential height during the days when polar lows were formed over the Nordic Seas. The result was a significant negative anomaly centered over Northern Norway, paired with a positive anomaly over Baffin Bay to the west of Greenland. This pattern is very similar to the northerly-flow modes of the pressure dipoles found by Skeie (2000) and Wu et al. (2004).

Wilhelmsen (1985) used synoptic weather charts to provide a synthesis of the movement of 71 polar lows with a confirmed wind speed of 7 Beaufort (near gale). A distinct polar low track was found, with most of the lows forming north of 70°N and moving in a southerly direction. These results were supported by

Harold et al. (1999a,b). In what must have been a monumental effort, Harold manually inspected satellite images spanning two years. 4054 mesoscale vortices (not only polar lows) were found over the Northeast Atlantic and the Nordic Seas, predominantly during winter. The main cyclogenesis regions were the northern Norwegian Sea and the Greenland Sea, and not the Barents Sea. In terms of wintertime cyclone occupation, most of the smaller systems (with a diameter of 200-400 km) were found over the Norwegian Sea and to the south of the Denmark Strait, while the slightly larger systems (400-600 km) occurred more frequently over the Greenland Sea near latitude 70°N.

Condron et al. (2006) followed up these results with a study of mesoscale cyclones (not necessarily polar lows) with a signature in the ERA-40 data set (Kållberg et al., 2004). They used an automated cyclone detection algorithm, and their results were by and large coincident with Harold et al. (1999a,b), except for the smallest cyclones, which were only detected 20 % of the time. The familiar maxima outside the coast of northern Norway, in the Iceland region and along the ice edge off the east coast of Greenland were detected. In addition, a high frequency of weaker cyclones was found near the British Isles. The region to the immediate west of Spitsbergen also had a high number of relatively weak cyclones. The strongest features were found over the Greenland Sea and to the south of the Denmark Strait. An additional interesting result was that cyclones were more likely to appear if they occurred close to synoptic observing stations, suggesting that the cyclone activity in uninhabited regions is higher than what can be gathered from reanalysis data.

The key regions for polar low development were confirmed by Bracegirdle and Gray (2006), who found three principal maxima in the Norwegian Sea, to the east of Spitsbergen and south of the Denmark Strait. In contrast to Condron et al. (2006), no activity was found along the coast of East Greenland. This is not surprising if one considers the different methodologies of the two studies. Condron et al. (2006) counted every single mesocyclone with no regards to the state of the surrounding atmosphere, while Bracegirdle and Gray (2006) counted features which were selected by a different automated cyclone detection algorithm, with the added constraint that the feature occurred in a cold-air outbreak. This methodology is described in more detail in Paper II, where similar constraints are applied to future scenario climate model projections. The upshot of this is that features outside the East Greenland coast did not form over sufficiently warm sea surfaces to be selected by Bracegirdle and Gray (2006). Their conclusion is that the more potent polar lows in the Nordic Seas north of Iceland occur most frequently in the Norwegian Sea around 10°E, with a secondary maximum in the centre of the Barents Sea. The climatology that is presented in Paper I is compatible with the above studies.

The seasonal cycle of polar lows is another area of interest. In Paper I the studies by Wilhelmsen (1985), Lystad (1986) and Noer and Ovhed (2003) are summarised in Figure 2. The extended winter from November to March is the busiest season with roughly 0.4 polar lows spotted per day, with the exception of February, when less than half of this was observed. The reason for this surprising nadir is still an open question and a subject for further study.

1.2.2 Driving mechanisms

The first detailed study of polar lows in the scientific literature was made by Harrold and Browning (1969), who studied a polar low which caused problems when it hit England and deposited large snow amounts. As the title of that paper suggests, this was thought to be a baroclinic disturbance, but at the same time it was obvious that convection played a large role in the development. Duncan (1977) studied three polar lows with a two-dimensional numerical model, and found that:

> It appears that polar-air depressions can be considered as shallow baroclinic waves, although the quasi-geostrophic assumption is not always reasonable. Conversion of available potential energy to eddy kinetic energy occurs in the lowest 200 or 300 mb of the atmosphere when the low-level static stability is small.

In the years to come there was no consensus about the idea that polar lows were predominantly baroclinic. Hans Økland at the University of Oslo and Erik Rasmussen developed the idea that polar lows were formed and intensified under the influence of heat fluxes from the warm ocean (Rasmussen, 1979). They claimed that CISK (Conditional Instability of the Second Kind; Charney and Eliassen,

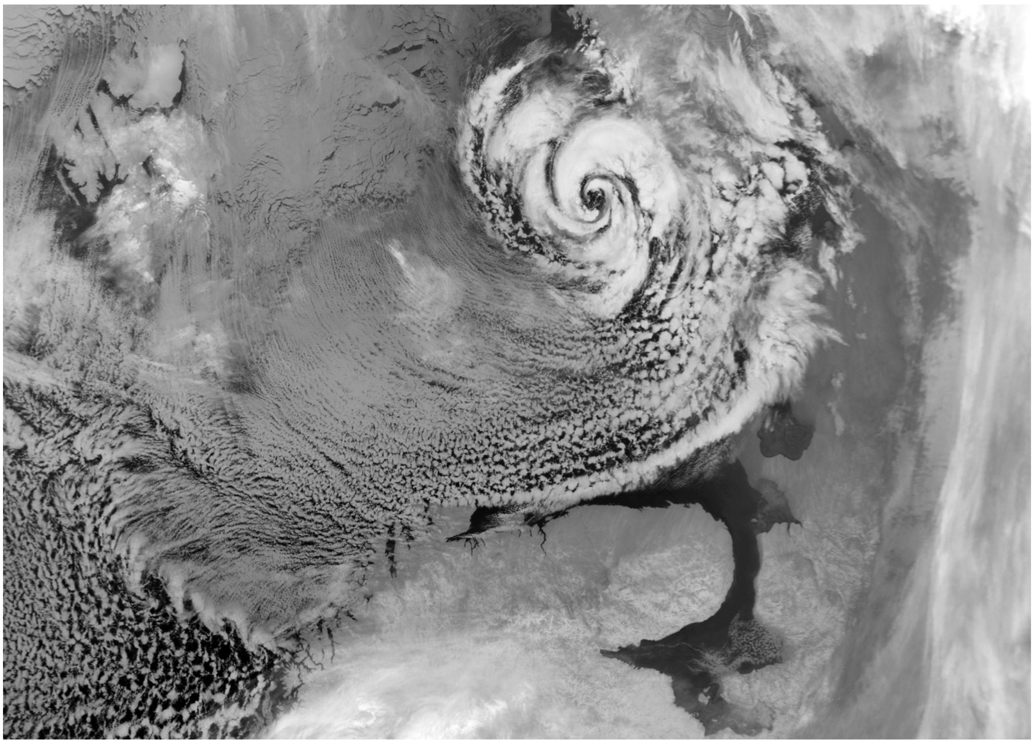

Figure 1.3: A satellite image from 0204 UTC on 20 December 2002. Copyright Dundee Satellite Receiving Station.

1964) was the driving mechanism behind the developments. This requires the presence of CAPE (Convective Available Potential Energy), or in other words: warm and conditionally unstable air at lower levels. In a climatological study by Wilhelmsen (1985), she detected CAPE in *all* of her 38 cases.

Disputing this importance of CAPE preconditioning, (Emanuel and Rotunno, 1989) claimed that air-sea interaction induced by strong surface winds (later denoted WISHE - Wind-Induced Surface Heat Exchange), which had been found to be an important mechanism for tropical cyclones without the presence of conditional instability (Emanuel, 1986), could theoretically explain the cyclogenesis of polar lows. He suggested that hurricanes are not observed because the Nordic seas cover too small an area to provide suitable conditions for intensification for a long enough period. WISHE mechanisms and hurricane development are generally too slow to account for rapidly developing polar lows. However, because of

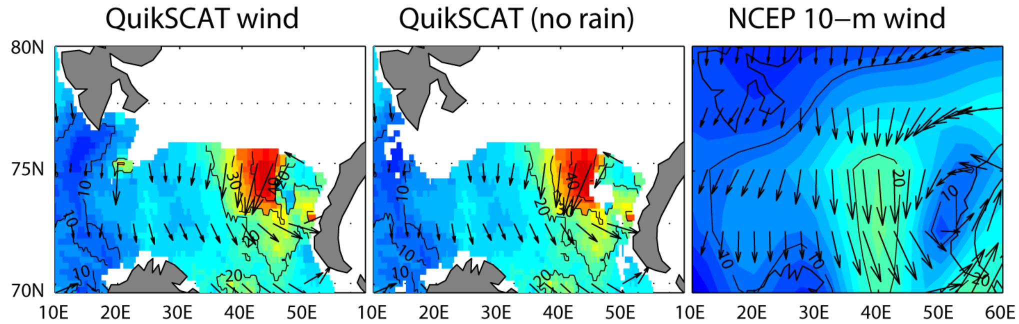

Figure 1.4: QuikSCAT and NCEP wind fields over the Barents Sea from the evening (1800 UTC for NCEP) of 18 December 2002. In the middle panel the rain-flagged QuikSCAT pixels have been deleted.

their similarities with tropical cyclones, a few polar lows have been referred to as "Arctic hurricanes" (Emanuel and Rotunno, 1989; Businger and Baik, 1991).

An example of a true Arctic hurricane is shown in Figure 1.3, a satellite image from the early morning of 20 December 2002. Visual inspection of this system strongly suggests that hurricane-like processes are at work. Bracegirdle and Gray (2006) compared this polar low to Hurricane Danny, a rather weak category one hurricane which made landfall in Alabama in 1997 (Blackwell, 2000). It is interesting to note that the QuikSCAT winds are at their most severe before the hurricane-like stage of the development. Figure 1.4 shows the QuikSCAT and NCEP winds from the evening of 18 December, during the initial intensification stage of the polar low. The wind speed in the cold air masses approaches a staggering 50 ms^{-1}. Note that the strongest winds are not rain-flagged, and can probably be trusted. During the transition from the baroclinic stage to the hurricane stage, the wind speed gradually weakens to approximately 30 ms^{-1} when the satellite image was taken. To our knowledge this case has not been studied in detail, and as such is it an obvious candidate for numerical simulation.

1.2.3 On the importance of vertical stability

Many or most polar lows form in shallow, unstable boundary layers. As pointed out by Duncan (1977), the conversion of energy takes place in the thin layer below

700 hPa. The unstable air is a result of cold air outbreaks from the sea-ice (or snow-covered land masses) over a warm ocean surface. The vertical temperature gradients lead to strong heating from below and very strong sensible and latent heat fluxes. Indeed, many studies have confirmed that release of latent heat plays a significant role during the mature phase of many polar lows (Blier, 1996; Mailhot et al., 1996; Bresch et al., 1997; Lee et al., 1998; Claud et al., 2004).

In his PhD thesis entitled "The role of convection in the intensification of polar lows" (Bracegirdle and Gray, 2006), Tom Bracegirdle manually picked out polar lows from satellite imagery and assessed the corresponding behaviour of certain atmospheric parameters. 58 polar mesocyclones (not necessarily fully-fledged polar lows) were identified from December 2001 to February 2002 and used in the analysis. The parameter that was found to be the best discriminator of polar lows was the wet-bulb potential temperature θ_w (he did not have access to the equivalent potential temperature θ_e) at 700 hPa minus the sea surface temperature SST. When this quantity is negative, the lower portion of the atmosphere is prone to convection of air parcels near the surface. θ_w was found to be only marginally better than the "dry" potential temperature θ. The hypothesis that this was because θ_w takes the dryness of the cold air masses into account was put forward.

On the basis of the empirical evidence found by Bracegirdle and Gray (2006), the 'dry' static stability was used as an indicator of marine cold air outbreaks in Paper II.

1.2.4 Reverse-shear polar lows

Polar lows often form along secondary cold fronts on the northwestern or western flanks of synoptic cyclones. In this region, the thermal wind at lower levels is in the opposite direction of the actual wind. This particular kind of polar lows is thought by some to be dominant in the Nordic Seas (Sigbjørn Grønås and the late Elmer Raustein, personal communication). A numerical study of polar lows by Grønås et al. (1987) supports this idea. All the four cases which were simulated took place in reverse shear. Paper I is an investigation of where, when and how often reverse-shear conditions occur in the Northern Hemisphere.

The first explicit mention of reverse-shear polar lows was made by Duncan

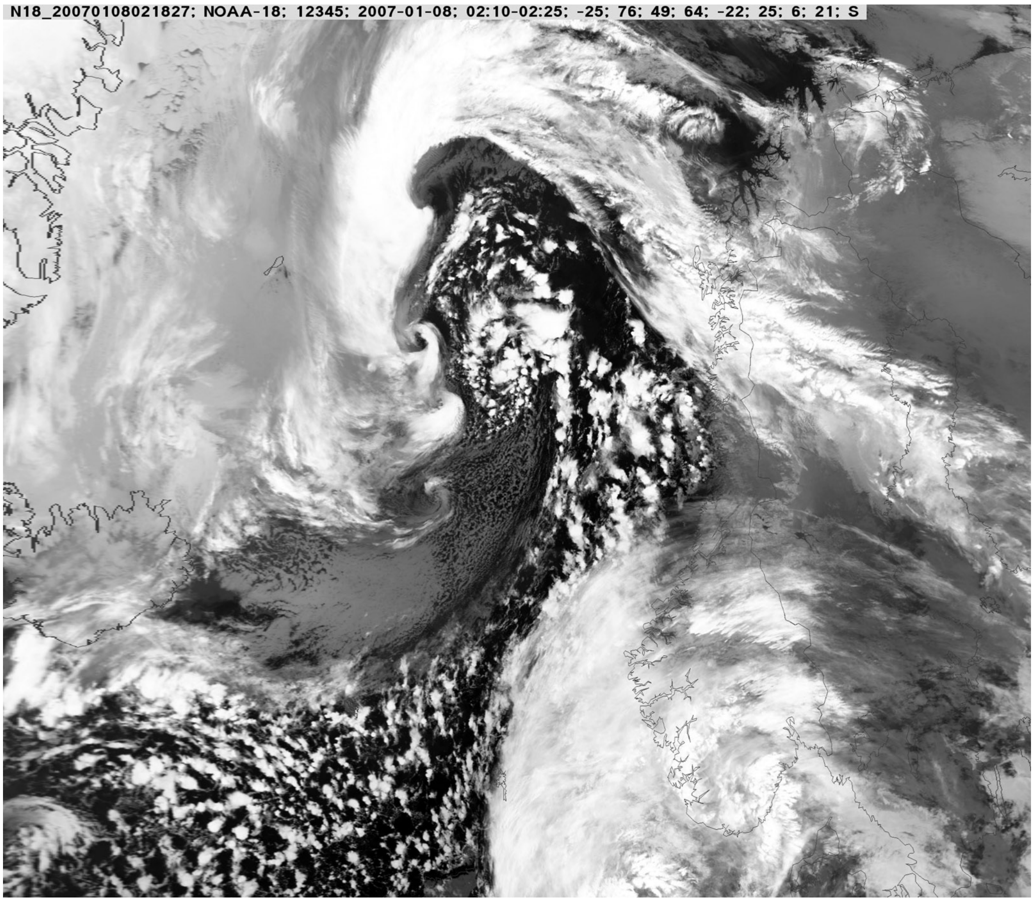

Figure 1.5: An wave-train of reverse-shear polar lows near Jan Mayen on 8 February 2007.

(1978). He observed that:

> Between Norway and Greenland it is not uncommon in winter for a northerly flow to have a southerly thermal wind, probably owing to the influence of the cold East Greenland ocean current on the western flank of the low in contrast to the relatively warmer water of the Gulf Stream on the eastern side.

In Figure 1.5, we see a wave-train of reverse-shear polar lows forming along the secondary cold front of a synoptic low.

Duncan (1978) pointed out that a disturbance in a typical northerly reverse shear flow will convert potential energy by a direct thermal circulation; warm air is lifted in the region of warm advection north of the surface low, and cold air descends in the region of cold advection south of the surface low (and under the upper-level trough).

Ideal conditions for growth now require a southward tilt in the vertical between the disturbance at the surface and at upper levels. The trough aloft should lag the cold anomaly by a quarter of a wavelength for optimal cold advection under the upper-level trough. The isolated effect of such a circulation when (often unrealistically) ignoring diabatic effects is to deepen (build) the trough (ridge) aloft.

Duncan (1978) called such conditions 'reversed shear flow' because the Northern Hemisphere large-scale midlatitude westerlies usually have the same direction as the thermal wind resulting from the north-south temperature gradient. In these more familiar circumstances, the geostrophic wind speed normally increases with height, and frontogenetic processes lead to a weakening of the surface winds.

1.3 Frontal systems

The North Atlantic Oscillation is not the only meteorological pattern to have been noted in previous times. In the ”King’s mirror” (”Kongespeilet” in Norwegian), a book that was written in 1250 AD, the following passage appears (translated from the Old Norwegian by Laurence Marcellus Larson in 1917 and copied from Stephenson et al., 2002):

> In reply to your remark about the climate of Greenland, that you think it strange that it is called a good climate, I shall tell you something about the nature of the land. When storms do come, they are more severe than in most other places, both with respect to keen winds and vast masses of ice and snow. But usually these spells of rough weather last only a short while and come at long intervals only. In the meantime the weather is fair, though the cold is intense. For it is in the nature of the glacier to emit a cold and continuous breath which drives the storm clouds away from its face so that the sky above is usually clear. But the neighboring lands often have to suffer because of this; for all the regions that lie near get severe weather from this ice, inasmuch as all the storms that the glacier drives away from itself come upon others with keen blasts.

In modern terms, the weather conditions described here would pass as katabatic winds and Arctic fronts near the ice edge.

1.3.1 Arctic fronts

The leading edges of the cold polar air that is advected over the ocean surface are referred to as Arctic fronts. Note that these systems are not to be confused with the much larger Polar front that separates the cold polar air masses from warm tropical air. Along Arctic fronts, the baroclinicity is high enough for polar lows to form if the upper-level conditions are right.

However, Arctic fronts are not only an important requisite for polar lows. Strong winds have been observed in a low-level jet to the north of the front on

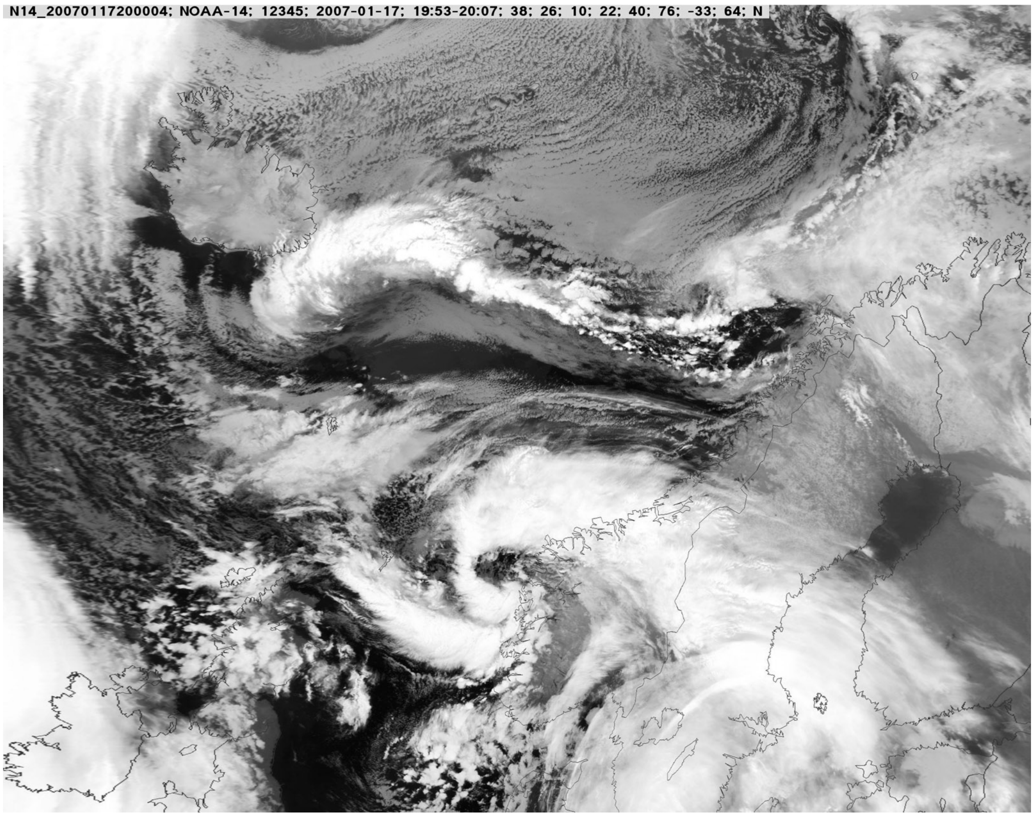

Figure 1.6: An Arctic front near Iceland.

many occasions, some with deadly outcome. As mentioned before, Økland (1998) suggested that a disaster near the ice edge on the east coast of Greenland in 1952 was due to severe amplification of the winds along the ice edge. In his paper (Økland, 1998), he studied a case during which a coast guard ship in the vicinity of Bear Island was surprised by sudden hurricane-force easterly winds. The same case was studied numerically by Grønås and Skeie (1999).

Grønås and Skeie (1999) emphasised the implication of reverse shear conditions on the wind field. In their simulations they found a low-level jet just over the boundary layer, and near the seas surface the model geostrophic wind speed was about $70 \mathrm{ms}^{-1}$. Thompson and Burk (1991) performed a numerical study of another Arctic front which had been observed by Shapiro et al. (1989) near the Spitsbergen ice edge during the Arctic Cyclone Expedition in 1984, and found a similar, albeit weaker, low-level jet along the front. Finally, Drue and Heinemann

(2001) found almost identical structures over the Davis Strait in 1997, with winds parallel to the ice edge and wind speed decreasing with height.

In Figure 1.7, a schematic representation of how reverse-shear conditions may develop on the east coast of Greenland. Initially, a surface low is moving into the Nordic Seas over Iceland towards the northeast. The air over Greenland is cold, and the thermal wind is directed along the ice edge from southwest to northeast. There is a weak trough aloft just behind the surface low. When the surface low passes Southeast Greenland, it pulls cold air southwards behind it. This leads to a deepening of the trough aloft and the isotherms are gradually shifted to a north-south alignment. The winds near the surface are now in the opposite direction of the thermal wind, and a region with reverse-shear conditions develop to the north and northwest of the surface low. Now the low-level winds in that region have to increase in strength to maintain thermal wind balance.

In Paper III, one of the fundamental properties of reverse-shear flow, that the geostrophic wind speed increases towards the surface, is tied to climatological winds derived from the QuikSCAT satellite-derived surface wind data set.

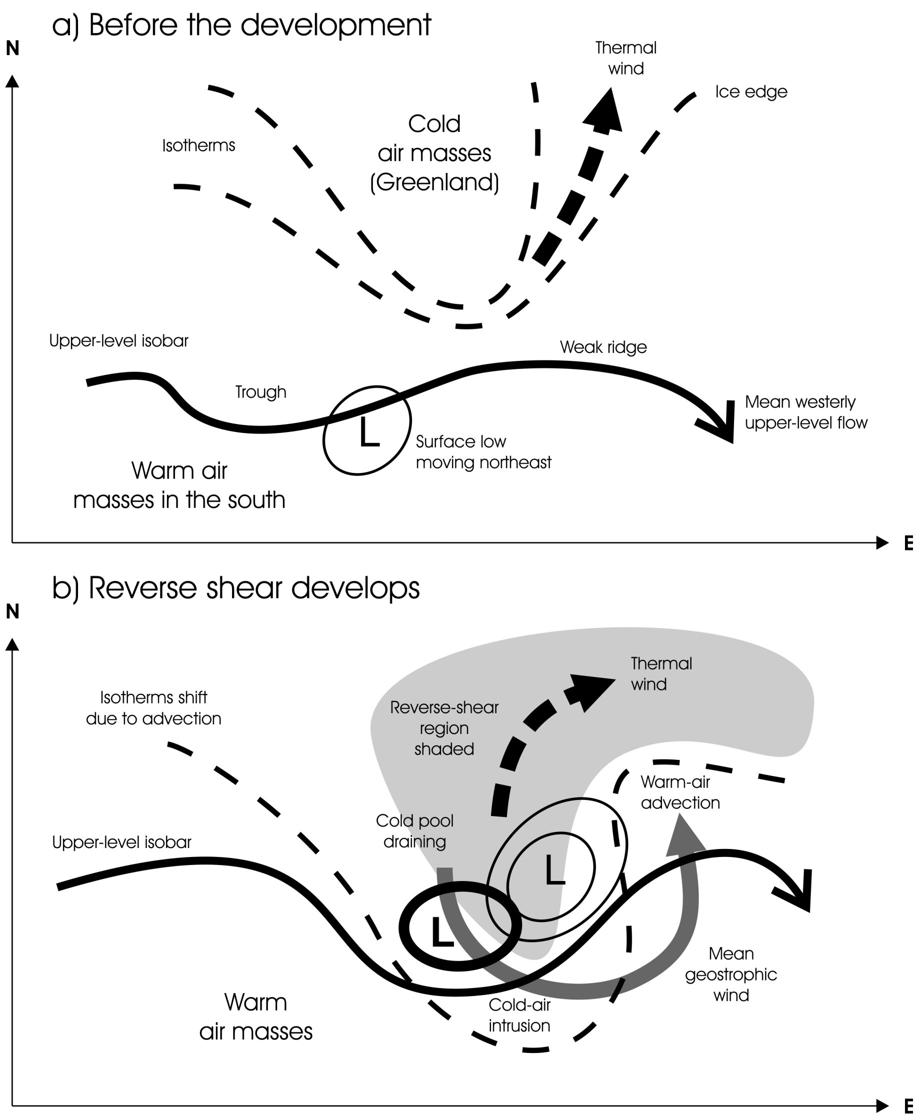

Figure 1.7: A schematic representation of how reverse shear develops with cold-air advection to the north and northeast of a surface low. See text for details.

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Chapter 2

Papers

2.1 List of papers

Paper I: ***A new climatology of favourable conditions for reverse-shear polar lows***

Paper II: ***Marine cold-air outbreaks in the future: an assessment of IPCC AR4 model results for the Northern Hemisphere***

Paper III: ***Severe winds in the Nordic Seas: a QuikSCAT climatology with emphasis on the marginal ice zone off the east coast of Greenland***