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Polar Lows in the Nordic Seas

A scientific and technical review

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1. Abstract

The scientific literature on poplar lows and polar low research have bee reviewed. The earliest references are from the early 1950ies when an interest among British and Scandinavian meteorologists were emerging. After launching of the Nimbus 3 satellite in the 1970ies, carrying infra red sensors, cloud signatures of polar lows over ocean areas could be used to detect polar lows. It is after this that the ubiquity of polar lows during Arctic cold-air outbreaks became apparent. During this period hat Scandinavian and British scientists developed different, and apparently contradicting, theories of the energetics of polar lows. The British relied on baroclinic instability while the Scandinavians believed the energy source were convetion and release of latent heat. Later, it was revealed that polar lows comprise a spectrum of events, from pure baroclinic to hurricane-like phenomena that are driven by condensational heating from the ocean. Polar lows affecting Britain, formed during cold-air outbreakes over the southern tip of Greenland, tends to be more baroclinic in nature than many of the cyclones observed along the coast of Norway.

Two pereiods of intense focus on polar low research are identified. First is the research during the 1980ies when the Norwegian polar lows project led to a large number of scientific publications on the subject. This period was followed by a certain decline in the interest for the topic. The International Polar Year(IPY) resulted in a renewed interest in polar lows with large scale observational campaigns in the Arctic.

2. Introduction

Intense meso-scale cyclones known as polar lows are frequently observed over the ocean in the Atlantic sector of the Arctic. During winter, cold and extremely stable air is formed over the ice-covered areas of the Arctic. During certain synoptic-scale weather patterns cold-air outbreak may be triggered and the cold Arctic air-masses become exposed to the relatively warm ocean surface. Such conditions promote strong deep-convection and the formation of polar lows with surface winds often exceeding 30 m/s. These small violent storms have been felt by coastal communities and seafarers over the centuries and are believed to be responsible for a number of shipwrecks. Meso-scale cyclones, with horizontal length scale of less than 1000 km, are seldom possible to detect with the sparse network of synoptic observations in the Arctic. Although the phenomena has been well known among weather forecasters, the small size and relatively rapid development has until recently made them almost impossible to forecast. The most commonly accepted definition of a polar low is (Rasmussen and Turner 2003):

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.

In Meteorology the study of polar lows is a “new” branch of the science. Virtually no scientific papers were published on the subject before 1960 and in was only during the 1970s that polar orbiting satellites revealed the ubiquity of mesoscale cyclones during Arctic cold-air outbreak. It was also during this period that the striking similarity with tropical cyclones were acknowledged. Polar lows displayed by the satellite images, reveals properties such as clear eye and spiral bands of deep-convective clouds. This has lead several authors to suggest the release of latent heat as one major energy source for at least a class of polar lows.

However, it is important to keep in mind the baroclinic nature of cold-air outbreaks. Very often, polar lows develop from disturbances on Arctic fronts that are formed when cold and dry Arctic air is exposed to oceanic heat fluxes. The Arctic fronts are characterised by strong horizontal temperature gradients in the lower troposphere and an intense low level jet. In such cases the presence of the front suggest that baroclinic instability plays a role in the polar low formation. Nonetheless, the deep convective clouds revealed at the same time by satellite images suggests that large amounts of latent heat must be released in the troposphere. Possibly, both baroclinic and diabatic processes are important during the early stages of polar low development. Pure Arctic hurricanes as described by Emanuel and Rotunno (1989) may represent the final stage for vertically aligned symmetric cyclones with no baroclinic potential left.

1. The Rescuing Deed of Hamningberg

Hamningberg is an abandoned village on the northern coast of the Båtsfjord peninsula in Finnmark, Northern Norway. Before 1965, when it was decided to depopulate the village, Hamnigberg was a lively fishing community where fishermen were hunting their catch in small open rowboats in the nearby waters. The village is located in an open bay facing the Barents Sea and has no islands outside to protect it from rough weather that frequently occurs in this area. In stormy weather the bay is extremely exposed to the rough ocean. The night between 19 and 20 Mai 1894 the whole fishing fleet of Hamningberg was at sea when a violent storm broke loose. The hurricane force winds caught the fishermen with complete surprise and as the waves rapidly grew it became impossible to take the boats to land. The most dangerous part of the sea in such conditions is the surf zone near the shore where braking waves creates a deadly barrier between the ocean and land, effectively trapping the men in their small open boats in the ferocious open sea. The women and children of Hamningberg could only watch in despair the mortal drama that took place in front of them as the major part of the adult male population were desperately clinging to their rowboats in a fight between life and death.

Figure 1: The fishing community Hamningberg in northern norway.

Before 1894, the vessels used for rescue operations were mainly large steamers. From a modern perspective these steamers are unsuited for operations directed towards small open boats. The ship hull could potentially crush the boats under the operation and hauling people on board in rough sea was extremely dangerous. Around 1890, the shipbuilder Colin Archer proposed building a smaller size rescue vessel tailored to operations along the Norwegian coast. Colin Archer later became famous for also building FRAM, the vessel that took Fridtjof Nansen on his famous voyage through the Arctic Ocean. In 1891 the The Norwegian Society for Sea Rescue (NSSR) was founded and its first vessel, RS 1, was set in to operation in 1893. At the time most people were sceptical about the abilities of a small size wooden rescue vessel compared to the large steamers in dangerous weather. RS 1 came to Vardø, the nearest town to Hamningberg, on Saturday 19 May 1894, only a day before the storm at Hamningberg. As news about the event reach Vardø, the local head of police contacted the steamers in the harbor and asked for a rescue operation. The steamers had to give in as the weather was too bad. As a final desperate attempt he then contacted the skipper of the new RS 1, which nobody believed could do anything under the circumstances. Skipper Nikolai Anthonissen and his crew took the challenge and successfully made it to Hamningberg. They used oil to calm the waves and hauled 22 wet and frozen fishermen onboard the vessel. Packed with its load, the vessel returned to Vardø. They then went for a second trip and brought another 14 men to a safe haven in Vardø. In what could only be described as a remarkable achievement all 36 men saved their life, not one single casualty occurred. The log book of RS 1 for the night between 20 and 21 Mai 1894 has one simple line which is almost austere in its modesty: “The crew will go to bed since there are no longer any men on the ocean”.

The following days the rescuing deed of RS 1 made headline news all over Norway. The success of the operation kick started the new organization NSSR and is of course a pivotal event in the its proud history. Skipper Nikolai Anthonissen was later awarded the kings gold medal for this achievement. Visitors to Hamningberg today can see the monument that was erected in 1994, 100 years after the event, in memory of the rescuing deed of Hamningberg.

Figure 2:RS1 Collin Archer, the first vessel of The Norwegian Society for Sea Rescue (NSSR)

In 1894 virtually no scientific knowledge of polar lows existed. Even synoptic lows were poorly understood as this happened many years before Willhelm Bjerknes founded his Bergen School of Meteorology and developed the modern model of low pressures. So how do we know that the Hamningberg event was caused by a polar low? First, the accounts of the extremely rapid change in weather conditions point in the direction of a polar low event. Also, the very low temperatures the preceding days is consistent with this. The observations recorded at Vardø for May 1894 show that the temperatures on 15 and 16 May are plunging from almost 9°C to below zero, confirming a cold-air outbreak. The precipitation for the 20 May is more that 20 mm, a very high value for the area, actually the second highest value recorded at Vardø in 1894, and indeed consistent with a polar low landfall.

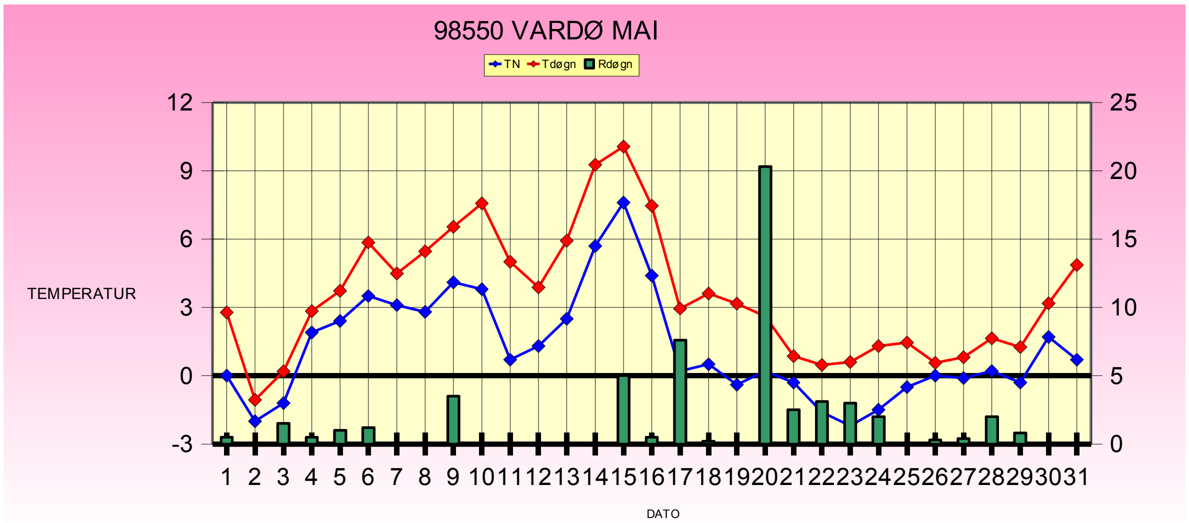

Figure 3: Observations of temperature and precipitation from the Vardø synop station for May 1894. Blue line is the night temperature and red is the daily average. Green bars show the 24 hour precipitation. Note the temperature drop from 15 May and the maximum precipitation on 20 May.

The most compelling argument however, is the reconstructed pressure chars based on pressure gauges from 1894. They can only describe the situations over land since no observations were taken over oceans at the time. The pressure chart for 19 May 1894 reveals a high pressure system over southern Greenland directing a flow of cold air from the Greenland ice cap over the ocean in the Greenland Sea. In addition, a low pressure system is situated over Russia in the area near Novaja Semlja that would

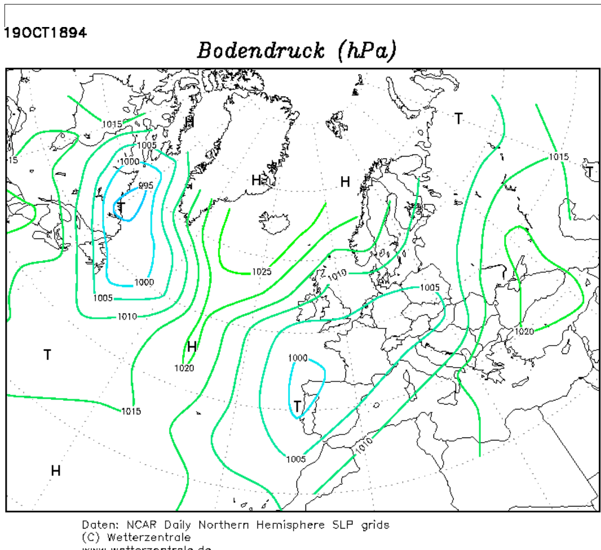

Figure 4: Reconstructed pressure chart for 19 May 1894.

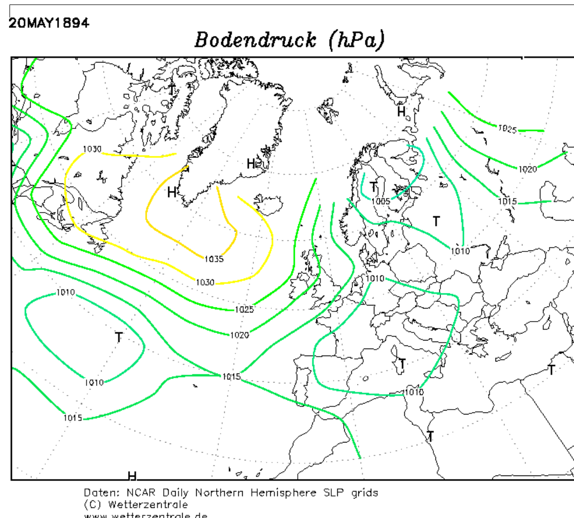

Figure 5: Reconstructed pressure chart for 20 May 1894.

have directed a flow of cold air from the Arctic sea ice over the Barents Sea. The total picture indicates a massive cold-air outbreak over the ocean areas from Greenland to the eastern Barents Sea. A weather situation like this would almost certainly have triggered polar low developments over the relatively

warm ocean. On 20 May a weak low pressure through is located over norther Scandinavia and the Cola Peninsula. It is unlikely that this weak low could cause the weather conditions experienced at Hamingberg. The Hamningberg event is therefore probably the oldest account of a weather event that we can, with a certain confidence, ascribe to a polar low.

2. Early days of polar low research

The earliest known reference to polar lows in the scientific literature is found in a book by Danevig (1954), a weather forecaster at the Norwegian Meteorological Institute in Norway, in a book of meteorology for air pilots. Here, Danevig discusses what he call "instability lows" along the coast of Norway during weather situations with cold northerly wind flow. He also presents a figure (FIGURE) sketching a typical cold-air flow pattern with meso-scale vortices that reveals a fairly good knowledge of this phenomena, decades before any satellite images were available. Obviously, weather forecasters in Norway were aware of polar low like features despite the lack of scientific literature on the subject. Clearly, the phenomena and its importance were also known to British weather forecasters who also seem to have been the first to use the term "polar lows". In the "Handbook of weather forecasting" issued by the Meteorological Office in 1964, a polar low is defined as "*a fairly small-scale cyclone trough (sometimes the surface isobars show only a minor ripple) embedded in a deep cold current which has recently left northerly latitudes*" (Lyall, 1972). British meteorologists also published some papers in the 1960's with case studies of individual polar lows as they were land folding over the British Isles (Harley, 1960; Stevenson, 1968).

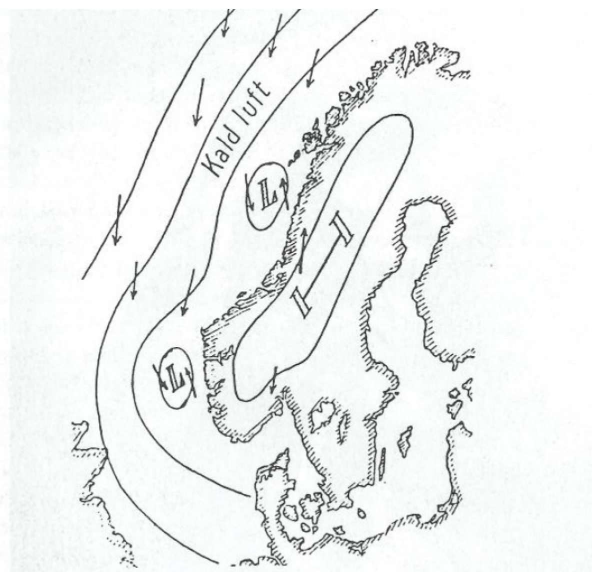

Figure 6: a sketch of meso-scale cyclones in a cold-air outbreak along the coast of Norway as envisaged by Danevig (1954).

In April 1969 NASA launched Nimbus 3, a so called second generation research and development satellite designed to test advanced meteorological sensor systems. Among these were infrared radiometers yielding information on the radiation emitted and reflected by the earth and its atmosphere. On 5 January 1970 the satellite recorded an image of a polar low to the west of Scotland (FIGURE), generally believed to be the first known satellite image of a polar low (Rassmusen and Turner 2004). Only 20 days later on 25 January the infrared sensors on Nimbus 3 terminated. The image was first presented in a paper by Lyall (1972) in a descriptive study of polar lows over Britain.

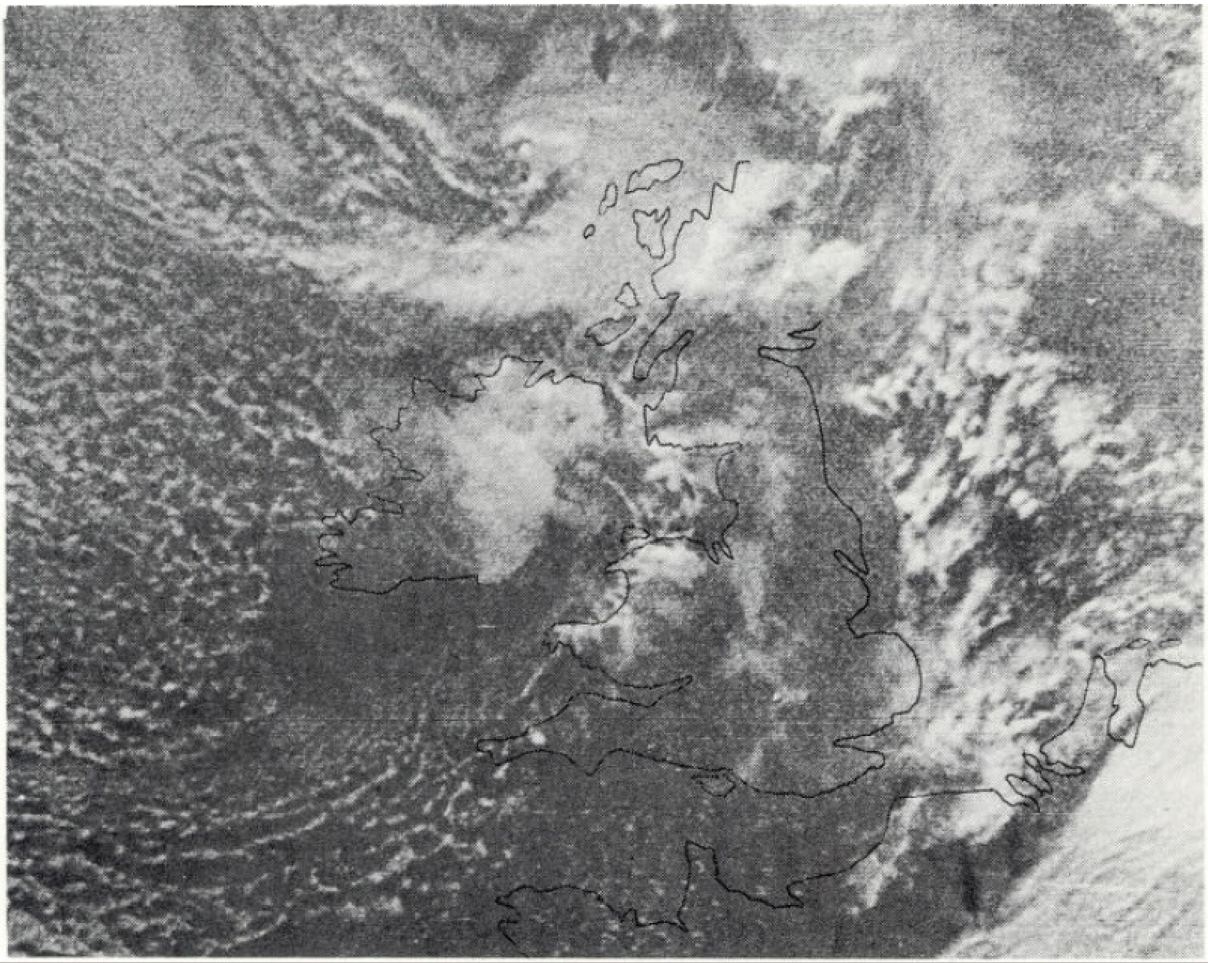

Figure 7: Infrared image taken by Nimbus 3 on 5 January 1970. This is the first known satellite image of a polar low. Cloud formations form the low can be seen just north of Scotland in this image.

The first attempt at a theoretical explanation of the dynamics of polar lows was carried out by Harold and Browning (1969), where they describes the airflow and precipitation in polar lows over Britain using radar information, synoptic data and on radiosondes. In this study they concludes that poalr lows are low level shallow features that are mainly driven by baroclinic instability. A similar view was taken by Mansfield (1974). During the 1970s Scandinavian scientists took a slightly different view, focusing more on the air-sea fluxes, deep convection and release of latent heat. (Økland, 1977; Rassmusen 1979). The striking similarities to tropical cyclones seen in satellite images makes if off course tempting to assume similarities in the driving forces as well. In the paper by Rassmusen (1979) he attempts to use the CISK theory (Convective Instabilbity of the Second Kind) on polar low development. The CISK theory was originally developed by Charney and Eliassen (1964) to explain how cumulus convection and low-level convergence cooperates in hurricane intensificarion.

In the beginning the baroclinic and convective theories were regarded as two conflicting explanations of the same phenomena. However, as Økland (1983) later argues, polar lows along the east coast of Greenland develops as baroclinic disturbances but that polar lows in the Norwegian and Barents Sea, where baroclinicity is weak, must be governed by other mechanisms. The most obvious candidate is heating by convection. So the reason for the different views was simply that the British Isles were more exposed to the polar lows that develops off the coast of Greenland that are more baroclinic in its nature while those experienced along the Norwegian coast are mostly of the convective type. The view today is that for most polar lows the two mechanisms work together and one often refers to a continuum of polar lows ranging from pure baroclinic events to so called "Arctic hurricanes" driven almost exclusively by heat and moist exchange between the ocean and the atmosphere. The cases belonging to either of the extreme ends of this continuum are however rare.

3. The 1980s and the Norwegian Polar low Project

During the 1980s the scientific interest in polar low research reach an all-time high. The are mainly two reasons for this. First, infrared satellite images of polar lows had been available since the early 1970s. By the turn of the decade routine satellite images were readily available and the scientific community became increasingly aware of how frequent polar lows actually were forming during cold-air outbreakes. The second reason was the introduction of the Norwegian Polar Low Project started in January 1983. The project was funded by some of the major offshore operators in the North Sea and was a joint effort between the Norwegian Meteorological Institute, SINTEF, OCEANOR and the universities of Oslo, Tromsø and Copenhagen. The project also included scientists from USA and UK. At this time the oil industry had been operating in the North Sea for about a decade. During this first period the offshore industry were lead by expertise from USA, normally used to operate in the Gulf of Mexico. The harsh weather and wave conditions of the winter-time North- Sea took most of them by surprise. To say that safety precautions were minimal is by all means an understatement. It all changed in 1980. The watershed for safety measures in the North Sea is 27 March this year when the Alexander Kielland platform capsized during a violent storm, the worst disaster in Norwegian waters since World War II. 123 perished and only 89 survived the accident. In 1983 areas north of the 62 latitude were licensed for oil drilling, areas far more exposed to polar lows than those further south were the industry hitherto had been operating. Polar lows posed a potential threat to future safety. Research was needed. It was time to take dangerous weather seriously.

4. Climatological investigations

An important task for the task for the Norwegian Polar Low project was off course to map the climatology of polar lows, such as frequency of occurrence, distribution through the seasons and intensity distribution. Here, the polar low climatology for the period between 1971 and 1985 were investigated (Lystead et al. 1986; Wilhelmsen 1985; Wilhelmsen et at. 1986). The studies were based on reanalysed urface weather maps, synoptic observations, infrared satellite images from polar orbiting satellites and climatological archive of objective meteorological analyses. Weather maps were scrutinized in order to document polar lows over the sea surrounding Norway. One of the major findings was that the main seasons for polar lows was from October to April. Polar lows were most frequent in December and January. In February, there were only two case, polar lows were found to be far more frequent in March and April than in February. This local minimum in February is still debated in the scientific community.

The lows were observed in weather situations with wind from NE, N or NW in the Norwegian Sea. and/or the Barents Sea, and with synoptic scale cyclones somewhere between Iceland and Novaya Zemlya. Half of the tracks crossed the area between Bear Island and the coast of North Norway. The propagation speed was usually between 8 and 13 ms^{-1} over the sea. and between 15 and 20 ms^{-1} over land.

Businger (1985) studied the evolution of the 500 mb height field during outbreaks of well-developed polar lows over the Norwegian and Barents Seas. In addition, 10 independent cases were chosen on the basis of infrared satellite imagery.

The study reveald the presence of significant negative anomalies in both the temperature and height fields at the 500 mb level over the Norwegian and Barents Seas, indicating strong positive vorticity and very low static stability over the area on the days when mature polar lows were present. The evolution of the height anomaly pattern shows ridging along the west coast of Greenland, and the development of a trough north of Norway, resulting in a northerly component of the flow aloft and8: at the surface over the Norwegian Sea, as much as 3 days prior to the outbreak of polar lows. The northerly surface flow results in the development of low-level baroclinicity. Evidence suggests that a rapid deepening, characteristic of polar lows, occurs coincident with the outbreak of deep convection. It is suggested that the outbreak of convection is organized by the baroclinicity. The evolution of the negative height anomaly prior to polar low outbreaks suggests forcing by a short wave aloft. The in-situ evolution, and wavelength of the height anomaly pattern suggest that topographical forcing by the high Greenland Plateau, in addition to the warm water of the Norwegian Sea, may enhance the development of polar low outbreaks off the Norwegian coast.

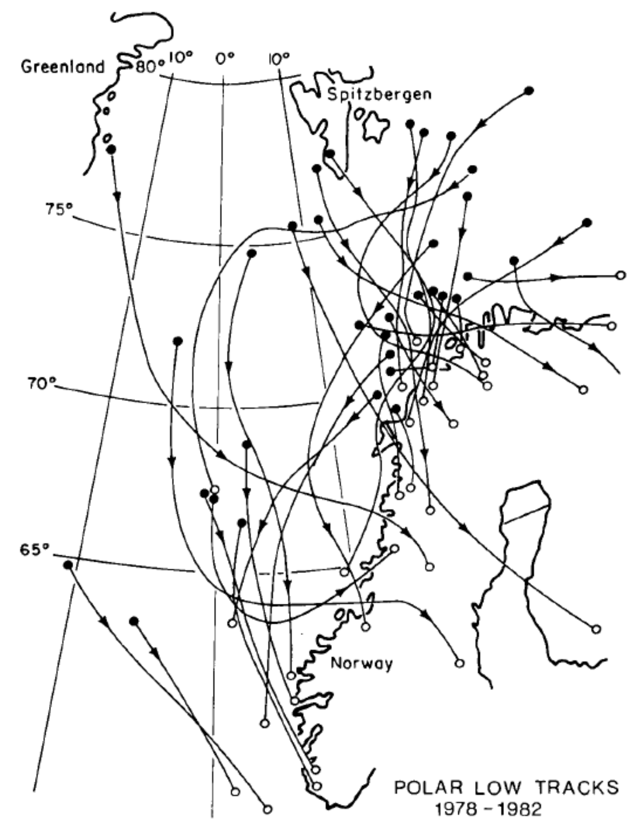

Figure 8: Polar low tracks found Willhelmesn (1985).

Carleton (1985) studied visible and infrared satellite images in connection with urface and upper-air synoptic observations for two years' (1977, 1978/79) mid-season months (January, April, July, October) to derive synoptic climatological information on the "polar low" and "instant occlusion" phenomena. One finding in this investigation was that the results support the role of the polar low as a synoptic indicator of anomalous winter circulation in the extratropics.

Ese et al. (1988) studied the large-scale flow pattern during the formation of polar lows over the Norwegian and Barents Seas. They found that in most cases a strong northerly airflow is located close to the east coast of Greenland. The geographical distribution of polar lows suggests a division of the events into two groups, a western group consisting of the lows first observed west of 5°E, and an eastern group consisting of those first observed east of the same longitude. When polar lows are formed in the eastern sector, the strongest positive anomaly is associated with the ridge over Greenland; the cold air in the strong northerly flow east of Greenland is then up to 8°C colder than normal. The location of this cold anomaly gives a westward tilt of the anomaly pattern with height.

Aakjær (1992) analysed 18 cases of polar lows (sub-synoptic cold air vortices) over Denmark in the 10 polar low seasons (November to April) from 1980–90. The investigations revealed that polar lows generally form in an almost moist adiabatic atmosphere with pre-existing large-scale positive vorticity, and suggested that this can explain why polar lows can have a horizontal scale down to 100 km and at the same time be stable systems persisting for several days. The strongest lows were found to have a strong baroclinic influence, but it was shown by using the model proposed by Craig and Cho (1989), that for most of the lows both baroclinic and convective processes can be of importance.

Harold et al. (1999a) used satellite imagery to study mesocyclones observed over the North-East Atlantic and Nordic Seas during the 2-year period October 1993-September 1995. An unexpectedly large number (4054) of mesocyclones were found, occurring throughout the year, although winter was the most active season. Most mesocyclones were observed in the northern regions of the study area, near the ice edge, and were small, with 86% of cyclones having diameters of <400 km. Most mesocyclones formed, and decayed, within 1 day and travel only short distances. It was found that the large-scale circulation plays a role in determining mesocyclone numbers as the two separate 12-month periods in the study exhibited very different characteristics.

In a follow up paper, Harold et al. (1999b) investigated causal mechanisms of mesocyclone and synoptic cyclone characteristics over the Northeast Atlantic and Nordic Seas are investigated using a 2-year database compiled from infrared satellite imagery. A strong seasonality was found, with peak activity in winter and a minimum in spring. A distinct interannual variability is also found. Smaller mesocyclones (<400 km diameter) were found to be strongly linked to the shallow baroclinic zone along the sea ice edge. Midsize mesocyclones, 200-600 km diameter, are often associated with cold air outbreaks following the passage of synoptic systems. A chart analysis confirmed this, showing that convective instability is the major mechanism for the origin of these storms. Although the temporal coverage of the database was short, some support for this was found in comparison with teleconnection patterns and also potential reasons for the large interannual variability.

In a climatological study, Bracegridle and Gray (2008) found that the difference between the wet-bulb potential temperature at 700 hPa and the sea surface temperature (SST) is an effective discriminator between the atmospheric conditions associated with polar lows and other cyclones in the Nordic seas. A verification study shows that the objective identification method is reliable in the Nordic seas region.

A 2-year data set of polar low events over the Nordic Seas was presented by Blechschmidt (2008). Polar lows were detected by combined use of thermal infrared AVHRR imagery and SSM/I derived wind speeds from the satellite climatology HOAPS (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data). A total of 90 polar lows were found in 2004 and 2005 with a maximum of polar low activity during the winter months. The main polar low genesis regions lie between Iceland and Finnmark in the Norwegian Sea, in the Barents Sea and in the lee region of Cape Farewell. Interannual variability in polar low activity results mostly from more frequent cold air outbreaks in 2004. Statistics for several atmospheric parameters (e.g., wind speed, precipitation, cloud top temperatures) which describe the intensity of the cyclones were retrieved from satellite observations.

Kolstad et al. (2009) investigated the spatial and temporal distributions of marine cold air outbreaks (MAOC) over the northern North Atlantic using re-analysis data for the period from 1958 to 2007. They used a simple index for identifying cold air outbreaks: the vertical potential temperature gradient between the sea surface and 700 hPa. It was found that atmospheric temperature variability is considerably more important than the sea surface temperature variability in governing both the seasonal and the inter-annual variability of cold air outbreaks. Furthermore, a composite analysis revealed that a few well-defined and robust synoptic patterns are evident during cold air outbreaks in winter. Over the Labrador and Irminger Seas the MCAO index was found to have a correlation of 0.70 with the North Atlantic Oscillation index, while over the Barents Sea a negative correlation of 0.42 was found.

Two key questions were addressed in this paper: what is the relative contribution from the atmosphere and the sea surface to the seasonal and inter-annual variability of MCAOs? Do MCAOs primarily occur in a given set of large-scale conditions?

They found the answers to these questions as follows:

1. As MCAOs occur frequently in the Nordic Seas, where SSTs are high, they found that the air temperature is more important than SSTs. The temporal frequency of the MCAO index used here is almost entirely dictated by the variance of the temperature aloft (and therefore of the atmospheric flow variability).
2. By means of a composite analysis, they found that a few well-defined and robust synoptic patterns are evident during MCAOs the regions studied (The SouthernRegion covers the Labrador and Irminger Seas, the Gin Seas include the Greenland, Iceland and Norwegian Seas and the Barents Sea). In the northern regions, north-easterly winds associated with regional pressure dipoles, with anomalous highs in the west near Greenland and lows in the east, are significantly tied to MCAOs. In the northern regions, north-easterly winds associated with regional pressure dipoles, with anomalous highs in the west near Greenland and lows in the east, are significantly tied to MCAOs. A negative association between MCAOs in the Barents Sea and the NAO index was found. In the southern region, a strong positive correlation between the two was found

5. Air craft observational studies

Polar lows are an almost exclusively marine phenomena, formed when cold air is exposed to a warm oceans. Of obvious reasons, very few conventional observations are available and most observational studies of polar lows over the ocean have to rely on observations from polar-orbiting satellites. In the early days of polar low research (see historic introduction), a number of papers were published of land folding polar lows using routine surface observations over land (Stevenson 1968; Harrold and Browning 1969; Lyall,1972). A weakness of studying polar lows over land is the fact that the character of the lows changes dramatically as the they land fold. The intensity rapidly decays and the orographic lifting results in fragmentation of the cloud pattern as the low discharges it water content in heavy rainfall.

In February 1984 the Arctic Cyclone Expedition had the NOAA P-3 Orion research air-craft stationed at Bodø airport in Northern Norway, exploring the msoscale structure of oceanic and atmospheric weather systems over the North Atlantic Ocean and Arctic Seas. On 14 February an Arctic front were investigated along the ice-edge south of Spitsbergen (Shapiro and Fedor 1989). The ice-edge front and jet formed in response to the horizontal gradients in sensible heating as very cold air flowed off the Arctic pack ice over the warm overlaying ocean along the west coast of Spitsbergen. Infrared satellite images revealed polar low development within shallow frontal baroclinicity. A second front was observed in the same area on the 18 February (Shapiro et al. 1989).

On 27 February 1984, the Arctic Cyclone Expedition carried out the first research aircraft measurements within a polar low (Shapiro et al. 1987). The low developed over the Norwegian Sea south of Jan Mayen in response to the baroclinic forcing by an eastward propagating upper-level synoptic-scale short wave. Observations from the NOAA WP-3D research aircraft documented the three-dimensional distribution of wind, temperature, moisture, and precipitation within the low. The polar low had a warm inner core and maximum surface winds of about 35 ms^{-1}. Heavy meso-convective precipitation was encountered within a frontal-like, mesoscale, baroclinic shear zone that spiraled into the low center from its southwestern quadrant. Vorticity and divergence values within the front reached 25 times 10^{-4} s^{-1} and 13 times 10^{-4} s^{-1}, respectively, where the frontal width narrowed to 10 km near the sea surface. Radar reflectivities exceeded 40 dBZ within the meso-convective precipitation band and were confined to low levels (below 3 km). The maximum total heat flux (sensible plus latent) from the sea surface into the atmosphere was 1000 W m^{-2}, comparable with that observed for mature tropical cyclones. Satellite cloud images revealed that this polar low was the most intense development in a family outbreak of 5 polar lows that formed as an east-west vortex chain between Iceland and the north coast of Norway over a 48 h period.

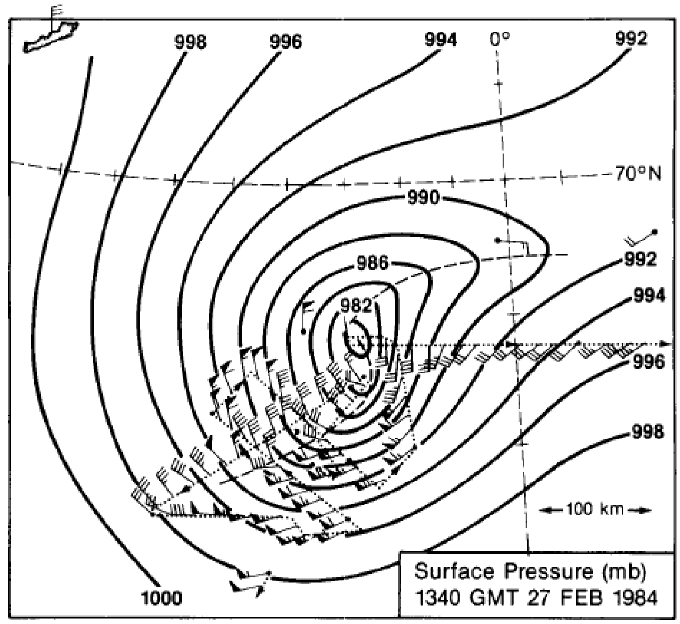

Figure 9: Observed boundary layer wind (below 300 m) and the surface pressure analysis from the research aircraft bservations of Shapiro et al. (1987).

The structure of a polar low that formed along the cast Greenland ice edge during the Coordinated Eastern Arctic Research Experiment (CEAREX) was described by Douglas et al. (1995), using NOAA WP-3D research aircraft and satellite observations. Satellite imagery showed a well-defined 400-km-wide comma cloud pattern during the time of the aircraft observations. Frontal zones with marked wind shifts and thermal gradients near the surface were associated with the polar low. Although the polar low's vorticity decreased rapidly with height between 950 and 800 mb, a secondary vorticity maximum was found in the upper troposphere associated with a short-wave trough. Doppler radar and aircraft observations showed the structure of the main precipitation band to be similar to that of other polar lows observed by research aircraft. In general, the structure of the polar low resembled, except for horizontal scale, the structure of midlatitude cyclones at a similar stage of cloud field evolution.

During the Lofotes cyclone experiment (LOFZY 2005), two polar lows were studied during a cold-air outbreak from the north in the lee of Spitsbergen on 7 March 2005 by Brümmer et al. (2009). Buoys, ship, and aircraft measurements as well as satellite imagery were applied to analyze the polar low bulk properties, the horizontal and vertical structure, and the mass, moisture, and heat budget. Both polar lows had a radius of 100–130 km and extended to a height of about 2.5 km. In the polar low centers the pressure was about 2–3 hPa lower and the air was 1–2 K warmer and drier than in the surroundings. Aircraft measurements in the second of the two polar lows show an embedded frontlike precipitation band north of the center. Here, the highest low-level winds with 25 m s^{-1} and the largest fluxes of sensible and latent heat with 290 and 520 W m^{-2}, respectively, were measured. Aircraft data show mass convergence in the subcloud layer (0–900 m) and divergence in the cloud layer (900–2500 m). Moisture supply by evaporation from the sea surface was about twice as large as that by convergence in the subcloud layer.

6. Satellite observational studies of polar lows

Moore and Vonder Haar (2003) used data from the Advanced Microwave Sounding Unit (AMSU) to study a polar low that occurred in the Labrador Sea on 17–18 March 2000. During its 40-h lifetime, the polar low was observed three times by AMSU, which captured the formation and subsequent intensification of the storm. The AMSU-A channel-5 (53.6 GHz) brightness temperature field clearly identified the warm core structure of the polar low, with storm center measurements 2–3 K higher than the background environment.

Also Caud et al. (2009) used AMSU for studying polar lows. They demonstrated the use of the AMSU-B channels at 183 GHz to locate convective polar lows in their incipient stage. This detection was based on temperature depression due to scattering by hydrometeors and confirmed by comparison with radar data. The method failed to detect weakly convective and mainly baroclinic polar lows.

Moore and Vachon (2002) used Syntetic Aperture Radar (SAR) to investigate polar lows. They claimed to documented the the presence of discontinuities in the wind field across very narrow fronts, seen as sharp lines separating different reflectivities in the SAR images.

7. Numerical simulations of polar lows

Early examples of the study of polar lows using numerical models are Grønås et al. (1987) and Nordeng (1987). In the work by Grønås et al. Polar lows are simulated with horizontal resolution ranging from 25 to 50 km, considered as high resolution at the time. They present the results of six simulations where polar lows occurred in The Norwegian Sea. The integrations started before any polar low was observed and lasted for 36 or 48 hours. The model created polar low disturbances at approximately the right position at the right time. They concluded however that the predicted intensity was generally too weak. They found that all the simulated polar lows were had an initial phase as baroclinic disturbances on a reversed shear flow. Not surprisingly, they also observed that the numerical model did not handle the observed rapid growth of the polar lows due to too coarse model resolution

In the work by Nordeng (1987), two polar lows from February 1984 are simulated. One objective here is to investigate the role of released latent heat on different scales as a driving mechanism for polar lows. The model simulations include a parameterization method for slantwise convection. The simulations showed that release of latent heat from condensation was crucial in order to obtain sufficiently strong developments.

In Cloud et al. (2004) a polar low which occurred in October 1993 over the Norwegian Sea was investigated using satellite observations and a numerical simulations. Numerical model fields were compared to quantities derived from TIROS-N Operational Vertical Sounder, the Special Sensor

Microwave/Imager, and satellite radar altimeter data. Despite better spatial resolution in the model fields, humidity and surface wind speeds were less organized in the simulations than in satellite retrievals. The number of vertical levels, especially for the lowest layers of the atmosphere, appeared to be an essential component for a good simulation of the trajectory of the low. They found that the polar low was the result of favourable flow conditions at the surface in the form of a shallow arctic front established near the ice edge, together with an upper-level potential-vorticity anomaly setting the stage for a positive interaction. Later on, the strong surface sensible- and latent-heat fluxes contributed to the extensive vertical development.

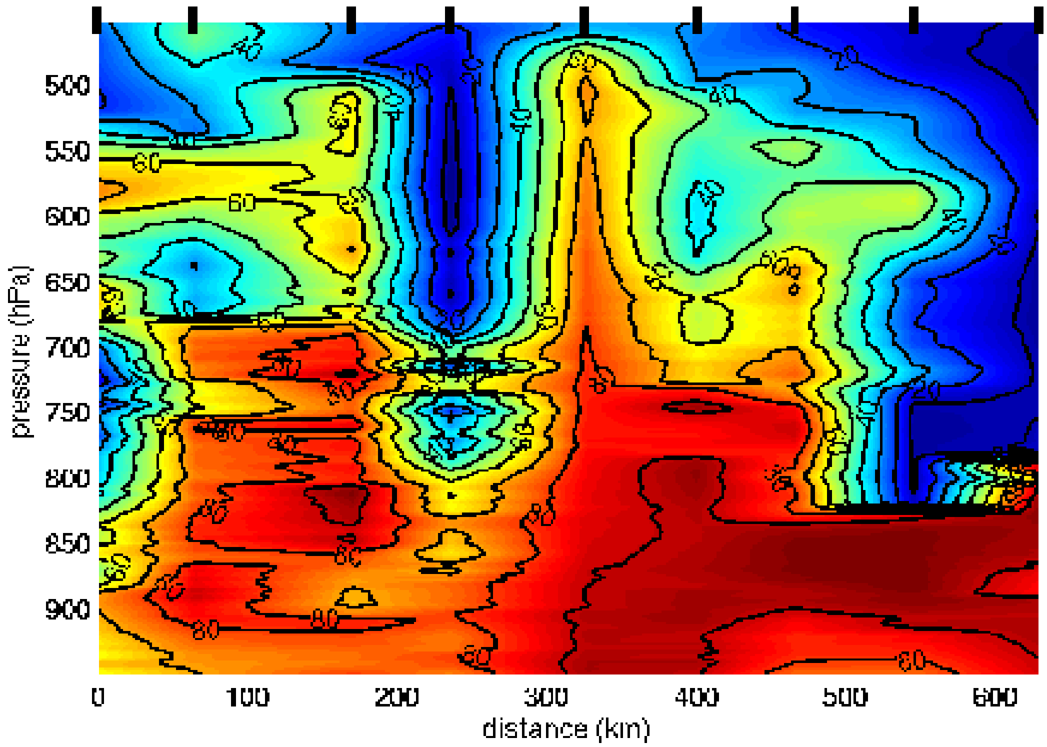

Figure 10: Relative humidity along a section through the polar low observed on 4 March 2008 during the IPY-THORPEX observation campaign. The plot is based on 9 air-craft dropsondes (marked by the black bars on top of the plot) along a straight line the made a slice thorough the centre of the low. The dry air seen at about 250 km is the eye of the low and is probably caused by intrusion of stratospheric air.

High resolution polar lows simulations today are about 5 km horizontal grid spacing. A nice example is the work by Yanase and Niino (2007) who present a number of non-hydrostatic simulations of polar lows. By vertically integrating the atmospheric water content they obtained images of the cloud patterns for the various simulations. They use this to analyze the cloud pattern for different degrees of baroclinicity, defined by the vertical geostrophic shear. The paper demonstrate that when baroclinicity is strong, non-symmetrical cloud patterns, such as comma clouds, occur. In the cases with no, or very little, baroclinicity the cloud patterns are more symmetric and hurricane like.

8. Polar low forecasting

Searching the literature for science for papers specifically targeting the challenges and state of the art of forecasting polar lows, one is surprised to find that almost no publications on the subject in the peer-review literature later than the work by Midtbø and Lystad in 1986. This is despite the fact that number of authors motivate their work based on the difficulties involved in accurately forecasting. What most of these publications do however, is to investigate numerical simulations of polar lows with off-line model systems. This should not be confused with forecasts for several reasons. Firs, they normally base the simulations on unrealistically good initial fields since the analyses are produced in a nonoperational context and involves more observations than what is available in near real time. Also, they almost always used analysed data at the lateral boundaries. Noer and Oved (2003) gave a detailed description of the procedures involved in forecasting polar lows from the perspective of forecasters on duty. Unfortunately, this has not been submitted any scientific journal, but only available through a link at the Trier University, Germany. Noer and Ovhed do also give a qualitative assessment of the forecast models at disposal at the Norwegian Meteorological Institute at the time and find them to be notoriously unreliable.

However, the seven years elapsed since 2003 have seen a number of improvements of operational weather forecasting systems, such as improved model resolutions, new and more sophisticated assimilation systems (a number of operational centres have since then implemented 4-D var), anmd more satellite data that goes into operational analyses. It seems to be an urgent need for an updated investigation and description of the current state of polar low forecasting.

The issue of improved forecasting of polar lows is one objective ot the Norwegian International Polar Year project IPY-THORPEX (see web page: http://ipy-thorpex.no/). From this project, publications focusing on the forecasting techniques and assessments of operational forecasting systems are in preparation. For instance Saetra et al. (2010) use a coupled wave-atmosphere model to re-forecasts the winter 2007 and asses the forecasts of selected polar lows. Kristiansen et al. (2010) run a number of forecast experiments of one specific polar low event, observed by GPS dropsondes during the IPY-THORPEX field campaign (Linders and Saetra 2010), using ensemble predictions. It is clear from both publications that the forecast quality of polar lows is steadily improving.

9. Past oceanographic studies related to polar lows

Despite the fact that polar lows are an almost exclusively marine phenomena, surprisingly few scientific papers discuss the atmosphere-ocean interaction and it implications for ocean circulation and possible feedback mechanisms to the atmospheric system. Emanuel and Rotunno (1989) applies the Carnot theory, originally developed for tropical cyclones (Emanuel, 1986), to investigate the effect of sea surface temperature on the polar low intensity. By considering the cyclone as a Carnot engine, working between a warm (the ocean) and a cold (the tropopause) reservoir, the maximum pressure drop is found by using the Bernoullis equation in combination with the first law of thermodynamics under the assumption that air-particles near the cyclone centre are saturated at sea-surface temperature.

Linders et al. (2010) investigated the polar low sensitivity to polar lows by running ensemble simulations with the axis-symmetric model used by Emanuel and Rotunno (1989), introducing various perturbations of the sea-surface temperature during the model simulations. They found the sensitivity of polar lows to be relatively modest. By extending the carnot model of Emanuel (1986) to include surface fluxes they proposed that the reason for this limited sensitivity is caused by the fact that saturations as sea-surface temperature do not occur, the air does not stay for a sufficiently long time in the boundary layer. The conclusion was that cooling temperature at higher levels in the troposphere is more important for the polar low intensity. Interestingly, Kolstad et al. (2009) came to a similar result based on a completely different approach. They were investigation the large-scale atmospheric flow in connection with cold-air outbreaks and were testing the temperature difference between the sea- surface and the 700-hPa surface as a polar low indicator. They found that the sea-surface temperature did indeed play a role, but that the variations hat higher tropospheric levels were more important.

The oceanic response to a moving hurricane has long been recognized (Price 1983). Entrainment of cold waters from deep layers leads to a cooling of the sea-surface temperature by a combination of extremely strong vertical mixing and large surface heat fluxes. Emanuel et al (2004) showed that the ocean's feedback is a critical parameter limiting tropical cyclone intensity. Some recent studies focus on the possible effects of deep cores of warm waters such as the Loop Current in the Gulf of Mexico and warm-core rings (Hong et al. 2000; Shay et al. 2000). Such features act as insulation to entrainment of the cold waters under the thermocline that normally hamper further intensification of the cyclone. Strong intensification of several hurricanes have been observed as they enter the areas of the Loop current in the Gulf of Mexico. In particular Katrina, which caused large disruption to the area around New Orleans when it made landfall in August 2005, intensified into a category 5 hurricane when it entered the warm Gulf of Mexico (Kafatos 2006).

In the ocean areas where polar lows often develop, the North-Atlantic Current (NAC) sub-ducts under colder and less saline waters and Arctic water flows on top of warmer and more saline waters. The result of this is the frequent presence of a temperature inversion in winter-time hydrographic sections in areas influenced by the NAC. Saetra et al. (2008) investigated the effect of intense polar lows on the upper ocean. They used microwave satellite images and numerical models to demontrate surfacve warming caused by the strong wind forcing from polar lows. They found that vertical mixing induced by surface stresses may lead to entrainment of waters from a warm and saline core beneath the sea-surface.

Rassmusen and Turner (2004) discuss the potential impact of polar lows on the cooling of the ocean and possible impacts of this on the oceanic thermohaline circulations. This part of the discussion at the last section of the book and no specific references are made. They speculate however, that the strong fluxes of latent and sensible heat during polar low events may in fact be a significant contribution to the buoyancy loss of the ocean. A similar approach is taken by Condron et al. (2008). They argue that polar lows are are underrepresented in atmospheric reanalysis data sets and are subgrid scale processes in most models used for seasonal or climate forecasting. They claim that this lack of representation, particularly over the Nordic Seas, has a significant impact on modeled ocean circulation due to a consequent underestimation of atmospheric forcing at the air–sea boundary. By using Rankine vortices a parameterization that allows the missing or underrepresented vortices in numerical simulations. They claim that the Greenland Sea Deep Water formation increases by up to 20% in 1 month when this effect is accounted for.

10. Ocean heat potential for Hurricane forecasting

The tropical cyclone heat potential (or sometimes referred to as hurricane heat potential) is defined as the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm (Leiper and volgenau, 1973; Law and Hobgood, 2007). The is based on the understanding that hurricane intensity is limited by the upwelling of cold water normally observed over waters with a shallow thermocline. As mentioned previously, deep cores of warm waters act as insulation to entrainment of the cold waters under the thermocline and may lead to extremely intense hurricanes. For this purpose, the heat potential as defined above is particularly attractive for hurricane forecasting is the fact that relatively reliable estimates can be made from the sea-surface height anomaly observed by satellite altimeter sensors (Lin et al. 2008). Another point to mention here is that hurricanes are exclusively driven by energy supply from the ocean surface. Virtually no baroclinicity is found in the tropical atmosphere where hurricanes occur. The integrated heat contained in the upper ocean therefore makes a very unique indicator of the possible intensity. This is probably very much in contrast to polar lows, for which the debate about relative importance of baroclinicity versus convective release of latent heat has been going on for as long as polar lows have been studied (see the historical section above and also Rassmusen and Turner, 2004). The view that polar lows are mixed systems of baroclinic and diabatic processes implies that the ocean temperature is not to the same degree controlling the cyclone intensity as in the case for hurricanes.

11. Application of oceanographic satellite data in synergy

Fu (2007) studied the response of the Indian Ocean to the periodic monsoons. In this invsetigation the author used scatterometer data from the European Remote Sensing Satellite together with SSH data from the *Jason* and Ocean Topography Experiment (TOPEX)/Poseidon radar. The SSH variability at 60–90 days was found to be coherent with sea surface temperature with a near-zero phase difference, showing the effects of the time-varying thermocline depth on SST, which may affect the wind in an ocean–atmosphere coupled process governing the intraseasonal variability.

Lapeyre (2009) investigated the dynamical properties of surface motions at mesoscales measured by altimetry and microwave. The mesoscale signal obtained by the altimeter is often considered to be associated with the first baroclinic mode, but recent results indicate that SST spectra and surface kinetic energy spectra derived from SSH have the same slope, which is not consistent with this hypothesis. In this paper a careful derivation of the vertical modes was done using the concepts of quasigeostrophic potential vorticity (QGPV) theory. Since the surface buoyancy can be interpreted as a Dirac function in PV, the traditional baroclinic modes have to be completed by a surface-trapped mode with no interior QGPV. The possible contribution of each mode was quantified in a simulation of the North Atlantic Ocean. The surface mode was found to give the largest contribution in terms of surface energy in most of the Atlantic. Its relative importance compared to the other modes was determined at first order by the large-scale forcing of PV and surface buoyancy. These results emphasize the necessity for a new interpretation of satellite measurements of sea surface temperature or height.

12. Numerical models in the Nordic Seas

Operational systems for atmosphere and ocean forecasting that covers the Nordic Seas is performed by a number of centres around Europe. A number of these have model domains that covers only parts of the areas of polar low formation. For the purpose of this study model domains are required to cover whole of the Nordic Seas including the Barents Sea. For this reason, the overview below only refers to operational model systems that fulfil this requirement. In paractice, we consider systems with domain that has its southern boundary south of the ridge between Greenland and Scotland, extends to the sea-ice boundary in the North and includes whole of the Barents Sea.

a. Ocean models

TOPAZ

The TOPAZ system is currently a part of the MERSEA
The system is currently being operated using the Ensemble Kalman Filter (EnKF, Evensen 2003, 2004).

The numerical cost associated with the use of these schemes is justified by the benefit of having time evolving error statistics and a fully multivariate analysis step. In a practical application, this implies that the same code can be used to assimilate various types of observations (SLA, SST, ice concentrations, ice drift but also *in situ* T/S profiles, ice thicknesses), but the CPU requirements becomes higher than for optimal interpolation schemes. Wall-clock times however remain relatively small because ensemble model integration is naturally parallel. TOPAZ uses the standard analysis algorithm with perturbation of observations.

NEMO

In UK, the operational ocean forecasting is the under the responsibility of the national Centre for Ocean Forecasting (http://www.ncof.co.uk/), which is a joint venture between several national institution. The main model tool is Forecasting Ocean Assimilation Model (FOAM). A key feature of FOAM is the assimilation of observational data into physically-based ocean and sea-ice models to ensure an accurate representation of the current ocean state. The model is then forced by 6-hourly forecast winds form the Met Office numerical weather prediction system, to forecast how the ocean and ice will evolve over the following five days. A global version of FOAM is run operationally on ¼ degree resolution, while a North Atlantic version is run on 1/12 degree resolution. The FOAM system has recently been transitioned to use a new core ocean model: the Nucleus for European Modelling of the Ocean or NEMO system, a freely available community model (http://www.nemo-ocean.eu/). An identical configuration of NEMO is also provided by the French institution MERCATOR (http://www.mercator-ocean.fr/)

ROMS

In Norway the operational ocean forecasting model is ROMS (http://myroms.org/). **ROMS** is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications. The norwegian Meteorological Institute runs the model over two domains that covers the Nordic Seas, one on 20 km horizontal resolution and one on 4 km horizontal resolution. Sea surface temperatures and sea-ice concentration from the OSI SAF products (http://saf.met.no/). The data are assimilated into the model system by using a nudging technique.

b. Atmospheric models

HIRLAM

The HIRLAM (High Resolution Limited Area Model) forecast system is the product of the cooperation between several European Meteorological Institutes. The model system consists of a 3D-VAR assimilation system, separate surface analysis and a numerical atmospheric short range forecasting component. Details of the system are given in (http://hirlam.org/). HIRLAM is a hydrostatic grid-point model, of which the dynamical core is based on a semi-implicit semi-Lagrangian discretisation of the multi-level primitive equations, using a hybridcoordinate in the vertical. Optionally, an Eulerian dynamics scheme can be used as well.The prognostic variables horizontal wind components, temperature , specific humidity and linearised geopotential height are defined at full model levels. Pressure , geopotential height and vertical wind velocity are calculated at “half” levels. For the horizontal discretization, an Arakawa C-grid is used. The equations are written for a general map projection, but in practice normally a rotated lat-lon grid projection is adopted. A fourth-order implicit horizontal diffusion is applied.

HARMONIE

The HARMONIE model is a non-hydrostatic spectral model, of which the dynamical core (developed by ALADIN) is based on a two-time level semi-implicit Semi-Lagrangian discretization of the fully elastic equations, using a hybrid coordinate in the vertical. Optionally, for larger domains and coarser resolutions the hydrostatic version of this semi-Lagrangian scheme can be used. An Eulerian dynamics core is available, but has been little used in recent years.The default upper air data assimilation scheme in HARMONIE is the 3DVAR scheme developed in ALADIN. To allow the model to be used for routine operational numerical weather forecasting, the model analysis and forecast code has been embedded in a system of scripts, executables, support libraries, documentation and tools. This overall HARMONIE system must be applicable in all HIRLAM institutes for both operational and research applications. As such, portability of the code and tools included is an important issue.

MET OFFICE UNIFIED MODEL (UM)

The Met Office's Unified Model (UM), at version 5.2 onwards, solves nonhydrostatic, deep-atmosphere dynamics using a semi-implicit, semi-Lagrangian numerical scheme (Cullen et al. 1997). The model includes a comprehensive set of parameterizations, including surface, boundary layer , mixed-phase cloud microphysics, and convection, with additional downdraft and momentum transport parameterizations). The model runs on a rotated latitude–longitude horizontal grid with Arakawa C staggering and a terrain-following hybrid-height vertical coordinate with Charney–Philips staggering.

13. Coupling of atmosphere and ocean models

There are a few different approaches that could be used when coupling together general circulatation ocean and atmosphere models. In most models that are not constructed to be coupled to other component models from the beginning, different simplifications and compromizes has to be made in the model physics and numerics to make the system realistic, stable and convinient in a coupled seting. For atmosphere models most of the challenges comes when the sea surface contains both ice and open water, but also the land-mask definition can be troublesome. For a global climate model, the two most important properties to conserve in the coupled atmosphere-ocean system, is the heat and freshwater content.Violating these properties will give long term drift in the system. However, in a regional, coupled, short range, forecast system, this might not be the most important. Instead, proper treatment of the boundary layers, and upper ocean mixing seems important. Also the coupling frequency should be short enough to resolve the processes that are important for the short time development of polar lows. For the present investigations we expect a coupling time step of approximately 1 hour to be fast enough to give a realistic simulation of the mixing processes in the upper ocean and their modification of the atmospheric boundary layer.

The horizontal grid of the models should be fine enough to model the polar lows and the ocean response. For the atmosphere, a 8 km resolution model has been shown to successful model the polar low development. However, a 8 km ocean model will certainly not describe all interesting ocean adjustments to polar lows, but we expect the most important heat flux and upper ocean mixing to be advequatly described. These are expected to be the most important processes for coupling back to the polar low, and these will also be most interesting and important for the present study.

There are several different tools that have been used when building coupled models. In Europe, the OASIS3 and OASIS4 (Redler et al 2010) systems has been widly used, while in the U.S., several institutions work towards the ESMF system. The OASIS4 system is a farily complete library with grid interpolation, communication, etc, but are still in a beta test phase. The ESMF is more a suite of software tools for building multicomponent earth sciens applications. Instead of simple library calls as used in OASIS, it requires more of an commen ESMF interface between the component models to ensure smooth communication between models. ESMF has been released in version 4. and are still in a development phase. In the span between these two systems, we also find the Model Coupling Toolkit (MCT) library (Larson et al., 2005; Jacob et al., 2005). This is a model comunication library, that are capable of handling the complex inter processor comunication between the model. This library has been used in many different systems as the NCAR CCSM3 and CCSM4, and for coupling the ocean model ROMS to the wavemodel SWAN and the atmosphere model WRF. The MCT has proven to be robust, flexible and efficient for building coupled models.

14. Assimilation techniques

The operational atmosphere and ocean models that cover the Nordic Seas today rely on a range of data assimilation schemes. Generally speaking the atmosphere models use on variational methods, e.g. 3D-VAR for met.no's models and 4D-VAR for ECMWF's models, whereas the ocean models use either some form of optimal interpolation (OI), e.g. for the FOAM system, or ensemble Kalman filtering (EnKF) like in the TOPAZ system. Atmospheric models generally use daily or shorter assimilation cycles whereas the ocean model systems typically use a weekly cycle (due to the relative sparcity of observations and the longer intrincic time scales of the ocean). Due to the difference in time scale in the ocean and atmosphere, it is not common to due a complete coupled initialisation or assimilation in of the system, even in seasonal forecast systems.

To our knowledge, no coupled ocean-atmosphere data assimilation systems are currently available.

15. Status of available satellite data

Table 1: Data to be collected for STARS-DAT, covering the winter seasons from 2005 to 2009.

Dataset	Where to access	Restriction on access/use
SST L2P	GHRSST LTSRF (http://ghrsst.nodc.noaa.gov)	Freely available
SLA from Envisat and GFO, gridded and along-track data	AVISO http://www.aviso.oceanobs.com	Freely available
SLA from ERS-2, Gridded and along-track data	ESA, availability to be confirmed by ESA	met.no is Cat-1 user
Wind vector from QuikScat and ASCAT	OSI SAF	Freely available, met.no is partner in OSI SAF

Wind speed and water vapour from AMSR-E	RSS http://www.remss.com	Freely available
AVHRR VIS/IR images	Locally received data, available in local archive	No restrictions
In situ meteorological data (synop,buoy,ship)	Locally received data through GTS, available in local archive	No restrictions
In situ sub surface data (XBT, ARGO gliders etc)	Coriolis (http://www.coriolis.eu.org); Institute of Marine Research (http://www.imr.no)	Coriolis: Freely available IMR: Available through cooperation agreement
NWP model runs	ECMWF: MARS archive HIRLAM: local archive	ECMWF: met.no is national member, has free access.
Observational data from IPY campaigns	IPY database is hosted by met.no	Freely available

SST L2P : Strength: Common format, several satellites

SLA: Weakness: limited coverage

Wind scatterometer: Strength: Good cooperation with data provider

Strength ASCAT: collocated in time with Metop SST. Weakness ASCAT: no nadir coverage

AVHRR VIS/IR: Strength: In-house availability.

HIRLAM NWP: Strength: Locally produced.

In situ meteorological data: Strength: In-house availability. Weakness: Few observations over ocean areas.

In situ sub-surface data: Strength: Strength: Provide daily temperature analyses for the Nordic Seas. Weakness: mainly based on ARGO boys with relatively few observations for the North Atlantic

Observational data from IPY campaigns: Very good coverage for the particular cases observed. Weakness: Limited number of cases.

16. Existing polar low and air-sea interaction projects

The Greenland Flow Distortion experiment (GFDex)

The Greenland Flow Distortion experiment (GFDex) is an international fieldwork and modelling-based project to investigate the role that Greenland plays in distorting atmospheric flow over and around it: affecting local and remote weather systems and, via air-sea interaction processes, the coupled climate system.
The project team includes scientists from the UK, Canada, Norway, Iceland and the USA. The UK Met

Office and the ECMWF are project partners, working with us to provide sensitive area predictions for the field campaign. GFDex is an IPY approved project, part of the IPY-THORPEX cluster, and is being funded by the Natural Environment Research Council, the Canadian Foundation for Climate and Atmospheric Sciences, EUFAR and EUCOS.

Coupled Boundary Layers/Air-Sea Transfer Defense Research Initiative (CBLAST DRI)

CBLAST focuses on processes that occur in the oceanic and atmospheric wave boundary layers, which are regions influenced by ocean surface waves.

The observational components include *in situ* investigations of ocean-atmospheric turbulence and mean flow from fixed towers and moorings, remote sensing of 2- and 3-D structure of the boundary layers and ocean surface, appropriate surface wave measurements with particular emphasis on small-scale and breaking waves, and Autonomous Underwater Vehicle (AUV) and aircraft-based measurements. The program will work toward quantifying the TKE budget and the momentum, mass, and heat budgets in the oceanic mixed-layer and atmospheric boundary layer. Novel instrumentation development efforts will be included, particularly for very high winds.

The modeling and simulation (e.g., LES and DNS) components are expected to develop improved, physics-based parameterizations of the fluxes (momentum, energy, heat, mass) and/or the coupled nature of the wave boundary layer. We are also interested in physics-based parameterizations of the direct coupling of the surface wave field with particular emphasis on small scale and breaking waves. An important product of this program will be parameterizations useful in larger scale, coupled ocean-air models.

The Norwegian IPY-THORPEX project

The project aims at improved forecasting of adverse weather in the Arctic with particular focus on polar lows. This project is a part of the Norwegian contribution to the International Polar Year 2007-2008. The project is led by the University of Oslo in cooperation with the Norwegian Meteorological Institute and the University of Bergen.

In February and March 2008 the project conducted a field campaign where and research air craft was stationed at Andøya in Northern Norway. During the campaign 15 flight missions were conducted, dropping a total of 147 sondes that successfully reported data back to the aircraft.10 of these missions (106 sondes) were in situations with cold air coming off the ice edge and where infrared satellite images revealed bands of cumulus convection over the ocean. In many cases polar lows were observed in the satellite images but missed by the aircraft.

17. Challenges for improved forecasting of polar lows.

Since the early 1990's surprisingly few papers on actually forecasting polar lows have been published. Most numerical investigations focuses on simulations of polar lows for the purpose of studying processes and understanding the underlying physics. A notable exception however, is the paper by Noer and Ovhed (2003), who gives a detailed description of the challenges met by forecasters during polar low conditions. One main point to take notice of is their experience of numerical models as "notoriously unreliable" when it comes to precise forecasts of polar low tracks and intensity. Obviously, much of this is due to the sparse observational network in the Arctic.

As the authors of this report is involved in the Norwegian IPY-THORPEX project, we know that there are a number of ongoing studies on forecasting capabilities and manuscripts in writing at the moment. Some of these are planed for a possible polar low special issue in 2011. Among these are studies using new physical parametrizations, such as air-sea coupling to ocean waves and improved convection parametrization, the use of high resolution ensemble predictions and the feasibility of using targeted observations.

The main forecasting challenges have been identified to be the limited number of observations available. During the IPY-THORPEX campaign a number of dropsondes were released in upstream areas of polar low formation. These observations were transferred to meteorological centres in real time via the Global Telecommunication System (GTS) and assimilated in to the meteorological models. The forecasts have later been redone without the additional observations provided by the field campaign. One of the findings was that these observations significantly improved the polar low forecasts. Forecasts where these observations are taken out fails completely in predicting both polar low track and intensity. The results suggests that targeted observations may be one way of obtain improved numerical forecasts. One may for instance imagine the air-force assisting the meteorological service by dropping sondes during certain weather event when polar low formation is imminent. Whether such air-force assistance is possible is of course dependent on political will to establish this type of cooperation.

18. Challenges for investigation of polar low impact on ocean circulation

The possible impact of polar low on the ocean circulation was discussed in section 10 above. The only investigation of this that we are aware of is the publication by Condron et al. (2008), who looked at the impact on the Greenland Sea Deep Water formation. We believe that there is a need to investigate this effect also in the areas where the North Atlantic currents looses most of its buoyancy during winter. The Fram Strait, areas south of Svalbard and along the coast of Northern Norway is prone to a large number of polar lows every year and are at the same time areas of great importance for cooling of the ocean current.

The main challenge for this is how to quantify the contribution of the heat loss from cold-air outbreaks in general and polar lows in particular. Especially if this is to be based on observations . Strictly, this requires very accurate information on SST and boundary layer air temperatures during these events. Rapid changes in SST during cold-air outbreaks are hard to obtain since most of the ocean areas affected are cloud covered and not visible for IR satellite instruments. The other option is to use numerical models which has certain shortcomings. The most important of these is probably the fact that we do not know how exactly these do reproduce physical processes in the ocean, in particular processes that involves vertical overturning of water masses. Despite this, we believe that this approach may give valuable information on the relative importance of cold-air outbreaks and polar lows on the thermohaline circulation in the North Atlantic Ocean.

To account for the low predictability of polar lows, certain groups within the IPY THORPEX are working on using Limited Area Ensemble Predictions. The have obtains some promising results indicating that the probability of high wind speed from high resolution ensemble prediction may give a good indication on areas areas where polar lows will hit.

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