An observation-based study of Arctic high-impact weather systems

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Contents

1 Introduction

1.1 Background

Until a couple of decades ago, it was common practice to include a prayer for fair and suitable weather during the weekly Sunday services under the Church of Norway. This prayer reflected the influence weather had on everyday life, which in Norway was strongly connected to farming and fishing. While too warm and dry weather could have a devastating effect on crops, storms were a threat to the large number of people who earned their living as fishermen. A tragic example of this occured on 11 March 1822 outside the western coast of Norway. The day started calmly and fishermen went out in their boats as large amounts of herring were reported at the time. During daytime the weather changed and a storm developed rapidly, leading to the shipwreck of more than 30 boats and the death of approximately 300 fishermen. An even worse catastrophe is known to have occured around year 1650, when severe weather led to the loss of approximately 500 lifes at the Norwegian coast. At this time there was no operational weather forecasting service, and people had to rely on their own experience and certain signs in nature.

Due to the establishment of forecasting centres and advances in the field of meteorology it is now possible to give an early warning on many of the dangerous weather events and prevent fatal accidents. However unforeseen storms may still occur and put human life and property at risk. In the Arctic maritime mesoscale cyclones, also known as polar lows, are still a challenge to forecasters and hence a potential threat to human activity. These cyclones have not been captured by the sparse conventional operational network in the arctic, and until recently most of the knowledge about them could be attributed to data from polar orbiting satellites. As well as representing a problem for operational weather forecasting, the sparse conventional network of observations has also been a limitation for the research on polar lows, and the processes governing their development are not known in detail. However numerical studies have pointed out diabatic effects connected to moist convection, forcing from upper level potential vorticity (PV) anomalies and low level baroclinic instability connected to arctic fronts as important mechanisms for formation and development of these cyclones. Arctic fronts delimit the cold air originating over the Arctic ice shelf from warmer maritime air, and may under cold air outbreaks be present over open sea far south of the ice edge.

While the cyclones refered to as polar lows in principle may develop anywhere over open sea at high latitudes, the area southeast of Greenland is known to have a high occurence of quasi stationary mesoscale cyclones (Blechschmidt et al., 2009). Numerical studies have pointed out orographic forcing due to Greenland as an important mecanism for formation of these cyclones, and they have commonly been refered to as Greenland lee cyclones. As for polar lows, also these cyclones give rise to hazardous weather, and the knowledge about them is mainly based on theoretical and numerical studies due to sparse observations.

In order to gain more insight into arctic weather systems a group of projects connected to the International Polar Year (IPY), known as the IPY-THORPEX project cluster, were launced with the following overall objective: “To improve the accuracy of high-impact weather forecasts in the Arctic region for the benefit of society, the economy and the environment.” These projects were the arctic part of the The Observing System Research and Predictability Experiment (THORPEX) program under the World Meteorological Organization, addressing the improvement of one day to two week forecasts of high impact weather. The Greenland Flow Distortion experiment (GFDex) and The Norwegian IPY-THORPEX which were two of the projects in the IPY-THORPEX cluster, both included major aircraft based field campaigns that aimed at providing unique observations of mesoscale weather systems. The GFDex project (Renfrew et al., 2008) addressed weather systems connected to the presence of Greenland such as barrier winds, tip jets and lee cyclones, and the field campaign took place from 21 February to 10 March 2007. During the 12 missions flown from the Keflavik airport on Iceland, in situ observations were obtained from instrumentations carried on the aircraft and 144 dropsondes were released. Observations were also obtained by the release of additional radiosondes from stations on Greenland as well as “on demand” release of radiosondes from Jan Mayen and vessels in the area.

The Norwegian IPY-THORPEX (Kristjánsson et al., 2011) addressed polar lows and arctic fronts over The Norwegian, Barents and Greenland Seas as well as orographic jets connected to Spitsbergen. The field part of the project was conducted from Andøya in Northern Norway and included 12 flights with a research aircraft and the release of 150 dropsondes during the period 25 February to 17 March 2008. In situ data were obtained by probes on the aircraft, and LIDAR systems carried onboard measured profiles of wind and humidity. Observations were also provided by buoys, coast guard vessels, additional radiosondes from stations in the area as well as unmanned aircrafts. Both campaigns provided an extensive amount of observations of arctic mesoscale weather systems, allowing researchers to reveal the secrets of these weather systems.

1.2 Objectives

The work leading to this thesis has been carried out within the Norwegian IPY-THORPEX project, applying data gathered during the Andøya field campaign and the GFDex field campaign. The objective of this work is strongly connected to the improvement of the forecasts of hazardous weather in the Arctic, which was stated as the overall objective of the entire IPY-THORPEX cluster. The achievement of this requires improvement and optimal use of numerical weather prediction (NWP) models as well as a broader understanding of arctic weather systems and the processes governing their formation and development. The research described in this thesis consequently has the following main objectives:

Increased insight into the structure of mesoscale weather systems in the Arctic, and the processes that govern their development.

Shed light on the role of spatial resolution for model simulations of Arctic mesoscale cyclones.

Arctic weather systems have been investigated in previous studies, but these have mainly been based on simulations with NWP models and theoretical considerations. In the present thesis observations obtained during the two field campaigns are used to investigate features such as jets and frontal zones, and the findings are discussed in the light of previous studies of similar weather systems. As well as increasing our insight into the three dimensional structure of arctic mesoscale weather systems, the observational analyses may also help us to understand the mechanisms in their development.

The observations also provide an opportunity to investigate the validity of conceptual models. The Norwegian cyclone model (Bjerknes and Solberg, 1922) and the Shapiro-Keyser model for cyclone-frontal evolution (Shapiro and Keyser, 1990) are based on research on extratropical synoptic scale systems and are widely used in operational analyses. But how well do these models apply to arctic mesoscale systems ? Another issue that will be addressed is the presence of an arctic tropopause fold connected to the arctic front. Shapiro et al. (1987) proposed a conceptual model of the troposphere including an arctic tropopause fold in addition to the polar and subtropical tropopause folds, and the validity of this model will be discussed in the light of the observations.

Operational NWP models ability to simulate the development of arctic mesoscale systems and predict hazardous weather that may accompany them are essential with respect to forecasting. The fact that mesoscale cyclones such as polar lows still may develop unforseen indicates that the NWP models are not able to simulate these systems sufficiently. The observations allow us to both verify operational model runs and to investigate how changes in a model affect its ability to simulate the observed systems. Intuitively we would expect that increasing a NWP models spatial resolution improves its skill, but while studies such as Lean et al (2008) and Niemala and Fortelius (2005) to a large degree support this notion, they have also showed that it is not obvious. We will here perform NWP simulations at different spatial resolutions and verify the simulations against the observations in order to find whether increased horizontal resolution improves the simulations of arctic mesoscale cyclones. An important aim would here be to find a recommended horizontal grid spacing for operational use.

2 Presentation of the research

The thesis includes the following three papers, and we will in this section give a brief presentation of each paper, including scientific background information, data and methods applied in the research, and how these studies are connected to the main objectives stated in the previous section.

Paper I
An assessment of a Greenland lee cyclone during the Greenland Flow Distortion experiment: An observational approach

Paper II
An observational study of a reversed arctic front during the IPY-THORPEX 2008 campaign

Paper III
The role of horizontal resolution for polar low simulations

The three papers are all results of research that benefited from the unique observations of Arctic mesoscale weather systems obtained during the two field campaigns described previously. In the two first studies the observations are used to investigate features such as frontal zones, jets and distribution of dry and moist air in order to gain insight into the processes governing the development of the systems as well their three dimensional structure. The third study is different from the other two in that it has less focus on the observed structure of the system, but involves a numerical experiment where we investigate the impact of increasing the resolution of an NWP model. Also in this study the observations have an essential role, as they are used to verify the different simulations in order find a recommended resolution for operational use. In summary the paper provides an observational approach to issues regarding the understanding of arctic weather systems as well as their prediction.

2.1 Paper I

The region southeast of Greenland has for a long time been known to have a high cyclonic activity (Pettersen, 1956; Harold et al. 1999) and severe weather. Numerical studies (Kristjánsson et al. 1999; Pettersen et al. 2003; Skeie et al 2006) have shown that the presence of Greenland's orography is essential for the development of cyclones in this area. Petersen et al. (2003) showed how cyclogenesis would occur under westerly wind due to flow splitting as the flow fails to pass over the Greenland Barrier. The present paper is an observational study of a quasi stationary cyclone southeast of Greenland that formed under westerly flow, and is hence referred to as a Greenland lee cyclone. On 3 March 2007 a flight during the GFDex campaign (Renfrew et al., 2008) was dedicated to the assessment of the cyclone, which at that time was at its mature stage, and a large amount of observations was obtained by dropsondes and instrumentation carried on the aircraft.

The formation of the cyclone started on 1 March under westerly flow over the southern part of Greenland, and continued on 2 March in a baroclinic zone that had formed along Greenland's coast. An assessment of radiosonde data from a station at the western coast of Greenland indicated stable air and and favourable conditions for flow splitting and lee cyclogenesis. While this indicates that flow splitting due to Greenland's orography had an important role in the formation of the cyclone, it is reasonable to believe that an upper level potential vorticity (PV) anomaly that swept over Greenland and reached the area of cyclogenesis on 2 March contributed to the deepening of the cyclone. This was confirmed by the use of PV inversion.

The investigation of dropsonde data and in situ measurements revealed a warm cyclone centre encircled by a frontal zone that extended northwards, delimiting the cold air towards the coast of Greenland and warmer air further east. A low level jet parallel to the Greenland coast with wind speeds exceeding 34 ms^{-1} close to the surface was observed in the cold air, which was trapped by an inversion at approximately 750 hPa. This level corresponds to the height of Greenland's orography in this area, and the low level jet observed had the pattern of a barrier wind (Moore and Renfrew, 2005) which occurs when cold and stable air is forced towards a barrier and fails to cross it. This may give rise to a strong flow parallel to the barrier, which in this case is the orography of east Greenland.

As mentioned, PV inversion indicated that an upper level PV anomaly contributed to the development of this lee cyclone, and according to Browning (1997) dry air descending from a downfolding in the tropopause is a manifestation of forcing from an upper level PV anomaly. Assessment of Skew-T diagrams and in situ measurements of ozone revealed a tropopause fold, and a slot of dry air extending deep into the troposphere indicated descending air. The observations hence showed a clear signature of forcing from the upper level PV anomaly, and the PV inversion performed on this anomaly indicated a contribution of 253 m to the deepening of the cyclone at 900 hPa. A numerical study by Kristjánsson et al. (2009) shed more light on Greenland's role on the development of this cyclone. While the Greenland barrier forced cyclogenesis by splitting the westerly flow, it hampered the baroclinic forcing on the cyclone. In addition to this Kristjánsson et al. found that Greenland forced the southwards path of the upper level PV anomaly, and that the cyclone would have developed approximately 500 km further east with Greenland absent.

In Figure 1 we present the Skew-T diagram from a dropsonde that was released over the cold air close to the east coast of Greenland capturing both the barrier wind and the tropopause fold. The figure clearly reveals the previously mentioned the low level barrier wind in the cold air, capped by an inversion at approximately 750 hPa which corresponds to the height of Greenland's orography. The inversion at approximately 430 hPa indicates the presence of downfolding of the tropopause in this area.

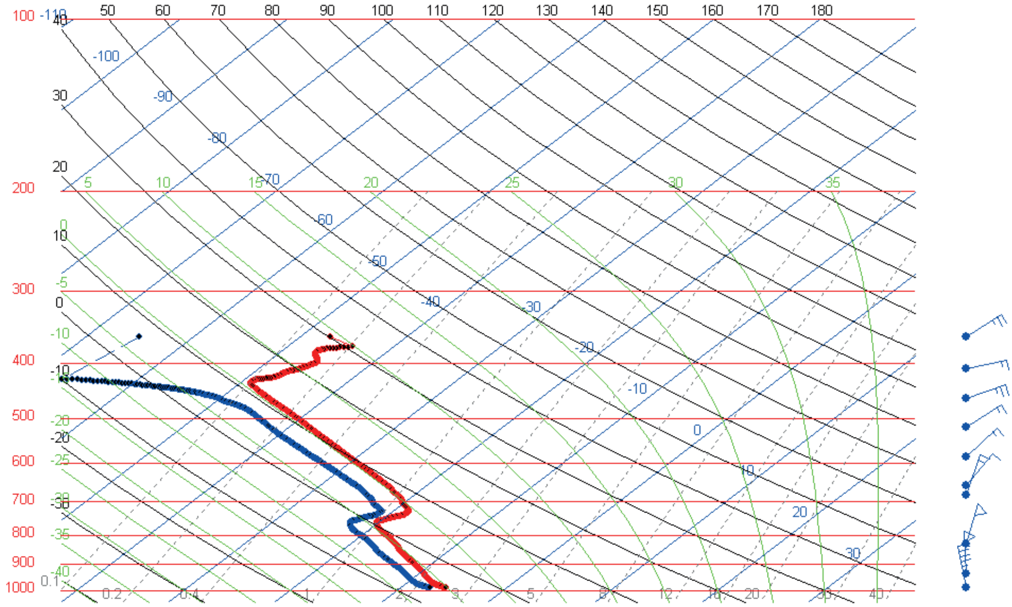

Figure 1: Skew-T diagram for a dropsonde released 3 March 2007 1152 UTC near the east coast of Greenland at 61.8° N, 41 ° W

During the low-level part of the flight the aircraft flew through the core of the cyclone while observations were continuously obtained by probes. In Figure 2 we have shown measurements of temperature, mixing ratio of water vapour and ozone concentrations obtained at 1900 m during this part of the flight. Temperature and water vapour mixing ratio (Figure 2 (a)) clearly show a combination of warm and dry air in the centre of the cyclone which is revealed by a 262 K peak in the temperature, while Figure 2 (b) indicates a maximum in ozone concentrations close to the cyclone centre. This warm and dry air is a strong indication of adiabatic warming due to descent, and the relatively high ozone concentrations could be a sign of stratospheric origin. Also trajectory calculations indicated that this air had experienced descent, which was probably forced by Greenland's orography. While the warm core of the cyclone was consistent with both the conceptual models of Bjerknes and Solberg (1922) and Shapiro and Keyser (1990), the upper level origin suggested here sharply contrasts both Shapiro and Keyser, who argued that the warm air originates in the baroclinic zone, as well as the warm sector origin proposed by Bjerknes and Solberg.

2.2 Paper II

Fronts located north of the polar front are commonly referred to as arctic fronts. These fronts separate cold air originating over the arctic ice cap from warmer maritime air and may under cold air outbreaks move several hundred kilometres equatorwards over open sea (Rasmussen et al., 2003). While the low level baroclinic instability associated with arctic fronts is an important mechanism in the development of polar lows (Van Delden et al., 2003), arctic fronts themselves may give rise to severe low level wind and hence represent a potential risk to maritime activity (Grønås and Skeie, 1999). The present paper is based on observations of an arctic front obtained by dropsondes and Doppler lidar on 28 February 2008 during The Norwegian IPY-THORPEX field campaign.

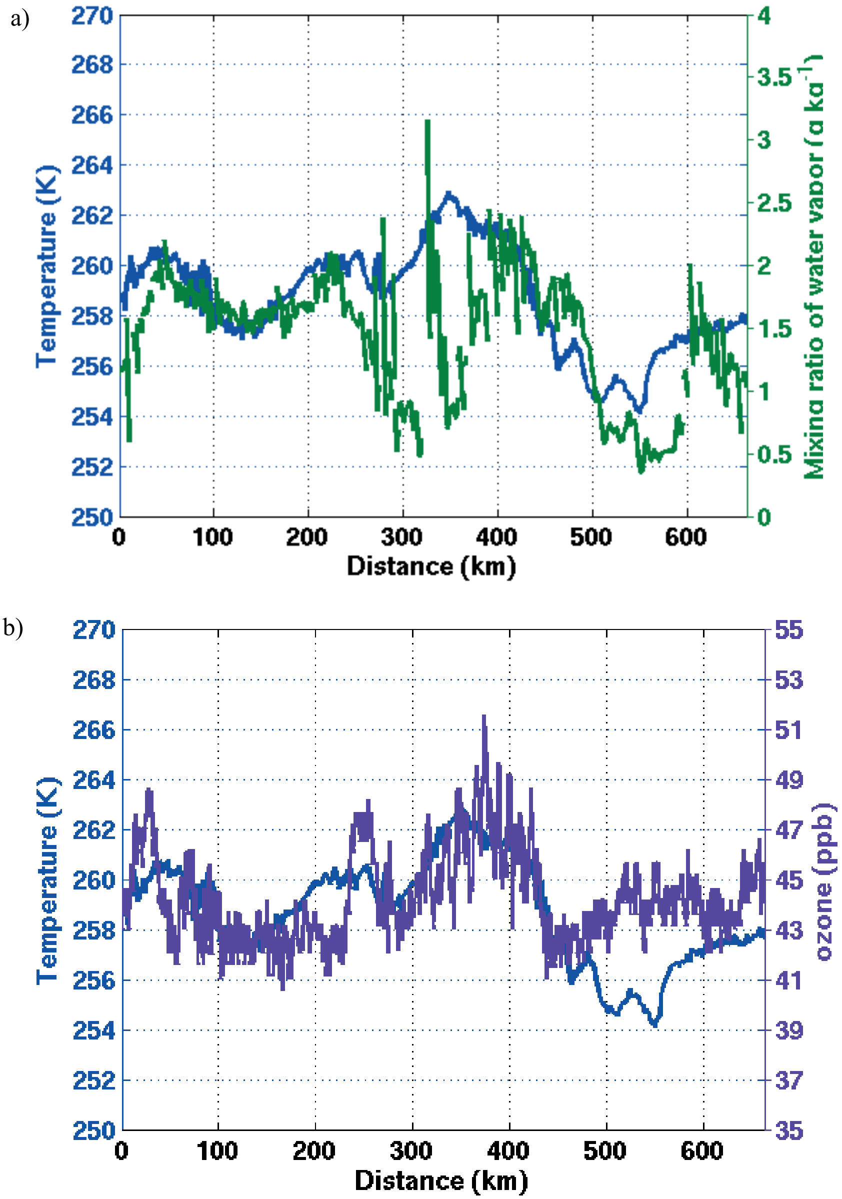

Figure 2: Observations obtained at 1900 m by probes carried on the aircraft. (a) Temperature (blue) and mixing ratio of water vapor (green). (b) Temperature (blue) and ozone concentration (violet).

At 27 February 00 UTC a meridional baroclinic zone over the Norwegian Sea delimited cold air associated with a quasi stationary cold core cyclone east of Greenland from warmer air adjacent to the Norwegian coast. During the following 36 hours simultaneous advection of cold air to the southeast and warmer maritime air to the northwest over the Norwegian and Greenland Seas caused the formation of a reversed front which on the 28 March 12 UTC appeared as a zonal baroclinic zone over the Norwegian and Greenland Seas, separating cold air to the south from relatively warm air to the north. At the same time extensive cyclogenesis took place over the Norwegian Sea, as two shallow warm core cyclones developed in the baroclinic zone and moved towards Greenland. The distance between the cyclones was approximately 700 km, which is consistent with the wavelength of maximum instability when the baroclinic zone is shallow and the low-level lapse rate is near adiabatic (Mansfield, 1974; Blumen, 1979).

The observations were obtained during a flight between 1126 and 1452 UTC on 28 February and were used to verify two operational NWP models as well as to investigate the mesoscale structure of this frontal system. By comparing operational 36 hour simulations from the HIRLAM and ECMWF models with objective analysis as well as dropsonde data we found that both models simulated the reversed frontal zone, but they placed the western part of it too far north. Both models also failed to simulate one of the warm core cyclones, resulting in considerable deviations between observed and simulated wind.

The dropsonde observations revealed a relatively shallow frontal zone delimiting warm maritime air to the north from a pool of cold air trapped below the frontal inversion air to the south. A low level jet north of the frontal zone gave rise to surface winds exceeding 20 ms^{-1} and wind speeds up to 40 ms^{-1} at 800 hPa, while wind speeds around 40 ms^{-1} observed over the cold air between 470 and 300 hPa were connected to an upper level jet. While the presence of the jets was revealed by the dropsondes, the high spatial resolution of the Doppler lidar turned out to be essential to capture the highest wind speeds associated with the upper level jet. The wind speed measured by the lidar during the flight is presented in Figure 3, which shows how the lidar data revealed the detailed structure of the upper level wind pattern. Although the range of the lidar was limited by the presence of clouds, it provided valuable upper level data, and we may conclude that the combination of lidar and dropsondes is beneficial for field campaigns.

The drosponde observations also revealed a slot of extremely dry air extending down to 700 – 800 hPa over the cold air south of the front, partly undercutting the moist air associated with the frontal cloud band. An assessment of the PV analysis from a NWP model indicated a downfolding in the tropopause south of the front. It is hence reasonable to interpret the dry slot as a sign of air descending from the tropopause fold, and the study provides observational support for the inclusion of an arctic tropopause fold in the conceptual model for the tropopause proposed by Shapiro et al. (1987).

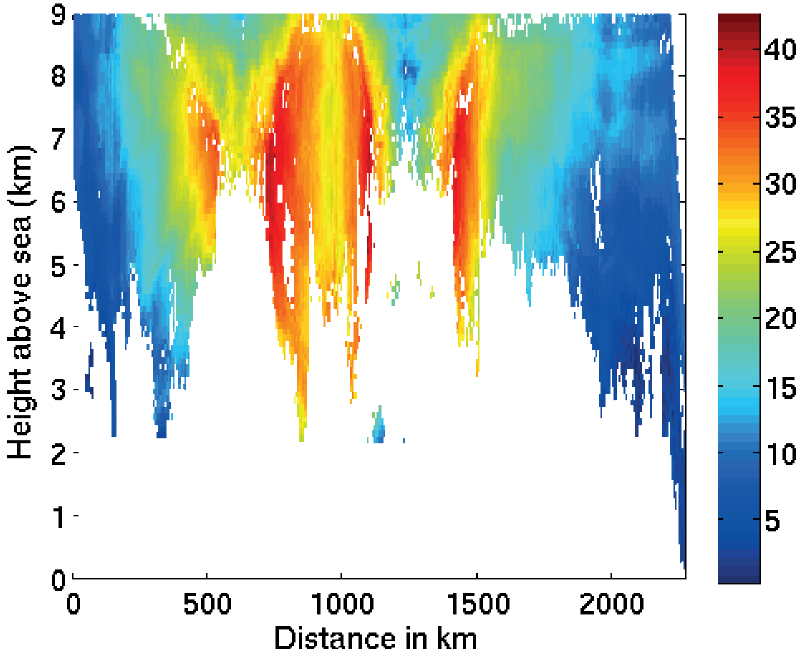

Figure 3: Wind speed (ms^{-1}) obtained by lidar on 28 February 2008 over the Norwegian and Greenland Seas.

2.3 Paper III

On 3 and 4 March 2008, during The Norwegian IPY-THORPEX field campaign, the full life cycle of a polar low over the Norwegian Sea was captured by the release of 55 dropsondes during three different flights (Kristjánsson et al., 2011). Two of the flights were carried out during the preconditioning and early development of the polar low on 3 March and the third flight captured the polar low at its mature stage, providing what probably is the most extensive amount of observations of a particular polar low. In the present study these observations were used to address the following question: Will increased spatial resolution of a NWP model give more accurate simulations of polar lows ?

In order to answer this question numerical simulations of the current polar low were performed by the Unified Model (UM) from the UK Met Office. Simulations initialized at 2 March 00 UTC were run at 12, 4 and 1 km horizontal grid spacing and both the sea level pressure (SLP) field and the 925 hPa wind were verified against dropsonde observations obtained during the two flights on 3 March. When decreasing the horizontal grid spacing from 12 to 4 km we found that the model simulated a SLP distribution and 925 hPa wind field that were closer to the observations. While a further improvement in the simulations was experienced when decreasing the grid spacing to 1 km, this was less pronounced, which could be due to the fact that the 1 km simulation was run on a smaller domain than the 12 and 4 km simulations.

A simulation of the current polar low with latent heating reduced by 90 % indicated that diabatic heating due to convection was an important mechanism in its development and a comparison between pseudo satellite images from the simulations at 12 and 4 km grid spacing and a conventional satellite image indicated that the model simulated a more realistic distribution of convective clouds at 4 km grid spacing. When running the model at 12 km horizontal grid spacing, we applied the UM's mass flux convection scheme (Gregory and Rowntree, 1990), while a modified version of the convection scheme allowing the model to handle large convective clouds explicitly (Roberts, 2003) was applied at 4 km grid spacing. For the 1 km simulations the convection scheme was turned off, as such a high resolution was considered to sufficiently resolve most of the convective clouds. In a study by Lean et al. (2008) addressing convective weather over England, simulations were carried out by the UM at 12, 4 and 1 km grid spacing, applying a similar representation of convection as in the present study. Lean et al found that 4 and 1 km horizontal grid spacing gave a more realistic handling of convection than 12 km grid spacing.

Figure 4 shows the 1 hour accumulated precipitation from simulations at 12, 4 and 1 km horizontal grid spacing valid at 3 March 18 UTC, and a comparison between the precipitation fields shows that while the 12 km simulation gave a widespread band of precipitation, the 4 and 1 km simulations gave a distribution with steep gradients and relatively high maximum values. These changes in the cloud distribution and precipitation field indicate that altering the spatial resolution strongly affected the distribution of diabatic heating and that the improved simulation at higher resolution was due to an improved treatment of convection.

In order to investigate the model's sensitivity to small changes in the initial conditions, additional simulations were started at 2 March 01 UTC and 02 UTC. While altering the start time by one or two hours turned out to have a relatively small impact on the simulations, starting the model 24 hours later at 3 March 00 UTC, dramatically reduced the performance of the 4 km simulation. A reasonable explanation for this is that the high resolution model needs sufficient time to create its own dynamics, and one should hence initialize the model at an early stage in order to benefit from the increased resolution.

Numerical experiments were also carried out on a polar low that occurred from 16 to 17 March, but in this case both the 12 and the 4 km simulations completely failed to produce the polar low. One possible explanation for this is the use of a very short forecast at the boundary for 3 – 4 March simulations compared to the 48 hour forecast used for the 16 -17 March case, and another is the complexity of the latter case with several developing vortices. In summary the study has shown that increasing the resolution of NWP models has the potential to improve forecasts of polar lows although this is case dependent.

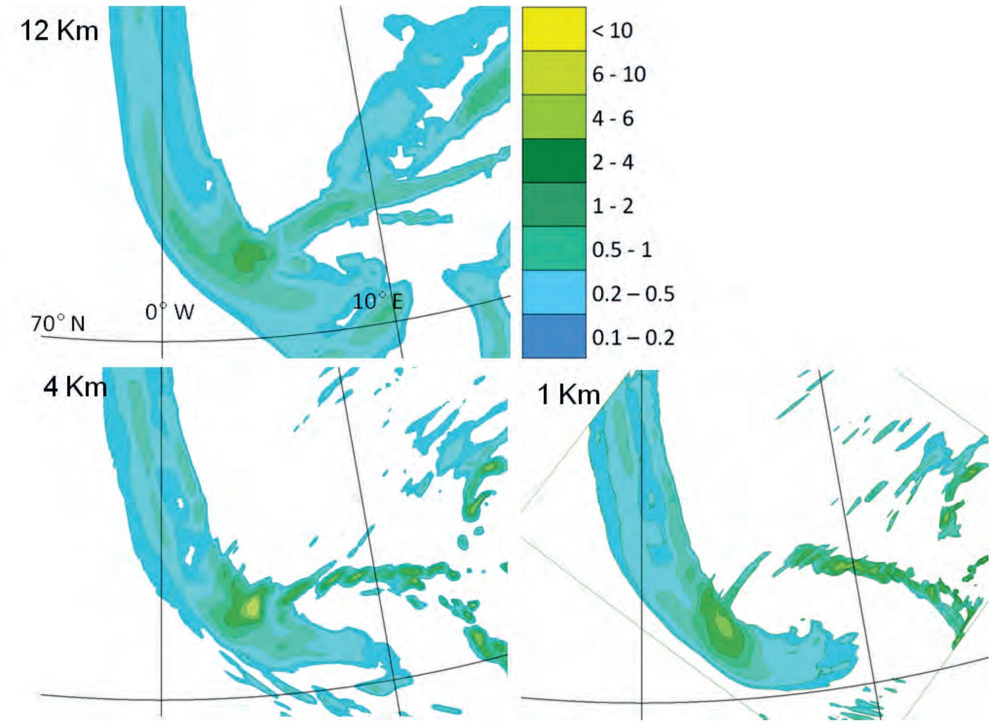

Figure 4: 1 hour accumulated precipitation (mm) valid at 3 March 2008 1800 UTC from simulations at 12, 4 and 1 km horizontal grid spacing.

3 Summarizing discussion and conclusions

The three papers in the present thesis addressed four different weather systems that occurred during the two IPY-Thorpex field campaigns. The SLP and equivalent potential temperature (θ_E) at 925 hPa from a 6 hour simulation of HIRLAM valid at 3 March 2007 12 UTC (Figure 5 (a)) shows the Greenland lee cyclone at its most intensive stage, while the reversed arctic front over the Norwegian and Greenland Seas that was investigated in Paper II is shown in the SLP and 925 hPa θ_E analysis from 28 March 2008 06 UTC in Figure 5 (b). The two polar lows investigated in Paper III are also presented in Figure 5 where Figure 5 (c) shows the 3-4 March polar low in the SLP and 925 θ_E analysis from 4 March 06 UTC and Figure 5 (d) shows the 16-17 March polar low in a similar analysis valid at 16 March 18 UTC. Hereafter we will refer to the Greenland lee cyclone case of 3 March 2007 as Greenland Low, the reversed arctic front of 28 February 2008 as Reversed Front, the polar low case of 3-4 March 2008 as Polar Low 1 and the polar low case of 16-17 March 2008 as Polar Low 2. The latter case will be left out of most of the discussion as it was not investigated in depth in Paper III.

At first glance the weather systems shown in Figure 5 appear to have little in common. The Greenland

Low was quasi stationary and under strong orographic influence while both Polar Low 1 and Polar Low 2 developed over the Norwegian Sea far away from the nearest orographic barrier. The Reversed Front case was different from all the other cases as the main feature here was the frontal zone extending from Greenland to the Norwegian coast. However the observations revealed that these weather systems also had several similarities. Similarly to the Reversed Front case, the observations from the Greenland Low case revealed a pronounced frontal zone. Both of these systems had a strong low-level jet with surface winds of 34 ms^{-1} in the Greenland Low case and surface winds exceeding 20 ms^{-1} in the Reversed Front case.

An observational study of the Polar Low 1 case (Føre et al., 2011) revealed that also this system was associated with a shallow arctic front and strong low-level wind. In Figure 6 the Skew-T diagrams from two different dropsondes released on 4 March 2008 during the flight targeting Polar Low 1 are shown. The presence of 25 ms^{-1} low level winds is revealed in Figure 6 (a), which also indicates an upper level jet above 350 hPa. The diagram in Figure 6 (b) is from a sonde released over the centre of Polar Low 1, and shows extremely dry air extending deep into the troposphere. For the Greenland Low case we argued that similar observations of dry air in the troposphere could be explained by stratopheric air descending into the troposphere from a downfolding in the tropopause, and that this was a sign of contribution from an upper level PV anomaly to the deepening of the cyclone. Likewise Føre et al. (2011) described the dry slot observed in the Polar Low 1 case as an indication of forcing from an upper level PV anomaly, and by applying PV inversion they found that this forcing contributed considerably to the deepening of the polar low. A similar dry slot was revealed by the dropsondes in the Reversed Front case, indicating descending air connected to a tropopause fold also here. It is hence reasonable to believe that the two intense warm core lows connected to the reversed arctic front were influenced by upper level forcing, but this has not been quantified through PV inversion.

The mechanism of upper level forcing on the development of extratropical cyclones is described by e.g. Holton (2004) and is an interaction between an upper level PV-anomaly and the low level baroclinic zone. The upper level PV anomaly induces a circulation which sharpens the low level temperature gradient and hence increases the baroclinicity. Nordeng and Rasmussen (1992) found triggering by an upper level PV anomaly to be essential in a case study of a polar low, and they doubted that there were any documented examples of polar low development without upper level forcing. Grønås and Kvamstø (1995) performed numerical simulations of four different cases with synoptic conditions favouring the development of polar lows and argued for the importance of upper level PV anomalies for their development.

While the role of upper level forcing in the development of extratropical disturbances has been described in both theoretical and numerical studies, we have in the present thesis provided extensive observational evidence for this mechanism. As described by Browning (1997), dry air descending from a downfolding in the tropopause can be considered as a manifestation of upper level forcing. Both the observations from the Reversed Front and the Greenland Low case revealed a slot of extremely dry air extending through most of the troposphere, the dryness of the air indicating stratospheric origin. The ozone observations obtained from a probe on the aircraft during the Greenland Low flight provided further evidence of upper level forcing as they revealed the tropopause fold from where stratospheric air descended into the troposphere.

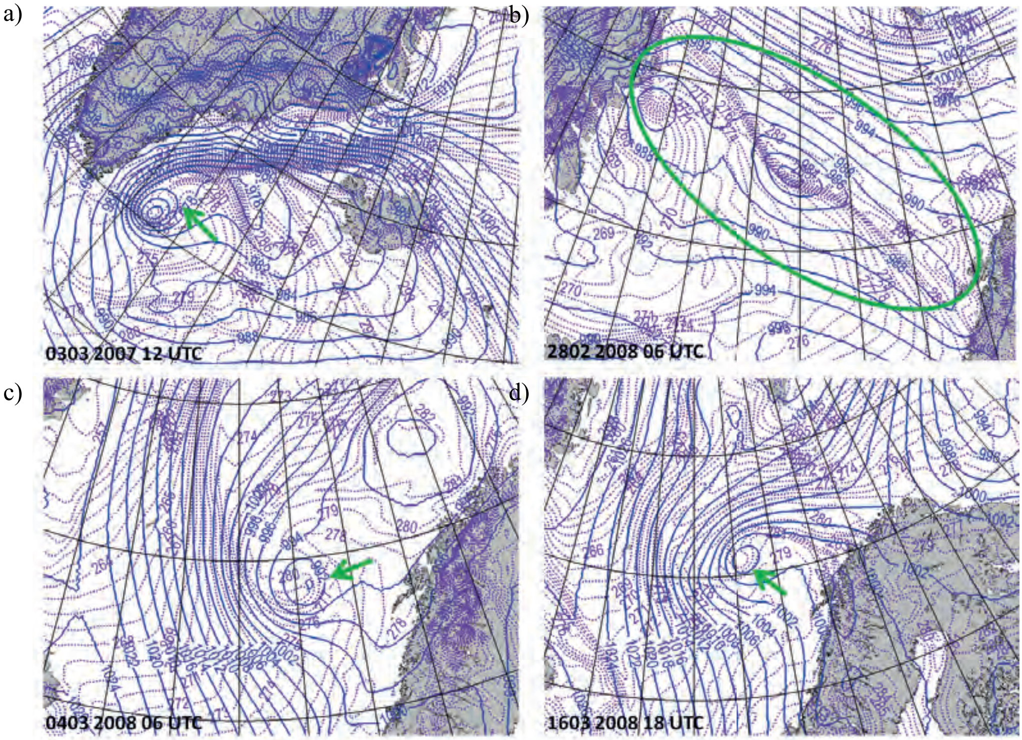

Figure 5: HIRLAM analysis of Sea level pressure (solid blue) and equivalent potential temperature at 925 hPa (dotted violet). (a) 3 March 2008 Greenland lee cyclone. (b) 28 February 2008 reversed arctic front. (c) 3-4 March 2008 polar low. (d) 16 -17 March polar low.

Shapiro et al. (1987) proposed a threefold conceptual model of the troposphere including an arctic tropopause fold associated with an arctic jet stream in addition to the polar and subtropical jet streams and tropopause folds. While the dry slot and the upper level jet found in the Reversed Front case clearly supports the the conceptual model of Shapiro et al., the frontal zone in the Greenland Low case appeared to be deeper and it was not so clear that this was an arctic front. However a jet stream analysis provided by California Regional Weather Server indicated that the upper level jet in this case was an arctic jet stream, and we may conclude that also in this case the observations support the threefold tropopause structure proposed by Shapiro et al. (1987).

The study of the Greenland Low case shows that conceptual models should be used with care as the observed structure of the cyclone and the front failed to match both the Shapiro and Keyser (1990) model for cyclone frontal evolution and the Norwegian cyclone model (Bjerknes and Solberg, 1922). This could be due to the fact that the Greenland Low development was under strong orographic influence of Greenland, but one should also keep in mind that the conceptual models were based on studies of synoptic scale cyclones that developed on the polar front. While only the Greenland Low case was discussed in the light of the Norwegian cyclone model and the Shapiro-Keyser model, we suggest that it would also be difficult to match the other cases into these conceptual models, given their small spatial scales and connection to arctic fronts.

The observations clearly documented the potential threat to human activity connected to the different weather systems in that they all gave rise to surface winds exceeding 20 ms^{-1}. Worst of them was the Greenland Cyclone case, where the low level flow was forced by the Greenland orography, and surface wind speeds up to 34 ms^{-1} were observed. In addition to this, in situ observations revealed a combination of cold air and high liquid water content. This is a favourable condition for icing, which was indeed experienced during the flight.

The severe weather conditions documented by the observations clearly underline the need for accurate forecasts and hence highly skilled simulations of arctic weather systems. The verification of data from the NWP models against observations performed for the Reversed Front case shows that there is room for improvement. A possible way to do this would be increasing the spatial resolution when running NWP models, and numerical experiments with increased resolution were performed on the Polar Low 1 and Polar Low 2 cases. These experiments were inspired by simulations of convective weather over England performed at different horizontal resolutions by Lean et al. (2008) who found that increased spatial resolution improved the simulations as it allowed explicit handling of convection. The clear improvement of the simulations of Polar Low 1 found when increasing the horizontal resolution was encouraging, and shows the potential for improved forecasts of high impact weather in the arctic.

The research that led to the present thesis has provided new insight into the mesoscale structure of arctic weather systems. While previous studies of such systems have mainly been based on numerical simulations, the observations obtained during the two field campaigns allowed us to perform research based on observations. Although the cases presented in this thesis were of different nature, we have seen that they also have common features. We will end this section by stating the conclusions of our research on mesoscale weather systems in the arctic:

Severe surface winds associated with low-level jets seem to be a common feature in arctic mesoscale systems. Particularly strong low-level winds accompany Greenland lee cyclones when the flow is forced towards the east coast of Greenland, giving rise to barrier winds.

Care should be taken when arctic mesoscale systems are analysed in the light of traditional conceptual models such as The Norwegian Cylone Model and The Shapiro-Keyser Model. While some of the observed features match the models, concepts such as warm sector, occlusion and bent-back warm front may not apply to cyclonic developments connected to arctic fronts. Subjective analyses with respect to these conceptual models may hence turn out to be misleading as they fail to reflect "real life".

The observations of upper level jets and downfoldings in the tropopause support the threefold structure of the tropopause argued by Shapiro et al. (1987). These observations also provide evidence of the essential role of upper level forcing in the development of arctic mesoscale cyclones.

Increasing the resolution of NWP models has the potential to improve the forecasts of arctic mesoscale cyclones. We will hence advocate the introduction of operational NWP simulations at 4 km horizontal grid spacing on a domain covering the Norwegian, Greenland and Barents Seas.

a)

b)

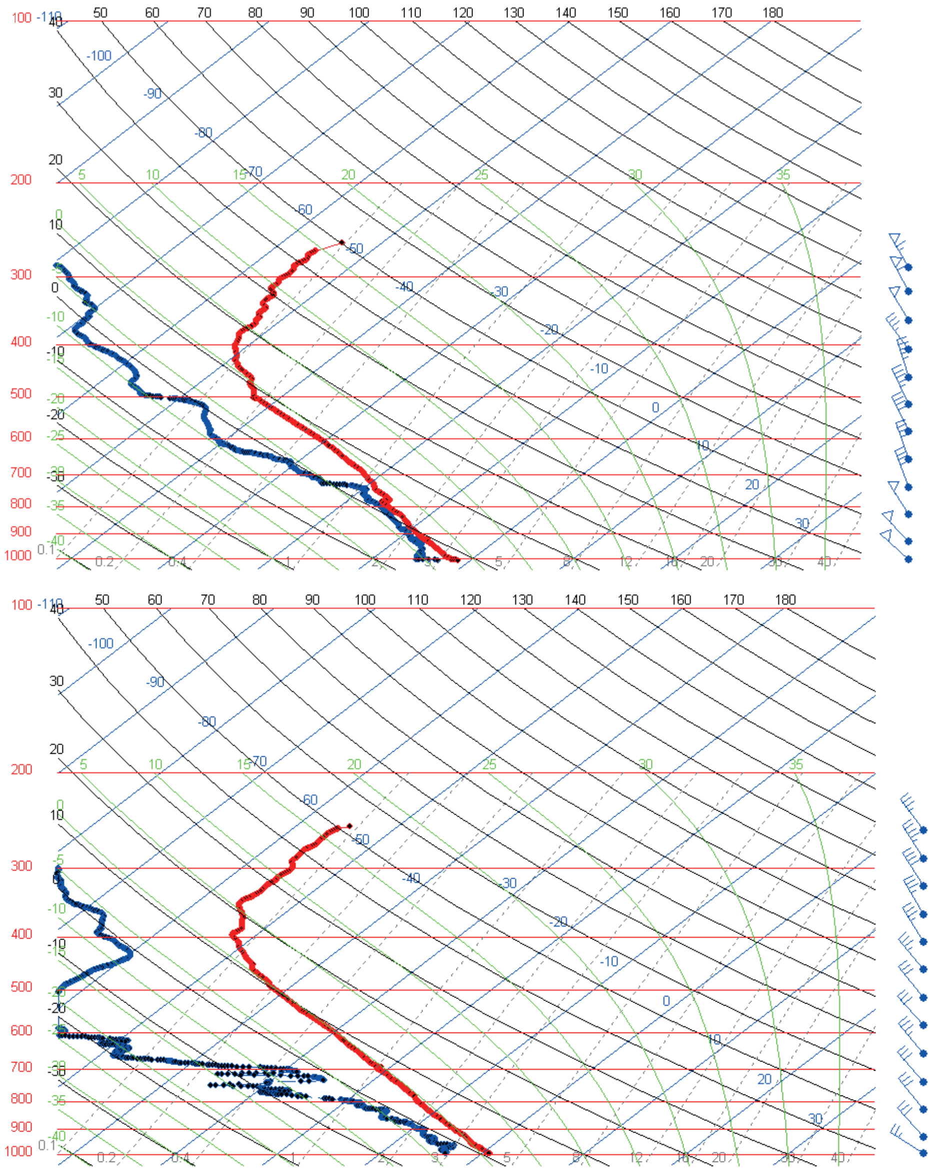

Figure 6: Skew-T diagrams from dropsondes released on 4 March 2008 . (a) Dropped at 1112 UTC at 66° N, 2.8 ° E southwest of the polar low centre . (b) Dropped at 1059 UTC at 66.9° N, 5.7 ° E over polar low centre.

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