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

Harold Mc Innes, a* Jón Egill Kristjánsson, a Harald Schyberg b and Bjørn Røsting b

a University of Oslo, Norway
b The Norwegian Meteorological Institute, Oslo, Norway

ABSTRACT: On 3 March 2007 between 0920 and 1545 UTC, the mesoscale structure of a mature lee cyclone southeast of Greenland was successfully captured during a flight with a research aircraft during the Greenland Flow Distortion experiment (GFDex). The cyclone was accompanied by hazardous weather conditions such as extensive icing and low-level wind speeds exceeding 34 m s⁻¹. Calculations based on atmospheric soundings from Egedesminde on the west coast of Greenland indicate that conditions were favourable for flow splitting and hence cyclogenesis in the lee of Greenland during the formation of the cyclone. PV inversion carried out on an upper-level southward-moving potential vorticity (PV) anomaly indicates that upper-level forcing as well as orographic forcing had an important role in the cyclone development. The frontal seclusion of the cyclone’s warm core was consistent with both the Norwegian cyclone model and Shapiro and Keyser’s model. However, it was not possible to match this cyclone precisely with any of these models, which is probably a consequence of the strong influence from Greenland on the cyclone development. In situ measurements showing a combination of warm dry air with relatively high ozone concentrations in the centre of the cyclone together with trajectory calculations indicate that this air had experienced considerable descent, probably induced by Greenland’s orography. The observations documented the cyclone’s mesoscale structure, and clearly revealed a deep tropopause fold. This tropopause fold is a manifestation of the forcing on the cyclone from the upper-level PV anomaly. Copyright © 2009 Royal Meteorological Society

KEY WORDS GFDex; tropopause fold; PV inversion

Received 23 January 2009; Revised 28 June 2009; Accepted 14 September 2009

1. Introduction

Over the last ten years there has been an increasing interest in Greenland’s impact on the atmospheric flow. This interest is a consequence of the hazardous weather often experienced in the vicinity of Greenland, as well as a desire to understand Greenland’s influence on the synoptic-scale development and predictability over the North Atlantic Ocean and Europe. In several numerical studies particular attention has been drawn to the area off southeast Greenland: Kristjánsson and Mc Innes (1999) carried out a study on Greenland’s orographic effect on developing extratropical cyclones. Case-studies with a numerical weather prediction (NWP) model in which Greenland’s orography was removed showed that the orographic effects were essential for the development of a characteristic secondary cyclone on the lee side of Greenland. Petersen et al. (2003) used an NWP model to study idealized flow over Greenland. They also carried out numerical experiments on real flow, removing Greenland’s orography. Simulations of idealized flow as well as real flow clearly demonstrated the role of orographic forcing on cyclogenesis southeast of Greenland.

The present study is mainly based on data obtained during the Greenland Flow Distortion experiment (GFDex). GFDex was the first observationally based study that had its main focus on meteorological features that are connected to the presence of Greenland (Renfrew et al., 2008). A main objective of GFDex was to provide observational data of meteorological features connected to Greenland in order to improve the understanding and ability to model these systems. The field phase of GFDex took place in February and March 2007 with a well-equipped research aircraft as the main observational platform. During the field study, twelve missions were flown from the base at Keflavik airport in southwest Iceland. A total of 144 dropsondes were released, and in situ observations were obtained from the aircraft. Supplementary observations were obtained by frequent radiosonde releases from Greenland, Iceland, Jan Mayen and from vessels in the area.

Between 1 and 3 March 2007 a deep cyclone formed east of southern Greenland, having the most rapid development between 2 and 3 March. The cyclogenesis took place in a baroclinic zone along the coast of Greenland, the position being fairly well predicted by the
NWP model HIRLAM (High Resolution Limited-Area Model: Undén et al., 2002). The synoptic situation was favourable for lee cyclogenesis, with westerly winds over Greenland at 500 hPa during the formation of the cyclone. At the same time, NWP models showed an outbreak of Arctic high-potential vorticity (PV) air that swept over Greenland from the north, reaching the area of cyclogenesis by 2 March. On 3 March a flight was dedicated to the assessment of the cyclone, which at that time was in the mature stage. In order to capture the mesoscale structure of the cyclone, in situ measurements were obtained from the aircraft at different levels, and 16 dropsondes were released. In the present study we will apply these data in a detailed analysis of the mesoscale structure of the cyclone. Trajectory calculations and PV inversion are used to investigate the results from the analysis in depth.

Shapiro and Keyser (1990) proposed a conceptual model of cyclone–frontal evolution based on numerical simulations and observational data from two field studies addressing marine cyclones: the Alaskan Storm Program (ASP) and the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICa). They proposed that the frontal structure could be divided into the following four phases during the life cycle of an extratropical cyclone: (1) incipient frontal cyclone, (2) frontal fracture, (3) bent-back warm front and frontal T-bone, (4) warm-core frontal seclusion. While the Norwegian cyclone model (Bjerknes and Solberg, 1922) has a frontal seclusion, the frontal fracture and frontal T-bone in the Shapiro–Keyser model strongly diverge from the Norwegian model. Shapiro et al. (1999) presented a summary of studies of the connection between the environmental barotropic shear and the life cycle of cyclones. These studies indicated that cyclones evolving without barotropic shear would have a life cycle consistent with the Shapiro–Keyser model, while cyclones evolving in cyclonic barotropic shear would develop as described by the Norwegian model. These life cycles were termed Life Cycle 1 (LC1) and Life Cycle 2 (LC2) respectively. It was hypothesized that while LC1 cyclones would develop beneath the vertically aligned polar and subtropical jet streams, LC2 cyclones would develop beneath the region of cyclonic shear north of the jet stream. The structure of the current cyclone will be discussed in the light of the studies of Shapiro and Keyser (1990), Bjerknes and Solberg (1922) and Shapiro et al., (1999), in order to investigate to what extent these conceptual models are consistent with our observations.

This study will also address the formation and deepening phases of the cyclone during 1–3 March. In addition to observational data obtained from flights and atmospheric soundings, data from NWP models will be assessed. In a study of the same cyclone (Kristjánsson et al., 2009), simulations were carried out with altered orography over Greenland, in addition to control simulations with standard orography. The purpose of these simulations was to investigate the role of orographic forcing on the cyclone. In the present study the impact of Greenland’s orography on the development of the cyclone will be discussed with respect to the work of Kristjánsson et al.. Their findings will, together with the observational analysis, PV inversion and trajectory calculations of this study, also shed light on how the outbreak of Arctic high-PV air influenced the cyclone.

2. Data and analysis

Data from dropsondes and in situ observations obtained on 3 March 2007 during the Greenland Flow Distortion experiment (GFDex) field campaign (Renfrew et al., 2008) are the main foundation of this study. The observational platform was the Facility for Airborne Atmospheric Measurement’s BAE 146 aircraft, from which dropsondes were released and meteorological parameters measured. The dropsondes were deployed from an AVAPS (Airborne Vertical Atmospheric Profiler System) which is installed on the aircraft. The dropsondes measured position, altitude, temperature, pressure, and relative humidity (RH) at 2 Hz frequency in addition to wind speed and direction. The dropsonde data were quality-controlled using the ASPEN dropsonde software (Martin, 2007). The quality control included outlier checks, filtering of suspect data points, pressure smoothing, temperature dynamic adjustment and wind dynamic adjustment. A more detailed description of the quality control can be found in Renfrew et al. (2009) and ASPEN User Manual (Martin, 2007).

The accuracy of the soundings was 0.4 hPa, 0.1 K, 2% and 0.5 m s⁻¹ for pressure, temperature, RH and wind speed, respectively.

In the current study, in situ observations of pressure altitude, temperature, dew-point temperature, ozone concentration and liquid water content were used. Pressure altitude was obtained from a reduced vertical separation minimum (RVSM) system with an estimated accuracy in static pressure of 0.5 hPa (Petersen and Renfrew, 2009). Temperatures were measured by de-iced Rosemont temperature sensors with an uncertainty of 0.3 K. A General Eastern hygrometer measured dew-point temperature with an uncertainty of 0.25 K above 273.15 K, increasing to approximately 1 K at 210 K. In the present study the water vapour mixing ratio was calculated from temperature, dew-point temperature and pressure. Liquid water content was measured by a Johnson–Williams probe which applies a heated wire resistance bridge. The measurement uncertainty is typically 10%. Measurements of ozone concentrations were obtained by a TECO 49 UV (ultraviolet) photometric instrument. A summary of the aircraft instrumentation is presented in Renfrew et al. (2008).

Matlab scripts provided by the GF Dex project team were used to process both in situ and dropsonde data from the aircraft. Cross-sections were made by interpolating data from the dropsondes onto a grid with 1 km horizontal and 1 hPa vertical resolution. Cross-sections of hydrostatic potential vorticity were calculated from gridded dropsonde data of temperature and wind vector with 10 km horizontal and 10 hPa vertical resolutions. Hydrostatic PV is defined in the American Meteorological Society glossary of meteorology.
(http://amsglossary.allenpress.com/glossary) by the equation:

\[
P = \alpha \left\{ -\frac{\partial v}{\partial z} \frac{\partial \theta}{a \cos \varphi \partial \lambda} + \frac{\partial u}{\partial z} \frac{\partial \theta}{a \partial \varphi} + \left( 2\Omega \sin \varphi + \frac{\partial v}{a \cos \varphi \partial \lambda} - \frac{\partial (u \cos \varphi)}{a \cos \varphi \partial \varphi} \right) \frac{\partial \theta}{\partial z} \right\} \quad (1)
\]

Here \( \alpha \) is the specific volume, \( v \) is the longitudinal component of the wind, \( u \) the zonal component of the wind, \( z \) the altitude, \( \theta \) the potential temperature, \( \varphi \) the latitude, \( \lambda \) the longitude, \( \Omega \) the angular velocity of the Earth \( (7.292 \times 10^{-5} \text{ rad s}^{-1}) \) and \( a \) the radius of the Earth \( (6.37 \times 10^8 \text{ m}) \).

In addition to the observations, data from NWP models and synoptic-scale analyses were used in this study. The Norwegian Meteorological Institute provided data from runs of the operational model HIRLAM (Undén et al., 2002), as well as synoptic-scale analyses. The HIRLAM forecasts benefited from data obtained during the campaign, since these data were sent to the Global Telecommunication System (GTS). Both fields from the model runs and analyses were prepared in the meteorological visualisation and production system DIANA (http://diana.met.no) at the Norwegian Meteorological Institute. PV calculations from the MM5 mesoscale model (Grell et al., 1995) provided by Storm Weather Center were also used in this study. The horizontal grid spacing in these model runs was 20 km and 12 km for HIRLAM and MM5 respectively.

### 3. Formation and development of the cyclone

We start by looking at the synoptic situation in the period 1–3 March 2007. Figure 1(a) shows the subjective sea-level analysis from the Norwegian Meteorological Institute at 1200 UTC 1 March 2007, while Figure 1(b) shows the height of the 500 hPa surface and the 500–1000 hPa thickness from the HIRLAM model. The HIRLAM fields are from a 6-hour model run and are valid at 1200 UTC 1 March. The surface analysis shows an occluded front in the Atlantic Ocean associated with an equivalent barotropic low. The gradual reduction in the tilt of the developing low over the following 24 hours indicates that this is a new developing baroclinic low.

Figure 3(a) shows the sea-level analysis from the Norwegian Meteorological Institute at 1200 UTC 3 March 2007. The cyclone that formed 24 hours earlier has deepened and is now located to the east of the southern tip of Greenland at 61°N and 37°W, with a minimum pressure of 974 hPa. The height of the 500 hPa surface (Figure 3(b)) indicates that the tilt of the cyclone has disappeared. The front connected to the cyclone is shown as an occlusion which extends southeasterwards to the North Sea. The analysis indicates strong pressure gradients between the cyclone centre and Greenland. The 500–1000 hPa thickness (Figure 3(b)) shows a sector of warm air which is connected to the centre of the cyclone, covering Iceland and extending towards the southern part of the North Sea, while a tongue of cold air is clearly visible over Greenland.

During the development of this cyclone, cold Arctic air was advected southwards over Greenland after entering Greenland from the north. The formation of the surface low took place at the northwestern edge of the old equivalent barotropic low. The gradual reduction in the tilt of the developing low over the following 24 hours indicates that this is a new developing baroclinic low.
northwest Greenland on 27 February (Kristjánsson et al., 2009). Figure 4 shows calculations of PV at the 290 K isentropic level, as well as sea-level pressure, from the MM5 mesoscale model. Results are shown at 24-hour intervals at 1200 UTC on 28 February and 1, 2 and 3 March, revealing that the outbreak of cold air was associated with a southwards-propagating upper-level PV anomaly. Figure 4(a) also shows the location of Ammassalik, from where radiosondes were released every 6 hours. The outbreak of high-PV air from the north moves southwards over Greenland and reaches the area of cyclogenesis on 2 March (Figure 4(c)). The sounding from 28 February shows, apart from a pool of cold air at the surface, warm air in most of the troposphere due to a decaying warm high-pressure centre. The tropopause was at that time located at approximately 250 hPa. By 1 March the air had cooled by approximately 8 K at 800 hPa and the tropopause had descended towards 300 hPa. The sounding from 2 March showed a tropopause as low as 450 hPa (Figure 5(c)), indicating that Ammassalik was in high-PV cold Arctic air, as predicted by MM5 (Figure 4(c)). By 3 March the tropopause had risen again to approximately 325 hPa, due to advection of low-PV warm air from the southeast into the area.

In order to understand the formation and deepening of the cyclone, three different features of the synoptic situation prior to 3 March must be considered: the westerly wind at 500 hPa over Greenland (Figure 1(b)), the strong baroclinic zone along the east coast (Figure 2(b)) and the outbreak of air with high potential vorticity from the north (Figure 4). The westerly flow over the southern part of Greenland is a favourable condition for cyclogenesis over the southeastern coast (Petersen et al., 2003). This can be explained by splitting of the flow as it fails to pass over the barrier due to large values of the non-dimensional height $\epsilon = Nh/U$ (Smith, 1989), $N$ being the Brunt–Väisälä frequency, $h$ the mountain height and $U$ the upstream wind speed. The calculation of $\epsilon$ requires considerable simplification of the atmospheric structure by employing a constant $U$ and $N$. Reinecke and Durran (2008) considered two different methods of estimating $N$, the bulk method and the average method. Based on numerical experiments for constant $U$ and different profiles of static stability they found that while the average...
method gave the best prediction of windward flow deceleration, the bulk method gave the most realistic prediction of flow splitting. In order to find whether flow splitting was to be expected in the current situation, we used soundings from Egedesminde on the western coast of Greenland (68.7°N, 52.9°W) to calculate $\varepsilon$ at 1200 UTC 1 March and 0000 UTC 2 March. On the basis of the conclusions of Reinecke and Durran (2008), the bulk method was applied to calculate the Brunt–Väisälä frequency. The mountain height was assumed to be approximately 3000 m and as upstream wind speed we applied the average of the measured wind speeds between ground level and mountain height. We then obtained Brunt–Väisälä frequencies of 0.0116 s$^{-1}$ and 0.0126 s$^{-1}$ and non-dimensional heights of 4.55 and 4.76 on 1200 UTC 1 March and 0000 UTC 2 March, respectively. Comparing these with the results of numerical experiments carried out by Petersen et al. (2003), they found blocked flow for non-dimensional heights greater than 3, inducing cyclogenesis on the downwind side of the barrier. Hence, we conclude that lee cyclogenesis was likely to occur southeast of Greenland during 1 March 2007.

4. The structure of the cyclone on 3 March 2007

4.1. The capture of the cyclone during the B275 flight

In the present section we will focus on data from the flight B275 which took place between 0920 and 1545 UTC on 3 March 2007. An AVHRR (Advanced Very High Resolution Radiometer) satellite image obtained as late as 0622 UTC 3 March (not shown) does not clearly show the location of the cyclone, and there is no indication of a well-organised cloud system. By contrast, a satellite image obtained at 1343 UTC (Figure 6(a)) clearly shows the tail of the front secluding the cyclone centre. A later satellite image obtained at 2335 UTC on the same day (not shown) indicates that the cyclone by then had weakened and moved south-southeast. Hence the cyclone must have been at its mature stage during daytime 3 March, after a rapid development during the morning hours.

The purpose of the flight was to capture the structure of the cyclone by releasing dropsondes and measuring in situ. The 16 dropsondes were released in two different flight legs from an altitude of 7900 m, except for the first dropsonde, which was dropped from 7300 m. Figure 6(b) shows the flight track with positions of the dropsondes marked as black points. The colour of the track indicates the altitude of the aircraft. The position of each dropsonde is also shown on the 1343 UTC satellite image in Figure 6(a). The first dropsonde leg, which here will be termed Leg 1, started at 1032 UTC at 62.5°N, 32°W, when the aircraft was heading towards Greenland. The last sonde of Leg 1 was dropped at 1127 UTC at 60.0°N, 41.0°W. The aircraft then headed northwards until it reached 61.8°N and 41.0°W at 1152 UTC, where the first dropsonde of the second dropsonde
leg was released. This dropsonde leg will hereafter be termed Leg 2. The last sonde of Leg 2 was dropped at 60.5°N, 36°W at 1225 UTC. The aircraft then turned 180° and headed northwestwards while descending to 1900 m in order to obtain low-level in situ observations of the cyclone structure. Just after 40°W the aircraft turned south-southeast, and headed for the core of the cyclone. The core was observed as a cloud-free area surrounded by a wall of clouds at 60°N, 38°W at 1331 UTC. The aircraft then turned to the northeast, still travelling at 1900 m until it reached 61.5°N, 33°W, after which it ascended to an altitude of 6400 m and returned to Iceland.

A MODIS (MODerate-resolution Imaging Spectroradiometer) satellite image from 1246 UTC (not shown) indicates that the cyclone centre was slightly north of 60°N at that time. Simulations with the HIRLAM model further indicate that the cyclone was moving towards the south-southeast during the flight, after it had been moving southwest in the preceding hours. It is important to keep the motion of the cyclone and the simultaneous movement of the frontal system in mind when viewing the observations together with the satellite images.

4.2. Jets and fronts

We will here assess observations of wind and temperature in order to reveal the structure of jets and fronts associated with the cyclone. Figure 7 shows the cross-sections of potential temperature and wind speed through the cyclone. Figure 7(a) shows that the leg cuts through a slice of warm air at approximately 400 km, with the coldest air towards Greenland. This warm air represents an important feature of the cyclone that will be discussed later in the text. The cross-section of wind speed (Figure 7(b)) shows a low-level jet to the southwest of the warm air with wind speeds exceeding 34 m s\(^{-1}\) near the sea surface and at 850 hPa. The HIRLAM model underestimated the strength of the surface wind, predicting wind speeds in this area of slightly less than 25 m s\(^{-1}\) at 10 m height in contrast to a wind speed of 30 m s\(^{-1}\) obtained from dropsonde 6 at the same height. Likewise, at 850 hPa HIRLAM predicted wind speeds of approximately 30 m s\(^{-1}\), while dropsonde 6 measured 35.5 m s\(^{-1}\) wind speed at this level.

The wind direction, which is shown in the figure by arrows, was northwesterly at low levels in the coldest air, while northeast of the slice of warm air the surface wind direction was from the east-northeast. This change
in wind direction indicates that Leg 1 was north of the cyclone centre, cutting the front associated with the cyclone at two different places. The dropsondes in Leg 1 were released about two hours prior to the satellite image in Figure 6(a), when the cyclone centre was further north than shown in the image. The sea-level pressures of 971 and 974 hPa from dropsondes number 4 and 5 respectively show that these dropsondes were released closest to the cyclone centre. These low values indicate that the strength of the cyclone was underestimated in the analysis shown in Figure 3(a).

Figure 8 shows the cross-sections of potential temperature and wind speed for Leg 2. Dropsonde 5 of Leg 2 was released close to dropsonde 4 of Leg 1, but the cyclone had moved slightly further towards the south-southeast due to the time difference of about 1 hour. The cross-section of potential temperature shows a frontal zone between sonde 1 and sonde 3, with the front shown as a violet curve. In Figure 8(b) we see a strong low-level jet on the cold side of the front with maximum winds exceeding 30 m s\(^{-1}\). The jet is confined to the area below 750 hPa, where it is delimited by a strong temperature inversion (Figure 8(a)). The abrupt decrease of wind speed with height and the strong temperature inversion at 750 hPa are probably due to trapping of the cold air below 750 hPa by the Greenland orography, which has an altitude of approximately 2000 m at this location. This wind pattern corresponds to a barrier wind (Moore and Renfrew, 2005), which will be discussed further in section 5. Further southeast, on the warm side of the front there is a jet at higher levels. The maximum wind speed in this jet was measured at 30 m s\(^{-1}\) by dropsonde 5 at 550 hPa, and a zone of high wind speeds associated with this mid-tropospheric jet extends between 750 hPa and 450 hPa. The cross-section of wind speed from Leg 1 also showed signs of a jet between 750 and 500 hPa in the same region but it was less pronounced. The southeastern part of Leg 2 cuts through the front which encircles the cyclone centre.

In situ measurements of potential temperature at 1900 m are shown in Figure 9. The highest potential temperature was measured at 1331 UTC in the core of the cyclone. This core of warm air secluded by the front is consistent with a mature cyclone in both the conceptual model of Shapiro and Keyser (1990) and the Norwegian cyclone model (Bjerknes and Solberg, 1922). The aircraft passed the cyclone centre only 12 minutes prior to the satellite image, and as Figure 9 shows, the maximum potential temperature coincides with the cyclone centre on the AVHRR image.

4.3. Tropopause fold and intrusion of dry air

Browning (1997) described dry air descending from a fold in the tropopause as an important part of the structure of extratropical cyclones, being a manifestation of upper-level forcing. This feature was earlier described by e.g. Danielsen (1964), who found that stratospheric air was extruded into the troposphere in the region of the tropopause fold. Gray (2006) found that mass exchange between the stratosphere and troposphere in a tropopause fold mainly could be attributed to latent heating and cooling processes with contribution from radiative and mixing processes. Figure 4 suggests a possible influence on the cyclone development of an upper-level PV anomaly. With reference to Browning (1997), we would therefore expect to see indications of tropopause folding and dry intrusion in the data from the B275 flight.

We start by viewing the cross-sections of relative humidity and specific humidity through Leg 1 (Figure 10). The cross-sections show that Leg 1 cuts through a slice of dry air centred on sonde 4. Major parts of this dry slot had a relative humidity of less than 20%, and it extended down to 850 hPa at dropsonde 5, where Figure 7(a) showed the slice of warm air. This combination of dry and warm air could be an indication of subsidence. In the frontal cloud band (sonde 6) the RH exceeds 80% up to 650 hPa, but the specific humidity is low due to the cold air. In the northeastern part of Leg 1, the relative and specific humidities are very high at low levels, indicating
Figure 7. (a) Cross-section of potential temperature in K, and (b) horizontal wind in m s\(^{-1}\), through Leg 1. The dropsonde closest to Greenland is to the left in the cross-section. The front is shown as a solid violet curve on both cross-sections. In (a) dark blue indicates cold air. In (b) dark red indicates wind speeds exceeding 34 m s\(^{-1}\). The arrows show the direction of the horizontal wind at different levels, with the length of the arrow being proportional to the wind speed.

warm moist air, while pockets of air with RH less than 20\% extend down to 600 hPa (dropsonde 1). The cross-section of RH from Leg 2 (Figure 11) shows many of the same features as for Leg 1: A slice of dry air centred on sonde 6 extends almost down to 900 hPa. Northwest of this dry air, there is humid air with RH greater than 80\% up to 700 hPa and RH greater than 60\% up to 500 hPa in the frontal zone. Together, the cross-sections of legs 1 and 2 have revealed a slot of warm dry air extending deep into the troposphere on the warm side of the frontal cloud band (200–400 km in Figure 10 and 150–250 km in Figure 11), and we will now look for evidence of the dry slot in the \textit{in situ} measurements of water vapour mixing ratio and potential temperature obtained at 1900 m (Figure 12). It turns out that these measurements clearly show a region of warm dry air between 300 and 400 km, where the flight track was marked in red in Figure 9. This maximum of potential temperature and a minimum of mixing ratio were at the core of the cyclone, indicating that the air had descended into this area and experienced adiabatic warming.

The dry slot shown in Figures 10–12 is a clear indication of subsidence which could be connected to a fold in the tropopause or descending air in the lee of Greenland. In order to investigate this further, we calculated cross-sections of hydrostatic PV from wind and temperature measured by the dropsondes (Figure 13). The cross-section of PV through Leg 1 (Figure 13(a)) shows high values of PV extending down to approximately 550 hPa between 200 and 400 km. Figure 13(b) shows...
high PV values extending below 600 hPa between 200 and 300 km in Leg 2. These high values of PV coincide with the observations of dry air in Figure 10 and 11 and could indicate a low tropopause in the area when defining the tropopause in terms of the 2 PVU (Potential Vorticity Units) isoline. According to Browning (1997), we would expect descent of air associated with this fold.

To investigate the credibility of the PV cross-sections based on dropsonde data, we assessed cross-sections of PV through the dropsonde legs from a 6-hour run of HIRLAM valid at 1200 UTC 3 March (not shown) and found that the PV data from HIRLAM gave the same indications as the observationally based cross-sections. In Leg 1 the 2 PVU isoline from HIRLAM extends down to below 600 hPa in the same area as the 2 PVU isoline calculated from the dropsondes extended down to 550 hPa. The HIRLAM prediction for Leg 2 is also consistent with PV from the dropsondes, indicating that the 2 PVU isoline extends below 600 hPa between 200 and 300 km. However the PV isolines from HIRLAM are much smoother than the isolines shown in Figure 13. The strong gradients and high maximum and minimum values of PV in Figure 13 are due to the calculation of PV from gridded dropsonde data and are not realistic. Hence these PV cross-sections provide a general view over the PV distribution rather than detailed information.

The high concentrations of ozone in the stratosphere compared to the troposphere make this a useful indicator of stratospheric origin. Figure 14 shows the concentration of ozone measured along the flight track at 7900 m. The figure shows that the ozone concentration is increasing as the aircraft travels along Leg 1. The ozone concentration measured prior to the abrupt increase at 400 km is consistent with ozone soundings from Sodankylä (67.4°N,
26.7°E) carried out by the Finnish Meteorological Institute. These soundings are like our in situ measurements obtained at a high-latitude location, and show a mean ozone concentration for March of approximately 100 ppb at 8000 m altitude. After 400 km, when the aircraft is travelling over the frontal cloud band, there is a jump from 140 to 230 ppb in ozone concentration. A possible interpretation of the jump in ozone concentration is that the aircraft at this point travels into the stratosphere. Figure 15 shows the skew-$T$ diagrams from sonde 4 and sonde 6. The slice of dry air from the cross-section is easily recognised in the diagram for sonde 4. The lapse rate gradually decreases above 500 hPa, but it is not possible to locate a clear tropopause from the temperature profile. The lack of a distinct boundary between the stratosphere and troposphere over the frontal zone is described by e.g. Wallace and Hobbs (2006), and indicates possible cross-tropopause transport in this region. The skew-$T$ diagram for sonde 6 is substantially different, with almost saturated air up to 450 hPa, where an abrupt change in lapse rate shows a clearly defined tropopause. The aircraft was at this time travelling at 360 hPa, which was approximately 1500 m above the tropopause if we define this in terms of the abrupt change in lapse rate.

In Figure 14 there are two local maxima of ozone between 0 and 400 km. The first maximum may be associated with a secondary low in the vicinity of sonde 1, the presence of a secondary low being indicated by the increase in sea-level pressure from sonde 1 to sonde 2. The second maximum is between 250 and 300 km, and is probably due to traces of stratospheric air that has descended from the tropopause fold. There is a sharp decrease in ozone concentration between 700 and 800 km, when the aircraft travels out of the cold high-PV air.

4.4. Liquid water content and icing

In situ measurements of liquid water content (LWC) at 1900 m are shown in Figure 16 together with temperature. The highest values of LWC exceeded 0.5 g kg$^{-1}$, and were measured in the cloud wall surrounding the cyclone centre (400–500 km), as well as in the frontal cloud band in the northwestern part of the flight track (70–150 km). The high values of LWC combined with temperatures of 258 K led to conditions favourable for icing, which indeed was observed during the northwest section of the low-level flight legs.

5. Discussion

5.1. Summary

During the period 1 to 3 March 2007 the formation and deepening of an extratropical cyclone took place to the southeast of Greenland. The cyclone formed in a baroclinic zone under westerly flow. At the same time high-PV air from the north swept over Greenland, reaching the deepening cyclone by 2 March, providing upper-level forcing during the next 24 hours. Satellite images obtained before and after the B275 flight indicate that the cyclone at this time was in its mature stage with maximum intensity. In the current section we will discuss the observations of the severe surface winds in light of the study of strong winds in the region by Moore and Renfrew (2005). We further discuss the observed slot of dry air and high ozone values as well as the outbreak of high-PV air from the north. We seek to quantify the role of upper-level forcing on the cyclogenesis with the aid of PV inversion and trajectory calculations. We will also perform a subjective reanalysis of the synoptic situation between Greenland and Iceland on 3 March based on data obtained during the flight.
Figure 10. Cross-sections through Leg 1. (a) Relative humidity (%), (b) specific humidity (g kg$^{-1}$). The front is shown as a solid violet curve in both cross-sections.

Figure 11. Cross-section of relative humidity (%) through Leg 2. The front is shown as a solid violet curve.
5.2. The wind field

Figure 17 shows a summary of the cyclone structure on 3 March 2007 based on data from the B275 flight. While the observations show a northeasterly mid-tropospheric jet on the warm side of the front, the most severe winds are confined to lower levels, forming a jet delimited by Greenland in the west and the bent-back front to the east. The air flows parallel to the front, turning cyclonically towards the east where the front starts to encircle the cyclone centre. Moore and Renfrew (2005) described three categories of high wind-speed events along the coast of Greenland. These were tip jets, reversed tip jets and barrier flows in the vicinity of the Denmark Strait. The strong low-level jet between Greenland and the bent-back front is consistent with Moore and Renfrew’s description of a barrier flow at the ‘Denmark Strait south’ location. Wind data from QuikSCAT obtained on 3 March (not shown) are also consistent with the wind field associated with barrier flow at this location. Although HIRLAM predicted the position of the cyclone and hence the wind pattern associated with the barrier flow well, it failed to predict the maximum strength of the wind, the HIRLAM wind speeds at 10 m and 850 hPa being approximately 5 m s\(^{-1}\) weaker than those observed at the same levels in Leg 1. The wind speeds being too low is probably a consequence of HIRLAM underpredicting the strength of the cyclone, as we will show later in this section. This could indicate a weakness in the model’s ability to handle the full effect of Greenland’s orography on the cyclone development.

5.3. Upper-level forcing

The measurements of humidity, temperature and ozone concentration discussed in section 4.3 indicated a deep fold in the tropopause over the cyclone. This tropopause fold was associated with the outbreak of high-PV air from the north, which reached the region by 2 March. Temperature profiles and ozone measurements indicated a deep tropopause fold extending down to 450 hPa over the area denoted by the yellow oval in Figure 17. Over the area denoted by the green oval, in situ measurements and data from dropsondes revealed very dry air together with high values of PV. Unlike the region denoted by the yellow oval, where the abrupt change in lapse rate showed a clear tropopause, it was not possible to identify the tropopause from the skew-\(T\) diagram in this region. Figure 13 showed the 2 PVU isoline extending below 550 hPa, which indicates that the tropopause could be even lower here if we define the transition between the troposphere and the stratosphere as the 2 PVU isoline. However due to the lack of an abrupt change in the lapse rate in this area (Figure 15(a)), as well as ozone concentrations approximately 90 ppb lower than further southwest (Figure 14), we propose that the tropopause fold was deepest over the region denoted by the yellow oval.

The slot of warm dry air extending down to the lower troposphere indicates that air in this area has experienced adiabatic warming due to sinking, and the lack of a distinct tropopause in terms of the lapse rate could indicate exchange of air between the stratosphere and the troposphere. A maximum of ozone concentration (not...
shown) exceeding 50 ppb was measured in the core of the cyclone while the rest of the ozone values obtained at 1900 m were mainly less than 45 ppm. This ozone maximum could, together with the relatively high temperature and dryness of the air, indicate possible traces of air with stratospheric origin in the core. To investigate this further, we carried out trajectory calculations with the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph, 2003). Figure 18 shows a 60-hour backwards trajectory ending at sea level at 1200 UTC 3 March at 61°N and 39°W, which was close to the cyclone centre. The trajectory indicates that an air parcel at this position had descended from approximately 550 hPa during the previous 60 hours, reaching sea level by the morning of 3 March. Several trajectory calculations were carried out with the same duration time, but with the end point at 500, 1000 and 1500 m above sea level, respectively. Like the trajectory ending at sea level, these trajectories also had the most extensive descent over the eastern coast of Greenland, where the trajectories reached sea level. The location of the descent indicates that it was attributable to Greenland’s orography, most likely associated with air at lower levels being drawn away from the eastern coast of Greenland due to the splitting of the flow described in section 3. In conclusion, the trajectory calculations indicate that the air in the cyclone centre had a history of descent, and that this air mainly originated in the upper parts of the troposphere below the southwards-propagating PV anomaly (Figures 4 and 18).

The observations of the tropopause fold and clear signs of descending air indicate that upper-level forcing from the PV anomaly may have contributed considerably to the development of the cyclone. In order to quantify this contribution we performed a PV inversion of this anomaly. We combined the inversion methods ST (subtraction from total) and AM (addition to mean), described by Davis (1992). This combination of methods has been successfully used by Røsting and Kristjánsson (2006) and Kristjánsson et al. (1999). For completeness, we also inverted a negative upper-level PV anomaly, two lower-level PV anomalies and two surface θ anomalies.
Figure 14. *In situ* measurements of ozone concentration (ppb) obtained at 7900 m. The dropsonde legs are marked by a horizontal line with points indicating the positions of the dropsondes. The observations were obtained between 1036 and 1224 UTC. This figure is available in colour online at www.interscience.wiley.com/journal/qj.

Figure 19 shows the contribution from the positive and negative upper-level PV anomalies to the 900 hPa height at 1200 UTC 3 March. The figure confirms the assumption based on the observations, that upper-level forcing had a major impact on the development of the cyclone between 2 and 3 March. While the contribution to the cyclone deepening at 900 hPa was $-253$ m (geopotential height) from the upper-level positive PV anomaly, the contribution from the negative anomaly was only 35 m. At 1200 UTC 3 March the positive upper-level PV anomaly had an amplitude of 3.5 PVU at 300 hPa over 61°N, 32°W. The negative anomaly had an amplitude of $-1.5$ PVU at the same level located over 57°N, 21°W. The contributions from the two low-level PV anomalies and the surface $\theta$ anomalies were small compared to the upper-level forcing, with $-41$ m from a low-level PV anomaly being the most pronounced. This anomaly extended along the southeastern coast of Greenland and had an amplitude of 1 PVU at 800 hPa.

### 5.4. Impact of the Greenland orography versus upper-level forcing

In section 3 we found by calculating the non-dimensional height at the western coast of Greenland at 1200 UTC 1 March and 0000 UTC 2 March that wind and stability conditions were favourable for lee cyclogenesis east of Greenland at this time. Kristjánsson et al. (2009) investigated the role of orographic forcing on this cyclone by performing simulations in which they had removed Greenland’s orography, as well as control calculations. They found that the control simulations in all cases reproduced the cyclone evolution rather well, while the effect of removing the orography depended strongly on the starting time of the calculations. Calculations without orography starting at 0000 UTC 2 March gave a deeper cyclone than the run with orography due to increased cold advection in the rear. The calculations show that the presence of Greenland’s orography hampered the baroclinic forcing of the cyclone, while at the same time phase-locking its position off southeast Greenland.

By contrast, the simulations without orography starting at 1200 UTC 28 February produced a cyclone approximately 1000 km further east instead of a lee cyclone between Greenland and Iceland, while calculations starting at 0000 UTC 1 March produced a cyclone with the position shifted approximately 500 km to the east. The shift in position of the cyclone was a result of an altered path of the southward-propagating PV anomaly when Greenland’s orography was missing. The study clearly shows the large impact of Greenland on the development of the cyclone, presumably both through the production of vorticity due to flow splitting and by guiding the path of the upper-level PV anomaly southwards over Greenland.

### 5.5. Reanalysis

On the basis of the observations obtained during the B275 flight and the AVHRR image from 13:43 UTC we performed a subjective reanalysis of the front positioning and pressure field for the synoptic situation at 1200 UTC 3 March 2007; see Figure 20. By comparison, the subjective analysis carried out by the duty meteorologist at the Norwegian Meteorological Institute at the same time is shown in Figure 3(a). The observations revealed a warm cyclone centre circled by a front, with a
temperature difference of approximately 5 to 6 K between the cyclone centre and the cold surrounding air. This warm seclusion, which is shown in the reanalysis in Figure 20, is consistent with both the Norwegian cyclone model and the Shapiro–Keyser model. According to one of the studies presented in Shapiro et al. (1999), Life Cycle 1 (LC1) cyclones would have a strong cold front and a weaker warm front, while Life Cycle 2 (LC2) cyclones had a relatively weak cold front compared to the warm front. It was not possible to localize a clear cold front from the observations, although the horizontal gradient of potential temperature in the easternmost part of Leg 1 (Figure 7(a)) could indicate that the leg cuts a front in this area. The 925 hPa temperature field at 1200 UTC 3 March (not shown) indicates a weak cold front south of Iceland while the warm front along the eastern coast of Greenland is much stronger. Shapiro et al. (1999) described a cyclone observed on 10 March 1987 during the Alaskan Storm Program (ASP) as an LC2 cyclone, the same cyclone also being assessed in Shapiro and Keyser (1990). This cyclone had several similarities with our cyclone, both having warm cores secluded by fronts that were almost vertical up to 900–850 hPa with decreasing slope above this level. These findings could indicate that the cyclone of this study is consistent with the Norwegian cyclone model, being analogous to LC2.

We further assessed a jet stream analysis from 0000 UTC 2 March 2007 provided by California Regional Weather Server, San Francisco State University, as well as the height of the 300 hPa surface from HIRLAM (not shown), in order to determine whether the cyclone developed within cyclonic shear as an LC2 cyclone. The data indicated a polar jet stream between 40° and 50°N and an Arctic jet stream between 65° and 70°N, but it was not possible to clearly determine the background shear over the area southeast of Greenland. In summary, the
Figure 16. In situ measurements of liquid water content (spikes, g kg\(^{-1}\)) and temperature (curve, K) at 1900 m.

Figure 17. A summary of the lee cyclone based on data from the B275 flight shown on an AVHRR satellite image from 1343 UTC 3 March 2007. The data were obtained between 1030 and 1430 UTC. The low-level jet and the mid-tropospheric jet are depicted by brown and dark blue arrows respectively. The bent-back front is shown as a red curve. The yellow oval indicates the region where temperature profiles and ozone measurements indicated a deep tropopause fold. The green oval indicates the region without a clear tropopause. The yellow Ls show the locations of the Greenland lee cyclone and a secondary low.

structure of the cyclone has several similarities with both the Shapiro–Keyser and the Norwegian cyclone models, but does not match any of them exactly. A possible explanation of this is that unlike the cyclones studied by Shapiro et al. (1999) and Shapiro and Keyser (1990), our cyclone developed under strong orographic influence.

There are two indications of a secondary low in the same area as dropsonde 1 was released. The sea-level pressure increased from 976 to 979 hPa between dropsondes 1 and dropsonde 2, indicating a minimum in pressure near dropsonde 1. There was also a local maximum of ozone concentration in this area which could be associated with stratospheric air. In the reanalysis from 1200 UTC 3 March in Figure 20, we have added a secondary low, consistent with these indications. As for the primary low, the lowest sea-level pressure measured by the dropsondes was 971 hPa from dropsonde 4 of Leg 1, north of the cyclone centre. Based on this observation combined with wind speeds exceeding 20 m s\(^{-1}\), it is very likely that the sea-level pressure in the cyclone centre was several hPa below 970 hPa, as we have indicated in the reanalysis.

6. Concluding remarks

The B275 flight successfully captured the mesoscale structure of a mature extratropical cyclone southeast of Greenland on 3 March 2007. Since operational models indicated westerly winds over Greenland on 1 March and cyclogenesis southeast of Greenland, it would be reasonable to assume that flow splitting due to the Greenland orography played a significant role in the formation and development of this cyclone. Values of non-dimensional height exceeding 4.5 on the western coast of Greenland at this time support this assumption, which is consistent with previous studies by Petersen et al. (2003) and Kristjánsson and Mc Innes (1999). The findings in this study also indicate that the upper-level PV forcing due to the outbreak of air from the north had an important role in the most rapid development of the cyclone which occurred during the hours prior to 1200 UTC 3 March. The contribution of this upper-level PV anomaly to the deepening at the 900 hPa surface was estimated by PV inversion to be as much as –253 m, greatly exceeding the contributions from the surface \(\theta\) and low-level PV anomalies. This upper-level forcing manifested itself as a pronounced tropopause
fold which was clearly revealed by an abrupt increase in ozone concentrations from 140 to 230 ppb as the aircraft travelled into it. The skew-$T$ diagram showed that it extended at least down to 450 hPa. A slot of dry air associated with this tropopause fold extended below 800 hPa, indicating descent and possible cross-tropopause transport.

The warm seclusion of this cyclone is consistent with both the Shapiro–Keyser and the Norwegian cyclone model. However, based on the observations of warm dry air in the cyclone centre with ozone concentrations approximately 5 ppb higher than in the surroundings, we suggest that much of this air had descended from the upper parts of the troposphere and traces of it even from the stratosphere, rather than originating in the

Figure 18. A 60-hour backwards trajectory from HYSPLIT ending at sea level 1200 UTC 3 March at 61°N and 39°W. Position of the lee cyclone is denoted by L while H indicates the position of the surface high pressure over Greenland.

Figure 19. Contribution to the 900 hPa deepening (in m) from an upper-level positive PV anomaly (blue curves) and an upper-level negative PV anomaly (red curves) at 1200 UTC 3 March. The height of the 900 hPa surface (in m) is shown as green dashed curves.

Figure 20. Reanalysis of the synoptic situation between Greenland and Iceland for 1200 UTC 3 March showing sea-level pressure in hPa (isobars) and the bent-back front.
warm sector (Bjerknes and Solberg, 1922) or within the baroclinic zone (Shapiro and Keyser, 1990). Trajectory calculation also indicated that this air had experienced descent forced by Greenland’s orography. This is another sign of Greenland’s major influence on the structure of this cyclone, which may explain the failure to match it exactly to one of the conceptual models.

Acknowledgements

This study has received support from the Norwegian Research Council through the project ‘THORPEX-IPY: Improved forecasting of adverse weather in the Arctic – present and future’ (grant no. 175992). The Norwegian Meteorological Institute provided data from the HIRLAM model and analysis. They also gave us access to their meteorological visualisation and production system DIANA and contributed with both technical and professional support. Ian Renfrew and the GFdex project team provided matlab scripts that were used to prepare data obtained from the aircraft. European Fleet for Airborne Research provided flight hours on the Facility for Airborne Atmospheric Measurement’s BAE 146 aircraft. AVHRR satellite images were provided by NERC Satellite Receiving Station, Dundee University, Scotland http://www.sat.dundee.ac.uk/. MM5 data were provided by Gard Hauge, Storm Weather Center AS. AMSR-E data were produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project and the AMSR-E Science Team. Data are available at www.remss.com. Department of Atmospheric Science, University of Wyoming provided radiosonde data. The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYPLIT transport and dispersion model and READY website (http://www.arl.noaa.gov/ready.html) used in this publication. During this study we had useful discussions with Inge B. Johannesen, Melvyn A. Shapiro, Guðrún Nína Petersen and Haraldur Ólafsson. Finally, we thank the anonymous reviewers for valuable comments that led to significant improvements in the manuscript.

References