A climatological study of polar lows in the Nordic Seas

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The climatology of polar lows over the Nordic Seas has been investigated using infrared satellite images for the period between 2000 and 2009. The same region was studied in the 1980s using traditional weather charts for the period between 1972 and 1982. One motivation for the present study was to revisit this climatology, but using a different decade and taking advantage of the vastly improved coverage and dissemination of infrared satellite images since the 1980s. The fact that forecasters at the Norwegian Meteorological Institute had introduced a routine to register polar-low events systematically from 2000 and onward also provided a unique opportunity for extending the existing repository of subjectively identified polar-low observations. On average we found 12 polar-low events per year in the region of study. This is more than the earlier investigation, but we believe that this can be explained by the fact that the previous study relied almost uniquely on weather charts with very little information from ocean areas in the Nordic Seas. The largest numbers were found in January with an average of 2.8 polar-low events per year. The study reconfirms the February minimum found in previous studies, but on the basis of our data we could not show that this minimum is statistically significant. It is suggested that this may be explained as a manifestation of the coldest winter month, when a surface-pressure high over the Scandinavian mainland is common and the large-scale atmospheric flow is less favourable to polar-low formation. This hypothesis was tested by calculating the mean sea-level pressure (MSLP) anomaly for January, February and March from an atmospheric reanalysis. This revealed a positive anomaly over Scandinavia and northwest Russia not found in the pressure distributions for January and March. Copyright © 2011 Royal Meteorological Society

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1. Introduction

Intense mesoscale 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 outbreaks may be triggered and the cold Arctic air masses become exposed to the relatively warm ocean surface. Such conditions are conducive to strong, deep convection and the formation of polar lows, with surface winds often exceeding 25 m s^{-1}. These small violent storms have impacted coastal communities and seafarers over the centuries and are believed to be responsible for a number of shipwrecks. From northern Norway there are several historical accounts of incidents that are believed to have been caused by polar lows, including the 'rescuing deed of Hamningberg' (https://stars.wiki.met.no/doku.php?id=history) in 1894, in which more than 30 fishermen were saved by a rescue vessel from the newly established Norwegian Society for Sea Rescue. Very few such incidents in the Nordic Seas are documented in the scientific literature. From the Japan Sea, one example is the storm on 11 February 1997, reported by Fu *et al.* (2004), in which three ships were lost. Polar lows, with horizontal length-scales smaller than 1000 km, are often missed by the sparse network of synoptic observations in the Arctic. Although the phenomenon was well-known among weather forecasters, the small size and relatively rapid development of these cyclones has until recently made them almost impossible to forecast. A variety of forcing conditions and mechanisms can be involved in the development of polar lows, making it difficult to define them solely by their dynamical characteristics. Thus, it has become common to use a more general definition for a polar low (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.*

Figure 1 shows an example of a well-developed polar low off the coast of northern Norway on 7 January 2009. The low gave storm-force winds and dense snow, recorded at the synoptic observation site at Banak. The weather conditions caused severe problems for both coastal and inland communities in northern Norway. The eye can be clearly seen at the centre of the low (bold arrow in figure). The smooth cirrus shield and wave structures to the west and north of the centre are typical of a strong low with deep convection. To the east of the main centre, two weaker centres can be seen (thin arrows in figure). Convergence lines, typical of the cold-air outbreaks in these areas, are seen in the area south of Svalbard.

The study of polar lows is a relatively new branch of meteorology. Virtually no scientific articles were published on this subject before the 1960s. The first known infrared satellite image of a polar low was obtained on 5 January 1970, when a polar low over the northern part of Britain was observed by Nimbus 3 (Lyall, 1972). It was only by the late 1970s that polar-orbiting satellites revealed the ubiquity of mesoscale cyclones during Arctic cold-air outbreaks. It was also during this period that the striking similarity to tropical cyclones became apparent.

Wilhelmsen (1985) investigated the climatology of polar lows in the Nordic Seas. This study covers 10 years between 1972 and 1982, and was probably the first climatological study of polar lows. At the time of publication, the data between 1972 and 1977 were incomplete; the full dataset was later published by Ese *et al.* (1988). The Wilhelmsen (1985) study is based on meteorological weather maps, synoptic observations from ships and coastal stations and a few satellite images. One of the main findings is the monthly frequency distribution of polar-low events. The maximum number of events is found in December and January. One feature in the frequency distribution that has since been widely disputed is the local minimum of events in February. Far more events are observed both in January and March than in February, according to this study.

In a more recent study, Blechschmidt (2008) used infrared satellite images to investigate the polar-low climatology over the two-year period 2004–2005. To distinguish polar lows from weaker mesoscale events, the author used a definition of polar lows similar to that of Rasmussen and Turner (2003), stated above. To find wind events of gale force or above ($15\,\mathrm{m\,s^{-1}}$), Blechschmidt used the satellite climatology Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data (HOAPS: Andersson *et al.*, 2010), which is based on passive microwave radiometers. In this study, the monthly frequency distribution is presented for each year separately. Generally, the number of polar-low events detected is much higher than that found by Wilhelmsen (1985). Blechschmidt found a total of 90 polar lows over the two-year period (45 per year), whereas Wilhelmsen counted 71 over a ten-year period (7 per year). Partly, this can be explained by differences in the areas covered. Wilhelmsen focused on the ocean region north of the ridge between Scotland and Greenland, while Blechschmidt considered a larger region, extending down to 60°N. In addition, since the study by Wilhelmsen is mainly based on weather charts, the general lack of marine observations is likely to cause a number of polar-low events to be missed.

Polar-low climatologies have also been investigated using physical constraints on numerical reanalyses (Kolstad, 2006) and operational numerical prediction models (Bracegridle and Gray, 2008). In the article by Bracegridle and Gray, a cyclone data base derived from the UK Met Office operational model is used to develop an objective method of identifying polar lows, which the authors then used to produce a climatology of polar lows over the five-year period 2000–2004. Interestingly, they also found a February minimum like that reported by Wilhelmsen (1985). A total of 105 polar-low events were identified over the five-year period in the study area, yielding an average of 21 per year. This is half the number found by Blechschmidt (2008) and more than twice the number observed by Wilhelmsen. Differences in methodology and study areas are to a large extent the cause for this.

Zahn and von Storch (2008) investigated the polar-low climatology of the North Atlantic by dynamical downscaling of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis for the period 1948–2006, i.e. a limited-area atmospheric model for the study area was nested into the NCEP/NCAR reanalysis. A tracking algorithm was then used to detect polar-low events. They obtained an average of 59 polar lows per year. Most polar lows were detected in the area between the east coast of Greenland and Iceland, an area not covered by the study of Wilhelmsen (1985). No significant long-term trend was found in the polar-low activity.

The impact of an anthropogenically warmed climate on the polar-low climatology was investigated by Zahn and von Storch (2010). They used a regional climate model to downscale projections for the end of the 21st century dynamically and found a decrease in polar-low activity. According to the authors, the main reason for this is the changes in sea-surface and mid-troposphere temperature. In their study they found that the mid-troposphere temperature rose faster than the sea-surface temperature, projecting a higher atmospheric stability associated with global warming.

The main objective of the current study is to re-investigate the polar-low climatology of the Nordic Seas, covering an

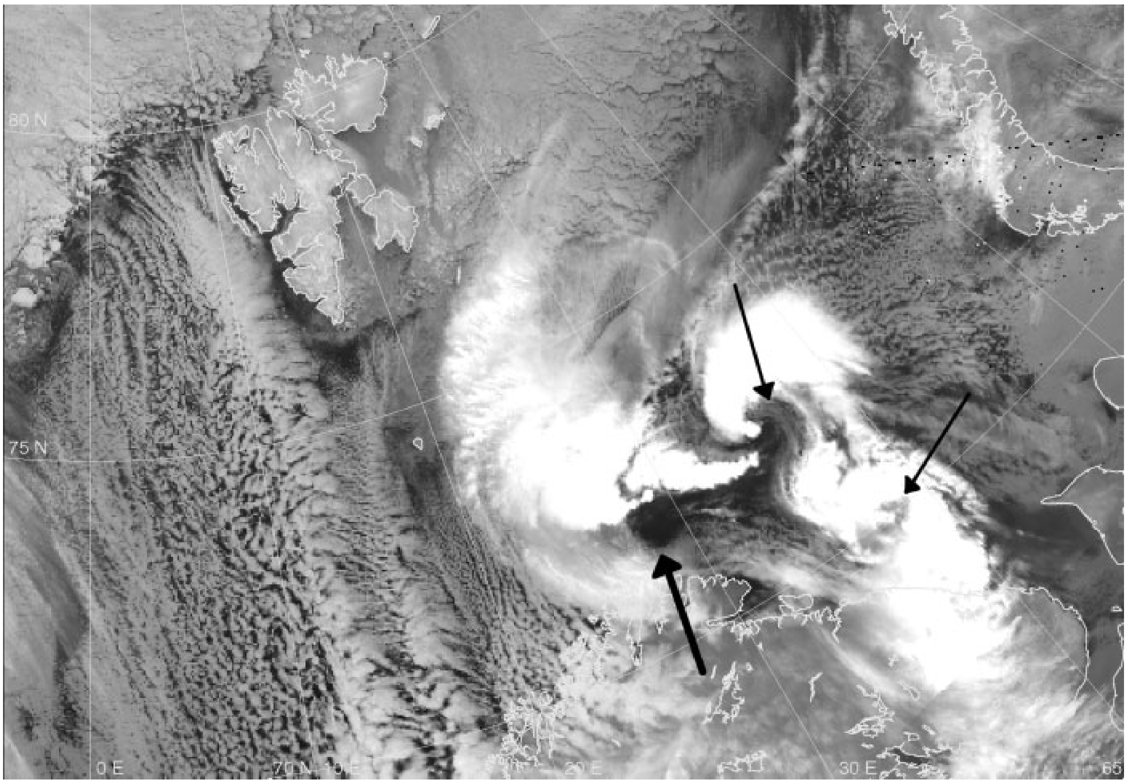

Figure 1. A polar low off the coast of Northern Norway on 7 January 2009 taken from NOAA's AVHHR. The Svalbard islands can be seen to the left in the upper part and the coast of northern Norway in the lower part of the figure. The bold arrow points to the centre of the polar low. The two thin arrows point at two weaker centres to the east of the polar low.

area similar to that of Wilhelmsen (1985) and for a similar time span. The study by Zahn and von Storch (2008) found no significant trend in the polar-low frequency from 1948 to the present. We will assume that this result is valid and also add the data from Wilhelmsen to ours to get a total data set of 21 years. Assuming the validity of their results, we extend the timespan of our analysis to 21 years by merging Wilhemsen's data and ours. We will investigate the frequency and distribution of polar lows by analyzing a list of polar lows for the 10-year period between 2000 and 2009 compiled by Noer and Lien (2010). The polar-low list is based on subjective observations by trained forecasters at the Norwegian Meteorological Institute, taking advantage of the vastly improved infrared satellite coverage since the days of the Wilhelmsen study. The list contains dates and positions of polar lows at the point of first identification as a fully developed system. Also, minimum centre pressure and maximum observed wind are recorded, whenever available. We will address the question of the average number of events per year, since different authors clearly have rather different frequency distributions ranging from over 40 to fewer than 10 per year. In addition, we will try to establish whether the February minimum is a robust feature or rather an artefact due to the limited number of observations.

The structure of this article is as follows. Section 2 explains the data, method and classification of polar lows. The statistics are presented in Section 3. In section 4 we analyze the monthly average mean sea-level pressure (MSLP) and relate this to the polar-low frequency in an attempt to explain the observed distribution. Finally, some concluding remarks are given in section 5.

2. Data and identification method

At the Norwegian Meteorological Institute (met.no) in Tromsø, polar lows are forecast on a regular basis throughout the winter season. The methodology used is based on the work of Wilhelmsen (1985) and Lystad (1986), but has since been modified as more knowledge and experience has been gained within the staff of forecasters and with the aid of modern observational and numerical tools. In 2000, a resource group was formed at the met.no office in Tromsø with the mandate to improve the existing methodology on polar-low forecasting. A central part of this work has been to record and store key data of observed polar lows. A list of polar-low cases has been assembled for further study. The study area is shown as the hatched area in Figure 2. This means that polar lows west of the line between Scotland and Greenland, i.e. those that commonly occur in the lee wake off the south tip of Greenland, are not included in the list. Frequently, polar lows occur in pairs or in a cluster of multiple low-pressure centres. In such cases, only data of the deepest low are recorded, but a comment is included to notify that this is in fact one of multiple lows. The list is updated annually and is freely available to the scientific community as a report, similar to Noer and Lien (2010), found at http://met.no/Forskning/Publikasjoner/.

The polar lows in the list by Noer and Lien (2010) are subjectively selected on the basis of the definition given in section 1. To record a polar low, forecasters are looking for atmospheric patterns typical for polar-low formation. Also, features during the developed or decaying phase are considered. The polar low adheres to a typical pattern of development that can be distinguished from related, less intense, phenomena and from smaller synoptic lows. A

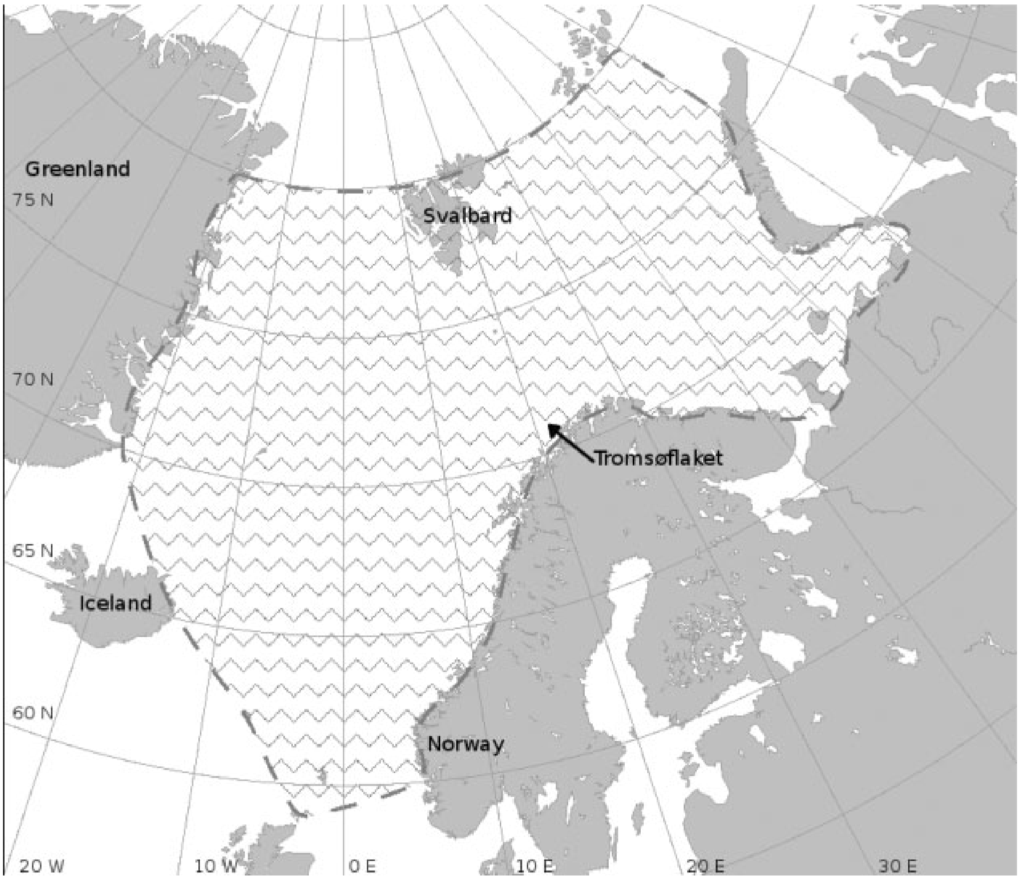

Figure 2. The polar-low climatology in this investigation covers the hatched area shown in the figure.

prominent feature is the destabilization of the lower layers by advection of cold air over warmer water, commonly referred to as a marine cold-air outbreak.

2.1. Data

The primary source of information is satellite data, mainly infrared imagery from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR). In addition, synoptic observations and scatterometer winds from the Advanced Scatterometer (ASCAT) and Sea Winds Scatterometer (QUIKSCAT) are used, whenever available, for classification of the cyclones. In some cases radar data are used. Model fields are used as the basis for analyses. At present, the High Resolution Limited Area Model (HIRLAM: Undén *et al.*, 2002) 12 km and 8 km is used for the areas covering the Norwegian and the Barents Sea. Close to the Norwegian coast, HIRLAM or a version of the UK Met Office Unified Model (Davies *et al.*, 2005) at 4 km resolution, run operationally at met.no, are used. In most cases it is possible to establish the wind speed associated with the lows, but not always. In many cases the wind is observed at coastal stations and, given the limited density of observations along the Norwegian coast and the complexity of the terrain, they do not necessarily represent the real maximum wind speed around the low, but somewhat less. Winds taken from ASCAT or QUIKSCAT data are area averages, but the resolution compared with the typical extent of maximum wind is such that they are considered reasonably representative.

2.2. Selection method

The polar lows in the list by Noer and Lien (2010) are subjectively selected on the basis of the definition given in section 1. When classifying polar lows at met.no, the primary diagnostic approach is examination of the development leading to the event. The polar low adheres to a typical pattern of development that can be distinguished from related, less intense, phenomena and from smaller synoptic lows. One prominent feature is the destabilization of the lower layers by advection of cold air over warmer water, commonly referred to as a marine cold-air outbreak.

An additional requirement is the passage of a cold upper-level trough with associated advection of potential vorticity. This leads to a destabilization of the air column further up to above 500 hPa.

Still, this combined destabilization is normally not sufficient for polar lows to develop. An additional area of low-level baroclinic instability is needed, from which the polar low will develop under the combined influence of the effects mentioned above. Typical examples are old occluded fronts, common troughs or areas of enhanced low-level convergence and convection. The patterns of development described above have been seen in all polar lows recorded at met.no so far.

An additional requirement for selection is that the bands of clouds and precipitation have a cyclonic appearance. Clearly identifiable eyes with cloud bands radiating out from the centre, with cloud-top temperatures of -40°C or less, are frequently observed. Showers of snow or hail and visibility lower than 300 m are common. The polar low is not necessarily symmetrical. Rather, the strongest wind and precipitation are found on the side where the mesoscale circulation acts in the same direction as the surrounding synoptic-scale wind field. Usually, this is on the western or northern side. On the opposite side, the mesoscale and synoptic-scale wind fields act in opposite directions, resulting in an area of weak winds and precipitation, a deceptively 'calm' area.

The sudden shifts in wind strength and direction are typical of polar lows. These are confined to narrow bands associated with the eyewall or along the bands of strong convection around the centre. Storm-force winds are found in about one third of the cases. According to the definition, a threshold of 15 m s^{-1} (gale force) is a criterion for polar lows. At met.no, this threshold is not always strictly adhered to, since the air masses of cold-air outbreaks are frequently advected with a similar velocity. Less intense phenomena, such as mesoscale cyclones that typically enhance the wind by 5–10 m s^{-1}, are not included in the selection, even if they generate wind speeds exceeding 15 m s^{-1}. Instead, the wind around the centre relative to the synoptic-scale ambient wind field is considered. Since this is often difficult to establish, no distinct value or threshold is set. A guideline established by Wilhelmsen (1985), that the polar low typically modifies the wind speed around the centre by 2–4 Beaufort, has been found to be helpful, but is not used as an absolute criterion.

Surface (10 m) wind, precipitation and other features such as pressure tendencies are taken from synoptic observations, observations from airports (METAR) or scatterometer winds from ASCAT or QUICKSCAT. The characteristic distribution of precipitation associated with polar lows approaching the coast is easily seen in weather radar imagery.

Prognostic fields are used to support the classification of polar lows. Figure 3 shows a satellite image of a polar low on 26 January 2007 and a corresponding cross-section of relative humidity and potential temperature are shown in Figure 4, taken from the operational analysis of the HIRLAM model at met.no. The cross-section is taken along the line depicted in Figure 3. As can be seen from Figure 3, the low is embedded in a wide cold-air outbreak covering the whole of the Nordic Seas. Cloud streets of gradually deeper cumuliform clouds can be seen streaming off the ice. In Figure 4, the left part of the graph corresponds to the northwestern end of the cross-section. Here, the air leaves the Arctic ice shield under a strong inversion layer. The mixed layer then deepens downstream until the inversion breaks down, at which point the moist warm air lifts to the next inversion layer. In this case this was not until 500 hPa and the subsequent low-layer inflow was strong enough to generate a well-defined vortex.

In the Nordic Seas, mesoscale cyclones occur frequently. They have the same cyclonic appearance and similar horizontal extent to polar lows, but do not break through the initial inversion layer closer to the ice edge. They differ from polar lows in having a smaller vertical extent of the associated cloud mass and generally lower surface wind and precipitation.

3. Statistical results

The ten-year list of polar lows for 2000–2009 contains 121 recorded cases, which means that, on average, each year has roughly 12 polar lows. Figure 5 shows the geographical distribution of the point at which the low was first identified as fully developed, i.e. early in its life span. The lows are fairly evenly distributed throughout the area of the Norwegian and Barents Seas. With a few exceptions, the lows are found north of 62°N, south of 75°N and east of the zero meridian, showing that they typically develop some distance downstream from the ice edge surrounding the area.

The highest concentration of polar-low identification points is associated with the areas of high temperature in the Norwegian Atlantic Current flowing northward off the Norwegian coast. Some weak maxima can be identified, the most pronounced around 72°N and 18°E in the area known as Tromsøflaket. This 'hot spot' is probably linked to cold-air outbreaks around the Svalbard area. Given the wedge shape of Svalbard, the northwesterly flow to the west and the northeasterly flow to the east of Svalbard meet off the tip of South Cape to form a convergence line flowing southwards, thus forming an ideal seeding area for polar-low development.

Cold-air outbreaks in the area between Svalbard and Novaya Zemlya account for many of the polar lows in the eastern Barents Sea. Figure 5 indicates that few polar lows occur in the eastern Barents Sea. One possible reason for this is the colder sea surface in this area, typically 2–3 °C during the winter. Also, there are small sea-surface temperature differences in the north–south direction, resulting in less transfer of sensible and latent heat under northerly wind conditions.

A more frequent precursor of polar lows in the Barents Sea is a northeasterly instead of northerly large-scale flow. Developments in such air masses tend to occur further west, outside the coast of Finnmark, where the gradients in the sea-surface temperatures are larger. In such a flow regime, with the cold air to the north as is nearly always the case in this area, the geostrophic wind has a component in the opposite direction to the thermal wind. In most of the literature on polar lows, this is referred to as reversed vertical shear (Rasmussen and Turner, 2003), in contrast to the typical southwesterlies with cold air to the north and the thermal wind acting to increase the wind with altitude. Reversed shear has been proposed as a favourable condition for polar-low development (Kolstad, 2006).

The monthly distribution of polar lows for every year between 2000 and 2009 is given in Table I. On average, we find 12 polar-low events per year compared with seven found by Wilhelmsen (1985). Based on the finding of Zahn and von Storch (2008) that there is no significant trend in the polar-low frequency from 1948 up to the present, we believe that this difference is mainly due to differences in methods. The study of Wilhelmsen almost solely relied on meteorological weather maps, which were mainly based on conventional observations. Over ocean areas almost no such observations are taken for operational meteorological purposes and it seems plausible that some polar lows were missed for this reason. Another factor is that Wilhelmsen had very limited access to Russian observations, and a number of polar lows in the eastern Barents Sea may have been missed. In the present dataset, a maximum of 19 polar lows was found in 2008 and a minimum of 4 was found in 2000. The average monthly frequency distribution is presented in Figure 6(a) (upper panel). In order to avoid the results being influenced by the fact that February has fewer days than other months, the number of events in each month in Table I was divided by the actual number of days in that month to obtain the daily frequency. The result was then multiplied by 30 for all

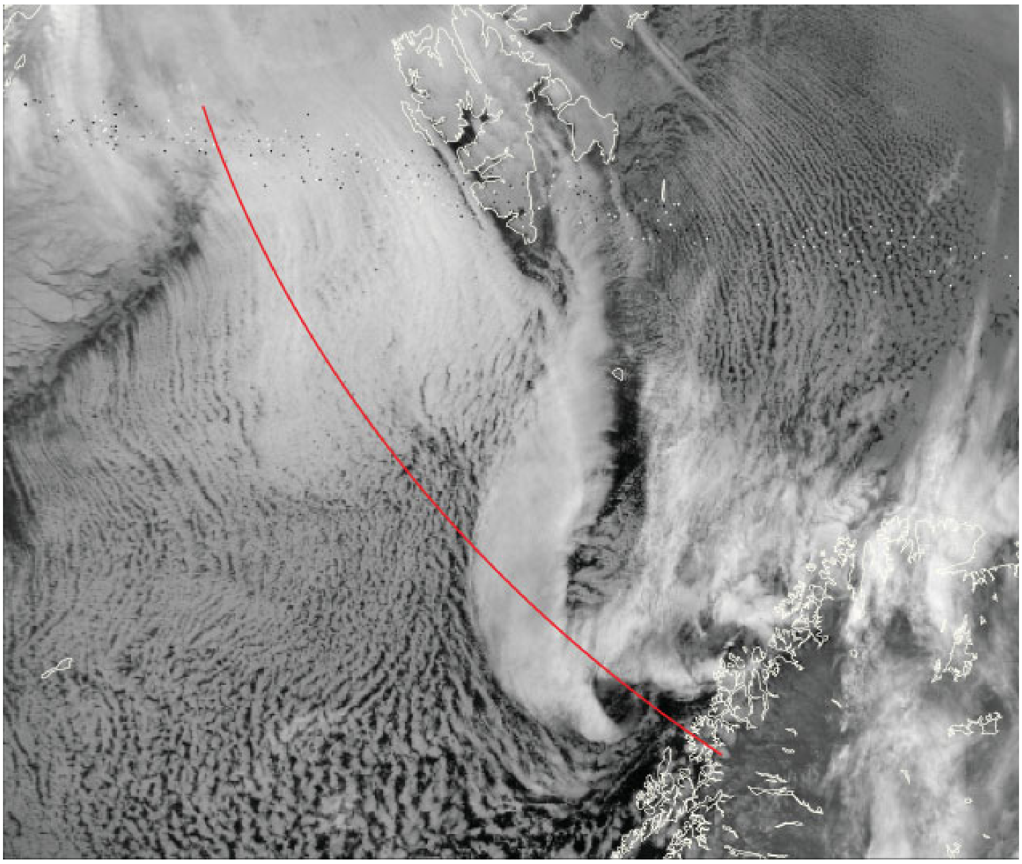

Figure 3. Polar low on 26 January 2007 off the coast of Northern Norway taken from NOAA's AVHHR. The solid red line shows where the cross-section of relative humidity and potential temperature from the operational HIRLAM analysis at met.no presented in Figure 4 is taken.

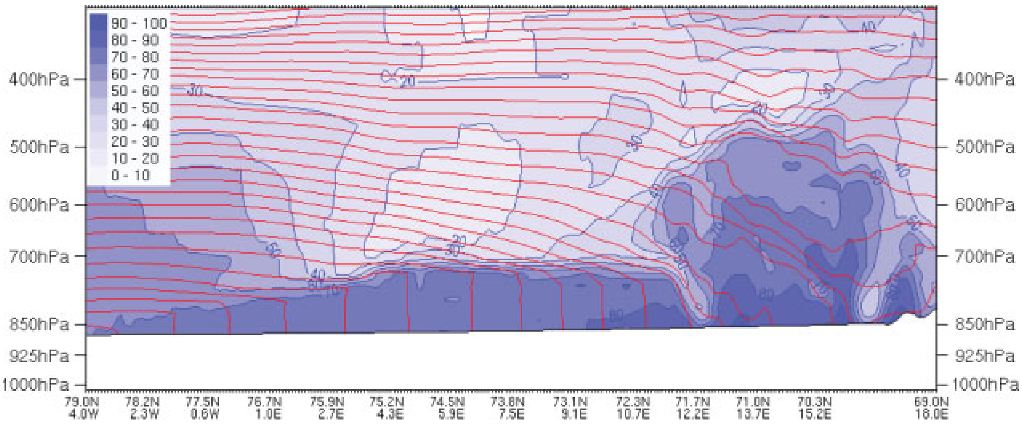

Figure 4. Cross-section along the red solid line in Figure 3 from the operational HIRLAM analysis at met.no. The left part of the graph corresponds to the northwestern end of the cross-section. Red solid lines are potential temperature and the relative humidity is presented as blue shading.

months, resulting in a frequency distribution as if all months contained 30 days.

The season for polar lows lasts from October–May, with a maximum in January and local maxima in November and March. The maxima in January and March have been rather consistent since the study started in 2000, reflecting the general characterization of the polar low as a winter phenomenon. It also fits well with the results from the study by Wilhelmsen (1985). The February minimum reported by Wilhelmsen is also seen in the data presented here. We propose that there is a link to the atmospheric situation in the coldest winter month, when a surface-pressure high over the Scandinavian mainland is rather common. Also, Zahn and von Storch (2008) found that such a mean pattern indeed influences the frequency of polar lows. A higher than normal mean pressure over the Scandinavian mainland favours southerly winds to the west of the Norwegian coast, which advect warmer air across colder waters. On average such a pattern enhances the likeliness of higher atmospheric stability and reduces the likeliness for polar-low development. This hypothesis will be further investigated in section 4, using MSLP anomalies from a global atmospheric reanalysis.

The average number of polar lows per month, together with the standard deviation, is given in Table II. Generally, the standard deviations for the winter months are of the same order of magnitude as the mean values themselves, confirming a rather large interannual variability. Also, note

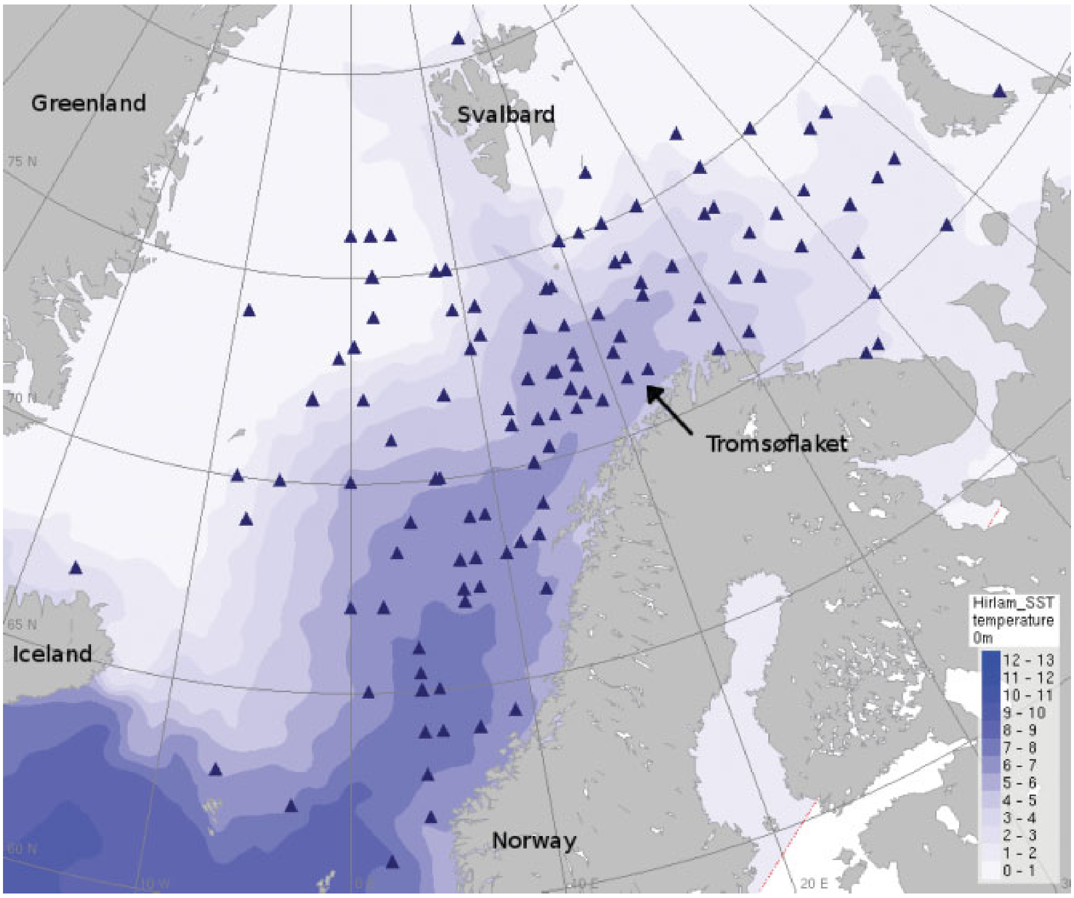

Figure 5. Position of polar lows 2000–2009. Blue shading shows the climatological mean sea-surface temperatures for January taken from the climatological archive compiled by Engedahl *et al.* (1997).

Table I. Polar low events for each month in the period from 2000 to 2009.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
Jan	2	1	5	5	2	3	1	4	2	3	28
Feb	0	2	3	0	2	1	0	2	2	6	18
Mar	2	3	2	2	3	4	2	0	5	1	24
Apr	0	1	0	0	0	2	0	2	2	3	10
May	0	0	1	0	0	0	0	0	0	0	1
Jun	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	1	0	0	1
Oct	0	1	0	1	0	1	1	0	1	0	5
Nov	0	4	0	0	5	2	1	0	6	0	18
Dec	0	1	3	5	2	1	2	1	1	0	16
Total	4	13	14	13	14	14	7	10	19	13	121

Table II. Monthly means and the corresponding standard deviations for the number of polar-low events in the period from 2000–2009.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	2.8	2.0	2.4	1.0	0.1	0.0	0.0	0.0	0.1	0.5	1.9	1.6
Std.	1.5	2.0	1.4	1.2	0.3	0.0	0.0	0.0	0.3	0.5	2.4	1.5

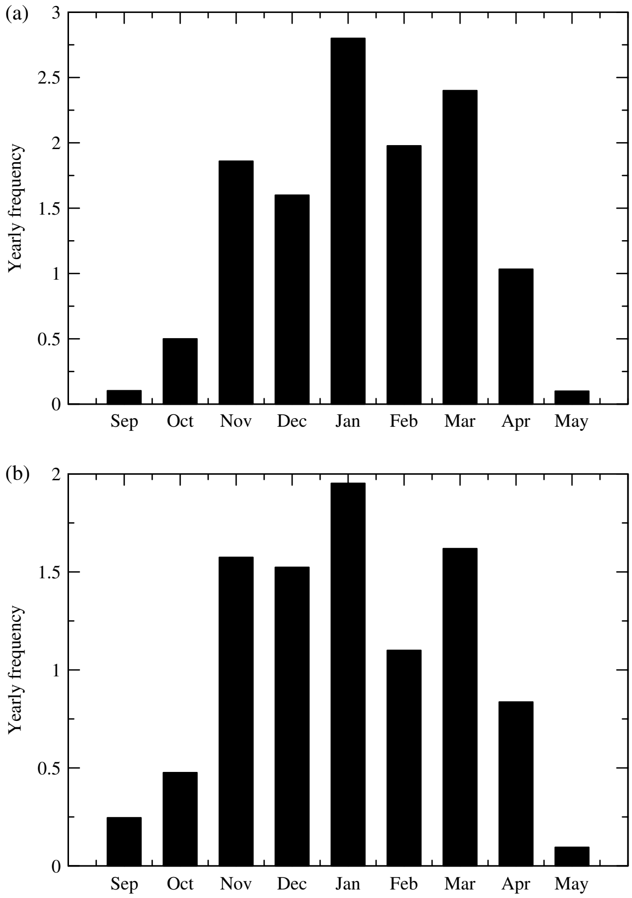

Figure 6. Frequency distribution for polar lows. (a) Result based on observations between 2000 and 2009. (b) Result when observations between 1972 and 1982, taken from Wilhelmsen (1985) and Ese *et al.* (1988), are included in the analysis.

that the differences between the mean values for successive months are generally much smaller than the standard deviation. So, to the question: *Is the February minimum a robust feature?* For a sufficiently long time series, a significance test could be used to quantify the probability that the differences between the means for January, February and March are statistically significant. However, as the number of years is limited to 10, these numbers would be dubious. As an example, when a Student's t test (Wilks, 1995) was used on the data set, the result was very sensitive to individual years. Taking one year of data out resulted in completely different values for the significance levels. Therefore, we decided to consider the question by presenting the standard deviations and comparing these with the differences of the monthly means instead. Judging from the standard deviations and the mean differences given in Table II, it seems rather unlikely that the February minimum found here is statistically significant. The difference between the February and March averages is only 0.4, while the standard deviations are 2 and 1.4, respectively. Although the February minimum was found in both studies, it is concluded that the variability is too large to claim that the minimum is statistically significant. It does not, however, mean that the February minimum can be rejected as a real feature.

In the article by Wilhelmsen (1985), only the observed polar lows for the last five years, 1978–1982, are listed. The data from 1972–1977 are found in the publication by Ese *et al.* (1988). Taking advantage of this, we can add those 10 years of data to the present data set to obtain a time series of double the length. The resulting monthly frequencies are presented as histogram in Figure 6(b) (lower panel). Like the results in Figure 6(a), the monthly averages have been weighted by the number of days in each month to avoid any influence of having too few days in February. Not surprisingly, since both data sets contain the February minimum, the local minimum is still present. The only difference between Figure 6(a) and (b) is that the local minimum for December almost vanishes. The average number of polar-low events per year in the autumn steadily increases until January. The standard deviations remain of the same order as in Table II and are not presented here.

The polar-low list by Noer and Lien (2010) contains wind-speed observations for most of the cases. However there are a number of events where the wind speed is missing. The statistics should therefore be taken with some caution. The monthly mean wind speeds are given in Table III, together with the highest observed value for each month. The monthly averages range from 37–47 knots (18.5–23.5 m s^{-1}). However, the monthly differences are not statistically significant. Note that the highest observed wind speed during the whole period was 70 knots (35 m s^{-1}), based on a QUIKSCAT observation. For such high wind speeds the scatterometer observations might be questioned. We did also plot the positions of the polar-low events with highest wind speed (above 50 and 55 knots) and found that they were evenly distributed over the study area.

4. Mean sea-level pressure analysis

In section 3 we proposed that the local minimum of polar-low events in February may be explained by the presence of a high-pressure MSLP anomaly over Scandinavia during the coldest winter month. To investigate this further, the MSLP anomalies for January, February and March have been calculated from the ERA-Interim analysis, which is the latest global reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim uses a 12 h 4D-Var data-assimilation system and covers the period from 1989 to the present (Uppala *et al.*, 2008). It is updated on a monthly basis subject to a two-month delay to allow for quality control.

Based on the ERA-Interim data, the winter climatology was calculated as the average MSLP for the winter months from December–March (DJFM) for the period between 2000 and 2009. The anomalies for January, February and March were then calculated by subtracting the winter climatology from the climatological averages of each individual month. The results are depicted in Figure 7. Figure 7(a) shows the result for January with a negative MSLP anomaly over Greenland, the Nordic Seas and the Arctic Ocean, and over parts of Scandinavia. This flow pattern is representative for situations in which synoptic low-pressure systems propagate in a direction from the southwest into the Nordic Seas and further into the Arctic. Here, polar lows form in the cold-air outbreaks to the rear of the passing synoptic lows. As the latter are fairly evenly distributed throughout the above-mentioned area, so too are the polar lows (Rasmussen and Turner, 2003).

The February MSLP anomaly is depicted in Figure 7(b). Here, a surface-pressure high prevails over the Scandinavian mainland and northwestern Russia, very much in line with

Table III. Monthly means and highest observed wind speed for the polar-low events between 2000 and 2009.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean (knot)	43.6	40.8	40.1	46.9	35.0	NaN	NaN	NaN	40.0	36.6	44.4	43.3
Max. (knot)	55.0	55.0	53.0	70.0	35.0	NaN	NaN	NaN	40.0	50.0	65.0	52.0

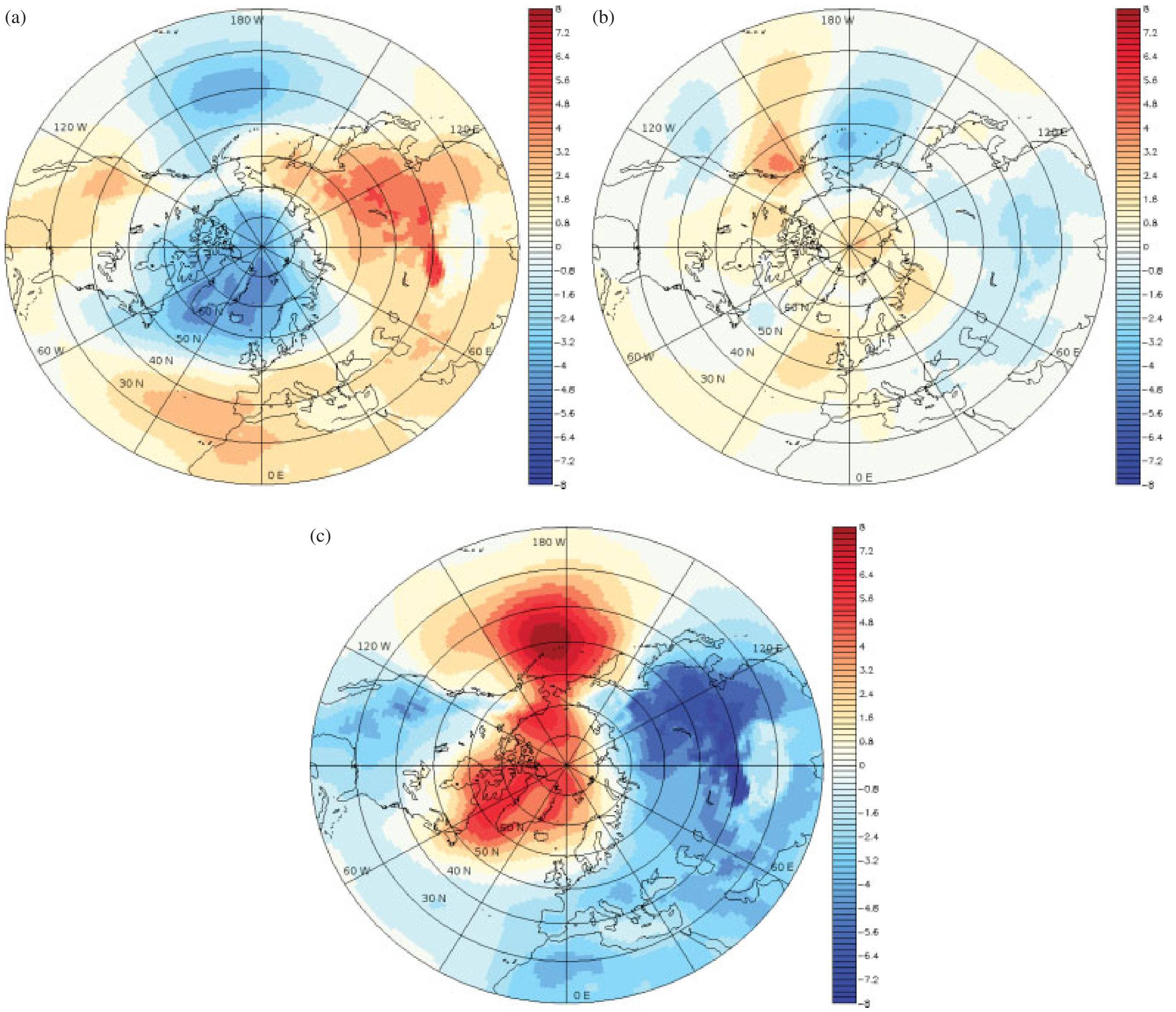

Figure 7. Anomaly from mean MSLP for (a) January, (b) February and (c) March. The mean MSLP is the average of the winter months from December–March for the period between 2000 and 2009.

the hypothesis proposed above. The anticyclonic circulation associated with this pressure distribution yields a weak southerly wind component over most parts of the Nordic Seas, resulting in stable stratification and conditions not favourable for polar-low development.

Figure 7(c) shows the March MSLP anomaly. The results exhibit a rather different pressure anomaly distribution from that found for January, where most of Greenland and the Nordic Seas were subject to a negative anomaly (low pressure). For March, there is a surface-pressure high over Greenland and most of the the Arctic, with a rather pronounced gradient over the Nordic Seas. This pressure distribution gives northerly winds over the ocean areas, in particular along the east coast of Greenland, leading to advection of cold Arctic air southward over the warmer ocean, which is favourable for polar-low formation.

By comparing the results for January and March, one would expect to see differences in the spatial distribution of polar lows for these two months and perhaps more polar lows in the western part of the Nordic Seas than in the eastern part for March. To investigate the storm events observed, January and March are divided into western and eastern polar lows, where the eastern polar lows are those that originate in the Barents Sea. Following the suggestion by Blechschmidt (2008) and Blechschmidt *et al.* (2009), the 15 °E meridian is used to separate eastern and western polar lows. Table IV shows the distribution of eastern and western polar lows for January and March for the period between 2000 and 2009. The two first columns shows the number of events for each area, the third column gives the χ^2 value, while the fourth and fifth columns give the significance level. The significance level has been estimated from a χ^2 test

Table IV. Polar-low events east of 15°E and west of 15°E for January and March, in the period between 2000 and 2009. The corresponding χ^2 and *P*-value are given by a χ^2 test (Wilks, 1995), where the null hypothesis states an equal chance of polar-low formation in the eastern and western parts.

	West of 15°E	East of 15°E	χ^2	P	$(1-P)\times 100\%$
January	15	13	0.14	0.70	30%
March	16	8	2.66	0.10	90%

(Wilks, 1995), commonly used when analyzing the relation between two or more categorical variables. In January a total of 15 western and 13 eastern polar lows are observed, while the corresponding numbers for March are 16 western and 8 eastern polar lows. The higher number of western versus eastern polar lows in March indicates that the large-scale flow pattern for this month favours developments in the Norwegian and Greenland Seas rather than in the Barents Sea. In this respect, January polar lows are more evenly distributed between eastern and western areas. The χ^2 test for equal expected events of western and eastern polar lows gives a significance level of only 10% in March and 70% in January, as shown in Table IV. Thus, at the 90% significance level, we can reject the null hypothesis of equal occurrence of polar lows in the western and eastern parts during March. This supports the hypothesis of more polar lows occurring in the western part in March.

The February minimum has been further analyzed by discriminating between years with three or more events in February and years with fewer than three events. Note that only 2002 and 2009 fall into the first category (see Table I). The average February MSLP anomaly for the two years with three or more events is shown in Figure 8(a), while Figure 8(b) shows the corresponding anomaly for the years with fewer than three events. In the first case (Figure 8(a)), a pronounced negative anomaly over Scandinavia is present, a rather different picture from the average distribution for February found in Figure 7(b). Interestingly, the anomaly for the years with few events in February resembles much more the distribution found in Figure 7(b), with an even more pronounced positive MSLP anomaly over Scandinavia and northwestern Russia. This supports the hypothesis that the tendency for high pressure in this area is the main cause for the observed February minimum.

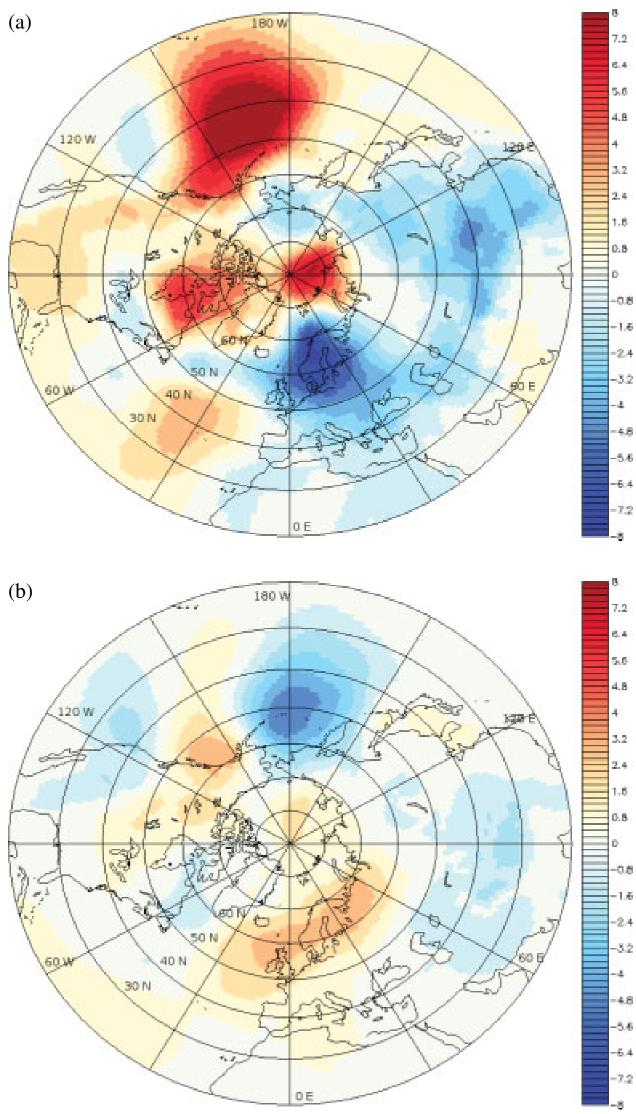

Figure 8. February anomaly from mean MSLP for years with (a) high occurrence of polar lows (three or more events) and (b) low occurrence of polar lows (fewer than three events). The mean MSLP is the average of the winter months from December–March for the period between 2000 and 2009.

5. Summary and conclusions

The main objective of this study has been to revisit the climatological study of polar lows carried out by Wilhelmsen (1985) for the same area, but for a decade in which the coverage by satellite images is vastly improved.

To a large extent this investigation confirms the findings of Wilhelmsen. The geographical areas most affected are similar, but the average number of events per year is higher in this study. In particular, the ocean areas mostly affected by polar lows coincide to a large extent with areas also influenced by warm waters. Along the coast of Norway, the Norwegian Atlantic Current brings warm saline waters into the Arctic, making areas, e.g. around Svalbard, unusually warm for such high latitudes. Wintertime water temperatures of 7 °C just south of Svalbard are not unusual. The large air–sea temperature difference during cold-air outbreaks is likely to promote polar-low development (Saetra *et al.*, 2008; Linders and Saetra, 2010).

Wilhelmsen found an average of seven polar low occurrences per year, while this investigation obtains 12. A reasonable explanation is that the former study did not have the advantage of an almost continuous coverage of infrared satellite imagery, making it more difficult to detect polar lows over the Arctic.

As in the study by Wilhelmsen (1985), a local minimum in February was detected. Interestingly, this February minimum has appeared in other studies as well (Bracegridle and Gray, 2008), both using different methods and covering a larger area. However, deciding whether this is a real feature or an artefact of the natural variability is difficult using statistical tests. If real, one possible physical explanation is that it may be a manifestation of the coldest winter month, when a surface-pressure high over the Scandinavian mainland is common. It is associated with a large-scale atmospheric flow pattern that prevents polar-low formation. Monthly

MSLP anomalies calculated from the ERA-Interim reanalysis reveal a positive anomaly (high pressure) over Scandinavia and northwest Russia in February that is not found in the anomalies for January and March. Further, this high pressure is not present during the years with more than three polar low events in February. This is taken as evidence that there may be a link between the apparent February polar-low minimum and the high pressure commonly observed over parts of Scandinavia during this month.

The observations available so far represent too short a time series for using standard statistical tests to establish the significance level as meaningful. However, judging from the magnitude of the differences between January, February and March compared with the respective standard deviations, it is concluded that the natural variability is much larger than the mean differences and that the results are unlikely to be statistically significant. This does not imply any claim that the February minimum is an artefact, but that longer time series are needed to establish this.

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