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Technical report No. 236
Bergen 2004

POLAR LOWS OVER THE NORWEGIAN SEA: TWO CASE STUDIES

by

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Polar lows over the Norwegian Sea: Two case studies

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ABSTRACT

A modified version of the former operational Norwegian limited area model NORLAM is used to investigate two different situations of polar low development in the Norwegian Sea. The first situation is at the end of February 1984 and the second at the middle of January 1998. We have investigated the mechanisms behind the development of polar lows in the two situations.

In both situations the polar lows were formed in strong baroclinic zones at the surface. In the first situation a series of polar lows were formed downstream of each other as an upper level trough moved rapidly eastwards. In the second situation two polar lows develops: the first one close to the ice border and the second downstream of the first one. Both lows were formed because of an upper level trough coming in from northwest of the surface baroclinic zone.

A series of experiments were performed to test the sensitivity of the simulated polar lows development to various physical processes. The main aim was to find the driving mechanisms for the polar lows, and to look at the differences between the two cases. The latent heat release, in both situations, was important for getting well developed polar lows. In the latest case the surface fluxes were very important for the development and intensification of the polar lows, while for the first case the surface fluxes had almost no effect. Two experiments with changed topography of Iceland for the first situation showed that Iceland had just a small impact on the polar low development.

According to *Businger and Reed's* classification, the polar lows in the first situation are of the short-wave/jet-streak type, while the polar lows in the latest case are of their Arctic-front type, or according to *Grønås and Kvamstø's* classification of the type Arctic outbreak polar lows.

1. INTRODUCTION

Polar lows are intensive small synoptic- to sub synoptic-scale cyclones that develop in the cold air masses north of the polar front. They are accompanied by strong wind and heavy precipitation. Four possible instability mechanisms are suggested to cause the development of these small-scale lows: baroclinic instability, barotropic instability, conditional instability of the second kind (CISK) and air-sea interaction instability (ASII).

Harley (1960) was the first to suggest that baroclinic instability was the reason for polar low development. The early view was that polar lows formed as a result of thermal instability when cold air masses from ice-covered land, flows out over the warm sea. The baroclinic instability theory was later supported by among others *Harrold and Browning* (1969), *Mansfield* (1974), *Duncan* (1977) and *Reed* (1979). *Charney and Eliassen* (1964) introduced the CISK-theory, which later was supported by among others *Rasmussen* (1977) and *Økland* (1977). The CISK-theory explains the polar low growth as a result of an interaction between cumulus convection and the large-scale circulation. *Emanuel and Rotunno* (1989) showed that ASII could explain the development of polar lows if there already existed a disturbance near the ground. *Mullen* (1979) showed that the necessary condition for barotropic instability often is present in polar low development, but barotropic instability alone is not sufficient for the development.

Observations and numerical simulations of polar lows suggest that an upper level trough that moves over a strong baroclinic zone at the surface initiates the polar lows. *Farrell* (1982 and 1984) found, when he considered a polar low development as described above, that when the short-wave trough approaches the surface depression, a tilt in the resulting vertical trough axis produces favorable conditions for a rapid deepening of the surface low, and that the scale of the low is that of the upper level trough.

According to *Businger and Reed* (1979), *Mullen* (1979), *Sardie and Warner* (1983), *Forbes and Lottes* (1985) and *Rasmussen* (1985) polar lows develop in two steps. First the polar lows develop due to baroclinic instability, and then the further development is caused by CISK.

Craig and Cho (1989) found that when polar lows had a spiral-shaped cloud pattern the development was dominated by CISK, while for polar lows with a comma-shaped cloud pattern, the development was caused by baroclinic instability.

Several classification schemes of polar lows have been suggested based on different factors. *Businger and Reed* (1989) based their classification on the baroclinicity, static stability and surface fluxes. They divided the polar lows into three different types: *i)* Short-wave/jet-streak type which is characterized by moderate baroclinicity and relatively weak surface fluxes, *ii)* Arctic front type with strong baroclinicity and strong surface fluxes, and *iii)* Cold-low type characterized by deep convection and strong surface fluxes.

In this paper numerical simulation of two situations of polar low development are studied. The first situation is at the end of February 1984, and the other is at the middle of January 1998. For both situations a set of sensitivity experiments was run in order to study the role of the different instability mechanisms. The paper is organized as follows. In section 2 the synoptic situation for the two situations of polar low development is described. Section 3 gives a description of the numerical model and the sensitivity experiments. In section 4 the evolution of the polar lows in the control runs is described and compared to observations, while section 5 gives the results from the sensitivity experiments. Finally section 6 gives a short summary and conclusions.

2. SYNOPTIC OVERVIEW

2.1 February 1984

The synoptic situation on February 26th 1984 at 12 UTC in the Icelandic region and the surface conditions in February 1984 is shown in Figure 1. The situation is characterized by a synoptic-scale low (L1) centered in the Denmark Strait, with a 500hPa trough centered over southeastern Greenland. In connection to this low a cold front extends southwestwards across Iceland leaving a strong baroclinic zone north of Iceland. At the ground the low-pressure system remains almost stationary during the following 24 hours, while the 500hPa trough moves eastwards. As the trough axis approaches a vertical direction, the synoptic-scale low weakens and dies out.

During the Arctic Cyclone Expedition in February 1984, the first research aircraft measurements within a polar low were carried out. This polar low is one of the polar lows investigated here. Observations from the research aircraft documented the three-dimensional distribution of wind, temperature, moisture, and precipitation within the polar low (*Shapiro et al.*, 1987). Figure 2 shows the surface pressure analysis at 13.40 UTC and the wind vectors at flight level between 12.21 and 16.10 UTC on February 27th 1984. The polar low is centered about 69°N and 3°W, and at the surface the central pressure is 979hPa. Wind maximum occurs northwest and south of the polar low, were the speed is more than 30m/s.

Figure 3 shows sketches of the key cloud features based on satellite imageries over the time period from 05.18 to 18.23 UTC on February 27th 1984 made by *Shapiro et al.* (1987). At 05.18 UTC there are three cyclonic cloud patterns in the Norwegian Sea, one in the Denmark Strait (system 1) and two northeast of Iceland, close to Jan Mayen (system 2 and 3). During the following 5 hours system 1 decays, while system 2 and 3 expand in area. Between 10.05 and 13.40 UTC system 2 dissipates, while system 3 forms a cloud free inner eye. From 13.40 to 15.24 UTC system 3 expands in size, and a new cyclonic cloud system (system 4) develops to the east of system 3. At 18.23 UTC there is an indication of a new cloud system (system 5) developing to the east of system 4.

2.2 January 1998

The synoptic situation on January 17th 1998 at 00 UTC in the Norwegian Sea is characterized by a synoptic-scale low located north of Norway at 72°N and 27°E, with a secondary low centered west of Bodø at 66°N and 12°E (Figure 4, top). In Figure 4 (bottom) om fargane??? the surface conditions (sea surface temperature, snow and ice cover) is shown. Over Greenland there is a high-pressure region, which remains almost stationary throughout the following 36 hours, while the synoptic low moves northeastwards and its pressure remains almost constant. East of Greenland, at about 70°N and 0°E there is a 500hPa-level trough. This synoptic situation gives wind from the cold ice masses out over the warm Norwegian Sea. This advection forms a baroclinic zone near the ice edge.

Figure 5a show a satellite image from January 17th 1998 at 07:38 UTC, a comma pattern shaped cloud pattern can be clearly seen east of Jan Mayen. From *Craig and Cho*'s finding this tells us that this polar low is dominated by baroclinic instability. Figure 5b show a satellite picture from January 17th 1998 at 17:27 UTC. The comma pattern is more developed and more extended and there is a cloud free inner core at about 68°N and 4°W. The cloud pattern has moved southward the last 10 hours. The picture from January 18th 1998 at 03:52 UTC (Figure 5c) shows that the cloud pattern has moved further southeast. The pattern is clearly more mature, and it has become more spiral shaped. We can see the cloud free core at about 65°N and 0°E.

3. MODEL DESCRIPTION AND EXPERIMENT DESIGN

The model employed here is a modified version of the former operational Norwegian limited area model NORLAM (*Grønås and Hellevik*, 1982; *Nordeng*, 1986; *Grønås et al.*, 1987). The modification is that the cloud and condensation scheme is replaced by the Sundqvist condensation scheme, allowing a prognostic evaluation of the cloud water (*Sundqvist et al.*, 1989; *Kvamstø*, 1992).

We have used 25km horizontal resolution, and there are 30 σ-levels between the surface and the top of atmosphere, which lies at 100hPa. The model domains for the two polar low situations are shown in Figure 6. The initial and boundary conditions are reanalyzes from the European Centre of Medium-Range Weather Forecasts in England, while the surface conditions (Figure 7)??? are from the Norwegian Meteorological Institute. The simulations in the first situation are for a period of 30 hours starting at 12 UTC on February 26th 1984, while for the second situation the simulations are for a period of 36 hours, starting at 00 UTC on January 17th 1998.

For both situations a set of numerical simulations with different surface parameters was run in addition to a control run, in order to study the importance of different instability mechanisms.

For the situation in February 1984 two simulations with changed topography of Iceland was made to investigate if Iceland had any effect on the development of the first polar low in this situation. In the first simulation (NIL84) the height of Iceland was reduced to sea level and the surface type was changed to ocean, while in the second simulation (DIL84) the height of Iceland was doubled at each grid cell. A simulation (NLH84) without latent heat release was made in order to study how important this heat release is on the development of the polar lows. To study the importance of the sensible and latent heat fluxes, one simulation with enhanced sea surface temperature (EST84) and one simulation with changed ice cover (ICC84) were made. In the EST84 experiment the SST was increased by 3°C from about 66 to 69°N and from 6 to 21°W. This area was chosen because the first polar low passes across this area after it has developed north of Iceland. In the ICC84 experiment the ice cover along the eastern cost of Greenland, between Iceland and Jan Mayen, was extended 600km further into the Norwegian Sea, and the SST was reduced in the same area to get a more realistic SST-gradient.

For the situation in January 1998 almost the same experiments were conducted. In the first experiment, NLH98, a simulation without latent heat release was made for the same purpose as in the first situation. In the EST98 run the temperature in the region where the polar lows developed and moved over is increased with 4°C, the region extends from 60°N to 70°N and from Iceland to Norway. In the DST98 experiment the SST was decreased by 4°C in the same area as it was increased in the EST98 run. In the IIC98 run the ice edge in the Norwegian Sea was extended 450km further east and the SST was adjusted to the new ice cover. In the RIC98 experiment the ice edge east of Greenland was straitened, which gave less sea ice in the

Norwegian Sea, and the SST was again adjusted. Figure 4 shows the different ice covers, the gray region shows the ice cover fore IIC98, the light gray region is from the control run and the solid line outside the others is the RIC98 case. These changes in ice cover tell us also about the importance of sensible and latent heat fluxes. From the straitening of the ice edge we can see if the polar low development is affected by the shape of the ice. A list of all the numerical experiments is shown in Table 1.

Table 1. Summary of the numerical experiments.

Name	Description	Name	Description
Situation 1 Initialized at 12 UTC February 26th 1984		*Situation 2* Initialized at 00 UTC January 17th 1998	
CNR84	Control run	CNR98	Control run
NIL84	Iceland replaced by ocean	NLH98	No latent heat
DIL84	Doubled height on Iceland	EST98	Enhanced SST west of Norway
NLH84	No latent heat	DST98	Decreased SST west of Norway
EST84	Enhanced SST east of Iceland	RIC98	Reduced ice cover
IIC84	Increased ice cover	IIC98	Increased ice cover

4. EVOLUTION OF THE POLAR LOWS

4.1 February 1984

The developments of the polar lows in February 1984 are shown in Figure 8. After 6 hours simulation, a mesoscale low-level trough developed north of Iceland, to the east of the upper-level trough, in a strong baroclinic zone connected to a cold front. During the following 6 hours the surface trough moves northeast-wards and develops into a polar low (L2). After 12 hours simulation this polar low is located at 68°N and 12°W and it has a central pressure of 998hPa at the surface. The strongest wind is found south of the polar low, where the wind speed is 17m/s. During the same time the 500hPa trough has caught up with L1, and the condition for further deepening of this low due to baroclinic instability is no longer favorable and it starts to fill. L2, which still lies to the east of the 500hPa trough, moves northeastwards and deepens during the following 12 hours.

A vertical cross-section through both L2 at the surface and the 500hPa trough after 18 hours simulation is shown in Figure 9. L2 lies in a strong baroclinic zone at about 69°N and 8°W. Above L2 there is very weak static stability up to about 550hPa. The upper-level trough, shown as a positive anomaly in potential vorticity, is located to the west of L2. Here the tropopause, defined as the level of 2 PVU (*Grønås and*

Kvamstø, 1994), extends down to 700hPa. West of L2 is an area with strong upward motion. The strongest vertical motion is found at 700hPa, where ω is less than -0.07hPa/s which correspond to a vertical motion of more than 71cm/s.

L2 reaches its most developed stage after 24 hours simulation with a central pressure of 988hPa. The wind speed has now become more than 24m/s both north and south of the polar low. At this time the 500hPa trough has overtaken this low, and a new polar low (L3), with a central pressure of 988hPa at the surface after 24 hours simulation, has developed downstream of the 500hPa trough, to the east of L2. L3 reaches its most develops stage after 26 hours simulation. At this time the central pressure at the surface is 987hPa and the wind speed is 26m/s northwest of this low. During the following hours both L2 and L3 dies out as the 500hPa trough catch up with these lows, and another polar low (L4) develop downstream of it. After 30 hours simulation L4 is located at 71°N and 10°E and the central pressure is 995hPa. The strongest wind of 25m/s is found southwest of this low. To the east of L4 there is a surface trough, most likely the first indication of a new polar low development downstream of the 500hPa trough.

Because there were no conventional meteorological observations over the Norwegian Sea at the time the polar lows developed, such observations cannot be used to verify the model. Satellite images have therefore become a very important tool for verifying models. By comparing the development of the polar lows in this simulation with the sketch of the key cloud features in the Norwegian Sea based on satellite images made by *Shapiro et al.* (1987), a very good agreement between the polar low developments was found. The model succeeded to develop all the polar lows that was found from the satellite imageries.

During the ACE-project aircraft measurements of a polar low was carried out (*Shapiro et al.*, 1987). This polar low is the same low as L3 in our simulation. By comparing the aircraft measurements from 13.40 UTC on February 27th with the results from our simulation at 14.00 UTC the same day, the polar low was lying about 100km further north in the simulation and the pressure in the center was 8hPa higher than the observed. Maximum wind speed was found northwest and south of the low as observed, but the wind speed was 5 to 10m/s lower in the simulation.

<u>*4.2 January 1998*</u>

Figure 4 shows the synoptic conditions at 00 UTC January 17th 1998. There is a high-pressure region over Greenland and a synoptic scale low centered north of Norway. This low moves slightly northeast during the simulation period. East of Greenland, at about 70°N and 0°E there is a 500hPa-level trough. The location of the high and low-pressure areas makes a sharp pressure gradient in the Norwegian Sea, just east of the 500hPa trough. The 500hPa trough moves southeast and enhances during the simulations.

During the following 6 hours a surface trough (TR1) develops in both pressure and temperature at about 71°N and 1°E (Figure 10a). This trough develops in a region with sharp pressure gradients and enhanced baroclinicity east of Jan Mayen. The height field trough located northwest of the surface trough at 70°N, 11°W, can also be seen at this time.

After 12 hours simulation TR1 has developed into a polar low (PL1) and it is located at 69°N and 1°W (Figure 10b). The central pressure of PL1 is 1001.5hPa and the wind maximum near the polar low is 27.5m/s. The trough in 500hPa is still sited northeast of the surface polar low, but it is deeper and closer to PL1. Another surface trough (TR2) has developed southeast of PL1 at 67°N and 4°E. This trough is affected by the same 500hPa trough northeast of the surface disturbances. From Figure 11a it is clear that there are two disturbances both in the upper levels and at the surface. The slantwise trough axis (between the surface trough and the upper level PV-trough) is flavorous for an up-spinning of PL1 and TR2. There is also ascending air over both PL1 and TR2, but the ascent near TR2 is strongest. Northwest of PL1 the Arctic Front is seen; this is a typical situation in favor of development of polar lows of the Arctic outbreak polar low type (*Grønås and Kvamstø,* 1994).

After 18 hours simulation PL1 has a pressure of 997hPa and it has moved southeast. Now PL1 starts to decrease and it dies out after 24 hours simulation. Through the last 6 hours TR2 has developed to PL2, its pressure is 995hPa (Figure 10c). In the height field, at 500hPa, there is also developed a closed low. This upper-level low is positioned northeast of the two polar lows, relatively close to PL1. There is now two polar lows in an area of about 200 km. These systems have to affect each other and it is likely that one will develop at the cost of the other. Six hours later PL2 has deepened further to 988hPa, has a wind maximum of 35m/s and is a well-developed polar low, Figure 10d. PL2 has moved southeast during the last 6 hours and has a well-developed cold front. The height disturbance is situated almost over the surface disturbance, but we can see that there is a new upper level disturbance west of the surface low.

Six hours later PL2 has almost reached the Norwegian coast and the pressure in the center is 985hPa (Figure 10e). The polar low has moved quite far in the last 6 hours, it is now located at 64°N, 4°E, this is 170 km southeast of the position 6 hours earlier. The disturbance in the height field has also evolved and it is positioned northwest of PL2. Figure 11b shows that the new PV-anomaly also has caught up with the surface low and it is situated straight over the surface disturbance. The polar low is mature and it is likely that PL2 will weaken and finally die out because the upper level anomaly has caught up with it. The only possibility for further intensification is that the surface disturbance locks on to one of the new PV-anomalies coming in from northwest, and in that way give a new up spinning.

After 36 hours simulation PL2 has a pressure of 983hPa (Figure 10f). The height disturbance is positioned almost directly over the surface disturbance. PL2 has reached the Norwegian coast and the PV-anomaly has passed the surface low.

In the area where the polar lows develops there is almost no observations. But at 62°N and 2°E the vessel Polarfront was positioned in the period when the polar low passed. When the pressure at Polarfront

Figur 12 viser…. and the simulated pressure at the same point are compared we find a great similarity. (Her komme det ein figure til!)The simulated pressure is mainly 2hPa less than the observed pressure, but the pressure follows the same curve. The position of the polar lows in the simulation and in the satellite pictures agree well, the only difference we can point out is that the simulated lows often are positioned slightly to the east of the observed lows. In the period from 17.27 UTC January 17th to 02.11 UTC January 18th there are no satellite pictures from the area, this is the time when there mainly are two polar lows, so it is impossible to say if there really was two polar lows or just one.

5. RESULTS OF THE SENSITIVITY EXPERIMENTS

5.1 February 1984

For this situation every change in the surface conditions is done in close connection to L2, therefore it is just the pressure in the center of L2 that is shown for the different sensitivity experiments (Figure 12). There are no changes at 500hPa between the control run and the sensitivity experiments, every change is close to the surface.

In the experiment with Iceland replaced by ocean (NIL84) L2 moves further north than in the control run (Figure 13) and the pressure in the center is about 3hPa lower. After 18 hours simulation this low turns southwards and is located 100km northeast of Iceland after 24 hours simulation. At the same time the pressure in the center of the low is 5hPa higher than in the control run. The reason for that L2 starts to fill much earlier in this experiment is that L2 lies further west and the 500hPa trough passes over this surface low much earlier than in the control run, then L2 cannot longer be intensified by baroclinic instability and weakens. L3 develops at the same time and place as in the control run, but the pressure in the center is 1hPa higher. L4 develops after 26 hours simulation, one hour earlier than in the control run. After 30 hours simulation this low lies about 100km west of L4 in the control run and the pressure is 2hPa higher.

In the simulation with higher topography on Iceland (DIL84) L2 moves further south (Figure 13) and the pressure in the center is between 1 and 2hPa higher. L3 develops at the same time as in the control run, but it is located about 100km east-southeast of its position in the control run. The pressure is 1hPa higher in the center of the polar low. In this simulation L3 does not die out as in the control run, but moves northeastwards and intensifies. After 30 hours simulation L3 lies at the same place as L4 in the control run, and the pressure in the center is 982hPa.

In the NLH84 experiment without latent heat release, a surface trough develops north of Iceland after 9 hours simulation, 3 hours later than in the control run. After 12 hours simulation this surface trough has developed into a polar low (L2) which is located at the same place as in the control run and with a central pressure of 1001hPa, 3hPa higher. During the following 12 hours L2 continues to move northeastwards and is located about 100km east-southeast of its position in the control run. The pressure in the center is between

4 and 5hPa higher than in the control run. In this simulation L2 does not die out as it does in the control run, but moves eastwards and deepens. After 30 hours simulation this low is located at 69°N and 1°E and it has a central pressure of 991hPa at the surface. A surface trough develops to the east of L2 after 16 hours simulation, 5 hours earlier than in the control run. This trough develops further into a polar low (L3), which after 18 hours simulation is located at 71°N and 6°W and it has a central pressure of 996hPa. L3 moves northeastwards during the following hours and after 24 hours simulation this low lies a few tens of kilometers north of its position in the control run. The pressure in the center is 4hPa higher. L3 moves eastwards the following 6 hours and is located at the same place as L4 in the control run, and the central pressure is 990hPa at the surface.

In the experiment with higher sea surface temperature northeast of Iceland (EST84) the pressure in the center of L2 and L3 are between 1 and 2hPa lower than in the control run. The most pronounced difference between the EST84 experiment and the control run is after 30 hours simulation. After L4 has developed to the east of L3, L3 does not start to fill as in the control run, but moves southwards. After 30 hours simulation L3 lies at 69°N and 3°W and it has a central pressure of 987hPa.

There are no differences between the simulation with increased ice cover (IIC84) and the control run before 18 hours simulation, when L2 has passed over the ice-covered ocean since it developed north of Iceland. The pressure in the center of L2 and L3 are between 1 and 2hPa higher than in the control simulation. L4 develops at the same place as in the control run, but this is located in a strong baroclinic zone just outside the ice-covered ocean in this experiment. After 30 hours simulation the central pressure in L4 is 993hPa, 2hPa lower than in the control run.

5.2 January 1998

For this situation most of the changes in the initial conditions were made in close connection to the two polar lows. It is just in connection to the polar lows that the changes make a significant difference between the control run and the sensitivity runs. This is why just the polar lows are discussed here.

Når TR1??? In the experiment without latent heat release (NLH98) the development of TR1 starts later than in the control run. A polar low first develops after 15 hours simulation, three hours later than in the control run. The trough develops almost at the same place as in the control run and in the first part of the simulation they move similarly. After 24 hours simulation PL1 in NLH98 is much further south than PL1 in the control run. This polar low is at this time a closed low with a central pressure of 998hPa (see Figure 14a), and it does not disappear through the simulations like PL1 does in the control run. After 30 hours simulation PL1 in NLH98 is positioned almost at the same place as PL2 in the control run. PL2 in NLH98 also develops later than PL2 in the control run. After 24 hours simulation PL2 in NLH98 is situated 250 km east of the same low in CNR98. PL2 in NLH98 is less developed than PL2 in the control run; the maximum pressure difference between they is 8hPa. Through the entire simulation the pressure in the NLH98 is higher than in the control run and the polar lows are less developed. For PL2 the difference is largest, 13.5hPa, after 36 hours simulation (Figure 14a).

After 12 hours simulation in the EST98 (increased SST west of Norway) run there is a closed polar low (PL1), 1hPa deeper than PL1 in the control run. There has also been developed a trough, TR2. After 18 hours simulation PL1 in EST98 is much deeper than PL1 in the control run. PL2 is a closed low, see Figure 14a. Through the simulations with enhanced SST the polar lows are much deeper than the polar lows in the control run (Figure 14a and b). Greatest difference is after 33 hours simulation where PL1 is 10.5hPa deeper than in the control run, and for PL2 after 30 hours simulation where it is 8.5hPa deeper than in the control run. The polar low positions are also changed, after 24 hours simulation PL1 is positioned further southwest than PL1 in CNR98, while PL2 in EST98 is positioned slightly northeast of PL2.

In the decreased SST west of Norway (DST98) run PL1 just exist for 8 hours and the entire time the centre pressure is about 4hPa higher than PL1 in the control run. After 24 hours simulation the pressure in the center of PL2 in DST98 run is 4hPa higher than in the control run. The low is also positioned southwest of PL2 in the control run, Figure 10b. The pressure of the polar lows in DST98 is through out the simulations higher than the pressure in the control run. The greatest difference is after 36 hours simulation where PL2 in the control run is 7.5hPa deeper than PL2 in DST98.

When we increase the ice cover (IIC98), the ice cover the area where PL1 forms in CNR98, see the dark grey Figure 4 (bottom). This leads to no formation of PL1 in this run, we just get a weak trough. PL2 in IIC98 develops at the same place as in the control run; this is expected since it is developed far from the ice edge. After 24 hours simulation PL2 is positioned south of PL2 in the control run and the pressure is 3hPa higher. From Figure 14b it is seen that the pressure in these two runs are almost the same.

After 24 hours simulation PL1's position in the reduced ice cover (RIC98, white in Figure 4, bottom) run is much further southwest than PL1 in the control run, PL2's position in the two runs is almost at the same place and there is only 1hPa in pressure difference. (See Figure 4 for changes in ice cover). This is as expected since PL2 is developed far away from the ice edge. It can be seen from Figure 14a that PL1 in RIC98 and in the control run follow the same pattern, but PL1 in the control run is at all times 0.5 to 2hPa deeper than PL1 is in RIC98. From Figure 14b it is seen that there are almost no pressure difference between the two runs, but after 24 hours simulation and further, the pressure is 1.5hPa deeper in the control run than in RIC98.

6. DISCUSSION AND CONCLUSIONS

In this paper a modified version of the former operational Norwegian limited area model was used to investigate two situations of polar low development.

The synoptic situation on February 26th 1984 at 12 UTC in the Icelandic region was characterized by a synoptic scale low in the Denmark Strait, with a 500hPa trough centered over southern Greenland. The surface low-pressure system remained almost stationary during the next 24 hours, while the 500hPa trough moved rapidly eastwards. A surface trough, which later developed into a polar low, developed in a strong baroclinic zone north of Iceland after 6 hours simulation. The 500hPa trough did not lock on to this polar low, but moved eastward. During the next 18 hours, series of polar lows developed downstream of the previous one, as the upper level trough moved rapidly eastwards.

In the first situation all the mesoscale lows seemed to be initiated at low levels by baroclinic instability. The static stability in the lower troposphere (below 700hPa) was very low, which implies that the preferred scale for the most unstable waves was small (mesoscale), whereas the scale of the upper-level waves, where the static stability was much stronger, was synoptic. The condition for phase locking of the upper and the lower waves was thus not favourable, with the result that the upper-level waves moved faster than the lower-level waves. The most favourable position of the lower-level wave, with respect to baroclinic growth, is just downstream of the upper-level trough. When the upper-level trough, due to its greater speed, overtook the lower-level wave, the lower-level wave did not grow any more, and gradually died out. The condition was then favourable for the initiation, due to baroclinic instability, of a new lower-level mesoscale wave downstream of the upper-level trough. In this way a series of low-level mesoscale waves (lows) formed and developed downstream of the fast-moving upper-level trough.

The synoptic situation on January 17th 1998 at 00 UTC in the Norwegian Sea was characterized by a high pressure region over Greenland and a synoptic-scale low north of Norway, with a secondary low over the ocean west of Bodø. A 500hPa-level trough was located above the ocean east of Greenland. The low-pressure system remained almost stationary during the next 36 hours, while the 500hPa trough moved southeast and strengthened. The first polar low developed in a strong baroclinic zone just south of the ice edge in the Norwegian Sea after 12 hours simulation. The 500hPa trough did not lock on to the polar low and 6 hours later a new polar low developed. This new low dominated the situation and the first polar low died out after 24 hours simulation. The 500hPa trough locked on to PL2 and spun it up for about 12 hours. After 30 hours simulation the 500hPa anomaly caught up with the polar low that started to fill.

In the experiment without latent heat release, the polar lows were less intensive. This indicates that the latent heat release was important for the development of the polar lows, but also that the polar lows developed even without latent heat release. This result is in good agreement with the result from similar sensitivity experiment made by e.g. *Albright et al.* (1995), *Blier* (1996) and *Bresch et al.* (1997).

An enhanced sea surface temperature had just a small impact on the polar low development in February 1984, while it had a large impact on the polar lows in January 1998, where the latter is constituent with the results from *Albright et al.* (1995) and *Blier* (1996). In both situations the surface fluxes of latent and sensible heat were stronger in these experiments than in the control runs (in total about 200W/m^2 higher for the polar low situation in February 1984 and about 450W/m^2 in January 1998).

An experiment with decreased sea surface temperature was only conducted for the polar low situation in January 1998. In this situation the surface fluxes were together about 300W/m^2 lower than in the control run. The polar lows in this experiment were much shallower and the first polar low died out much earlier than in the control run. This and the previous experiment shows that the surface fluxes from open ocean was very important for the polar lows that developed in January 1998. In this situation the stronger surface wind in the enhanced SST experiment, with a maximum of 43m/s compared to 35m/s in the control run, shows that there could have been a feedback mechanism between the surface fluxes and the wind speed, which contributes to the up-spinning of the polar lows (*Albright et al*., 1995).

For the situation in February 1984 an experiment with ice covered ocean north and northwest of Iceland was conducted. This experiment corresponds to an experiment without surface fluxes, since the polar low moved over ice-covered ocean, where the surface fluxes was very weak (about 30W/m^2), throughout its lifetime. In this experiment the polar low was almost as intensive as in the control run. Similar experiments have been made by *Albright et al*. (1995), *Blier* (1996) and *Bresch et al.* (1997). In their experiments the polar low either failed to develop or was much less intensive compared to the control run. The result from this experiment and the experiment with enhanced sea surface temperature, show that the surface fluxes was not very important for the polar low development here.

Two experiments with changed ice edge were made for the situation in January 1998. A straitening of the ice edge, which also led to less sea ice along the Greenland east coast northeast of Jan Mayen, had only a minor effect on the polar low developments as discovered in the polar low situations in *Albright et al*., 1995 and *Bresch et al.*, 1997. In the other experiment the ice edge was moved further east which led to more sea ice northeast of Jan Mayen. In this simulation the first polar low failed to develop because the region where the polar low developed in the control run was covered with sea ice in this experiment. This tells us that the 500hPa trough was not sufficient to develop polar lows with out surface fluxes and strong baroclinicity. The second polar low developed far from the ice edge and was not specially affected by the changed ice edge.

For the first situation (February 1984) two sensitivity experiments with changed topography of Iceland were made to see if Iceland had an important role for the first polar low development in this situation. The result of these experiments showed that Iceland had just a small impact on the polar low development. In the experiment with Iceland replaced by ocean the pressure in the center of the polar low was slightly lower, while in the experiment with double height on Iceland, the central pressure was slightly higher. This was probably caused by respectively higher and lower surface fluxes where the polar low developed in these situations compared to the control run. A changed wind field over Iceland when the topography was changed caused a difference in the tracks of the polar lows.

The sensitivity experiments showed that the polar lows in both situations developed due to baroclinic instability when an upper level trough moved over a baroclinic zone at the surface. For the situation in February 1984 the surface fluxes had just a minor role in the further development, which is absolutely not the case for the other polar low situation. According to Businger and Reed's classification (*Businger and Reed*, 1969) the polar lows in the first situation must therefore be of the short-wave/jet-streak type, while the polar lows in the second situation are of the Arctic front type or an Artic outbreak polar low according to *Grønås and Kvamstø* (1994).

REFERENCES

Albright, M. D., R. J. Reed and D. Ovens (1995). Origin and structure of a numerically simulated polar low over Hudson Bay. *Tellus*, **47A**, 834-848.

Blier, W. (1996). A numerical modeling investigation of a case of polar airstream cyclogenesis over the Gulf of Alaska. *Mon. Wea. Rev*., **124**, 2703-2725.

Bresch, J. F., R. J. Reed and M. D. Albright (1997). A polar low development over the Bering Sea: Analysis, numerical simulation and sensitivity experiments. *Mon. Wea. Rev*., **125**, 3109-3130.

Businger, S. and R. J. Reed (1989). Polar lows, in 'Polar and Arctic lows', *A. Deepak publishing,* 3-46.

Charney, J. and A. Eliassen (1964). On the growth of hurricane depression. *J. Atmos. Sci.,* **21**, 68-75.

Craig, G. and H.-R. Cho (1989). Baroclinic instability and CISK as the driving mechanisms for polar lows and comma clouds. Polar lows, in 'Polar and Arctic lows', *A. Deepak publishing*, 131-140.

Duncan, C. N. (1977). A numerical investigation on polar lows. *Quart. J. Roy. Meteor. Soc.,* **103**, 255-268.

Emanuel, K. A. and R. Rotunno (1989). Polar lows as Arctic hurricanes. *Tellus,* **41A**, 1-17.

Farrell, B. (1982). The initial growth of disturbances in a baroclinic flow. *J. Atmos. Sci.,* **39**, 1663-1686.

Farrell, B. (1984). Modal and nonmodal baroclinic waves. *J. Atmos. Sci.*, **41**, 668-673.

Forbes, G. and W. Lottes (1985). Classification of mesoscale vortices in polar airstream and the influence of the large-scale environment of their evolutions. *Tellus,* **37A**, 132-155.

Grønås, S. and O. Hellevik (1982). A limited area prediction model at the Norwegian Meteorological Institute. *Technical Report*, The Norwegian Meteorological Institute, Oslo, Norway.

Grønås, S., A. Foss and M. Lystad (1987). Numerical simulations of polar lows in the Norwegian Sea. *Tellus*, **39A**, 334-353.

Grønås, S. and N. G. Kvamstø (1994). Numerical simulations of the synoptic conditions and development of Arctic outbreak polar lows. *Tellus,* **47A**, 797-814.

Harley, D. (1960). Frontal contour analysis of a "polar low", *Met. Mag*., **89**, 141-147.

Harrold, T. W. and K. A. Browning (1969). The polar low as a baroclinic disturbance. *Quart. J. Roy. Meteor. Soc.*, **95**, 710-723.

Kvamstø, N. G. (1992). Implementing the Sundqvist scheme in the Norwegian limited area model. *Met. Rep. Ser.,* **2**, Geophysical Institute, University of Bergen, Norway.

Mansfield, D. A. (1974). Polar lows. The development of baroclinic disturbances in cold air outbreaks. *Quart. J. Roy. Meteor. Soc.,* **100**, 541-554.

Mullen, S. E. (1979). An investigation of small synoptic-scale cyclones in polar air streams. *Mon. Wea. Rev.,* **107**, 1636-1647.

Nordeng, T. E. (1986). Parameterization of physical processes in a three dimensional numerical weather prediction model. *Technical Report*, The Norwegian Meteorological Institute, Oslo, Norway.

Rasmussen, E. A. (1977). The polar low as a CISK phenomenon. *Rep. No.,* **6**, 77 pp.

Rasmussen, E. A. (1985). A case study of a polar low development over the Barents Sea. *Tellus,* **37A**, 407-418.

Reed, R. J. (1979). Cyclogenesis in polar air streams. *Mon. Wea. Rev.,* **107**, 38-52.

Sardie, J. M. and T. T. Warner (1983). On the mechanism for the development of polar lows. *J. Atmos. Sci.*, **40**, 869-881.

Shapiro, M. A., L. S. Fedor and T. Hampel (1987). Research aircraft measurements of a polar low over the Norwegian Sea. *Tellus*, **39A**, 272-306.

Sundqvist, H., E. Berge and J.E. Kristjansson (1989). Condensation and cloud parameterization studies with a mesoscale numerical weather prediction model. *Mon. Wea. Rev.*, **117**, 1641-1657.

Økland, H. (1977). On the intensification of small-scale cyclones formed in very cold air masses heated over the Ocean. *Inst. Rep. Ser.*, **26**, Geophysical Institute, University of Oslo, Norway. 25 pp.