Sensitivity of Mesoscale Weather Systems Near Ice-edge to the Surface Conditions : Investigation in WRF

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Introduction:

The earliest research into severe mesoscale weather systems in the Arctic goes back to 1950s and since then there have been numerous studies about the structure and dynamics of severe Arctic weather. To mention a few, Sanders, 1955; Harrold and Browning,1969; Rabbe, 1987; Grønås et al, 1987; Shapiro et al, 1987; Grønås and Skeie, 1999. The advection of cold and stable air mass from the ice sheet into relatively warm, open water of the Norwegian or the Barents seas, popularly termed as Marine Cold-air Outbreak (MCAO), has been regarded as the major cause for the Arctic extreme events. MCAOs are mostly observed during the winter and are characterized by large magnitude of air-sea heat fluxes and development of convective boundary layer further downstream (Brummer 1996).

Apart from the terrain induced features, extreme weather events in the Arctic region can be categorized into Arctic fronts (AF) and polar lows (PL). Being a shallow lower-level feature, an Arctic front separates the cold, stable Arctic air mass and warm, unstable marine airmass with sharp temperature and moisture discontinuities across. Most of the AFs are associated with a low-level mean flow being north-easterly and opposite to the thermal wind (Kolstad and Bracegirdle, 2008). The winds in the frontal zone are very strong and can reach hurricane force and cause innumerable accidents (Grønås and Skeie, 1999). The second category in the Arctic extreme weather are the mesoscale cyclones called Polar lows which often form in relation to AF. These vortices develop in the cold-air outbreak when an upper-level potential vorticity anomaly is coupled with the lower-level vortices.

In this study, we present a case observed during the IPY-THORPEX field campaign (www.ipy-thorpex.com) conducted during February-March 2008. Most of the features, that are supposed to be present for the development of a polar low, were seen on this day. However, the polar low did not develop. The reasons for this are investigated here.

The approach:

The case recorded on the 1st of March had a low-level baroclinic front formed as cold and stable Arctic air advected over to the ice-free and relatively warm sea-water. A vortex had formed on the front. This baroclinic development is simulated in Weather Research and Forecast model (WRF) and is considered as the control run (called CNTL hereafter). In order to identify which mechanisms suppressed spinning up the disturbance to a PL, we have made model sensitivity experiments removing the sea ice, removing the Spitsbergen terrain and increasing sea surface temperature (SST) by 5 K.

Model simulation set-up:

WRF model has been used. The model is hydrostatic and has terrain-following eta levels in the vertical. WRF single-moment 3-class (WSM-3) microphysics (Hong et al 2004; Dudhia 1989) has been used to include 3 hydrometers: water vapour, cloud water/ice and rain/snow. Parameterizations of sub-grid scale convective and cloud processes are accounted for by the Kain-Fritsch scheme (Kain and Fritsch 1990; Kain and Fritsch 1993). The surface layer parameterizations follow Paulson 1970; Beljaars 1994; Zhang and Anthes 1982. The boundary layer scheme used in the model is described in Hong and Pan 1996.

The grid-length in the model domain is 9x9 km. The model resolves 51 eta levels. All the experiments are initiated at 00 UTC 29th February 2008.

Results:

Control run:

Figure 1 shows the satellite image of the AF taken by NOAA-4, at 12 UTC on the 29th of February 2008. The surface wind speed was around 15 ms^{-1} as measured by ASCAT and QuickSCAT at 25 km resolution. The surface analysis (blue curve and the green indicator) indicate the occlusion in the front and the high probability for the snowfall along the front. Dense cloud streets behind the front imply the advection of cold-air from the Arctic ice-cap. Mean sea level pressure pattern simulated by WRF at the same time shows the vortex that was formed at the surface.

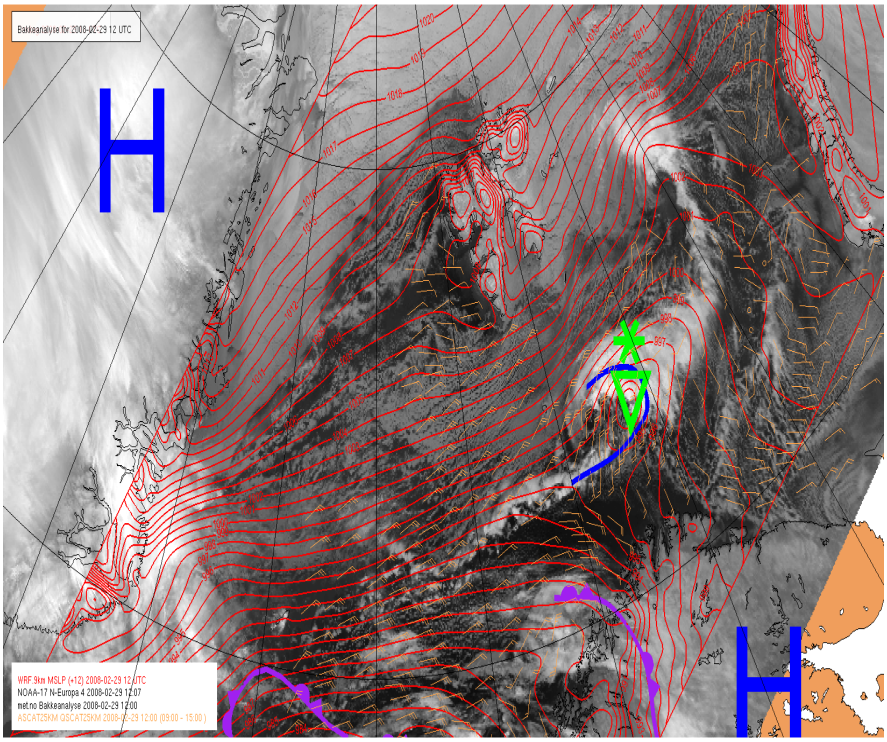
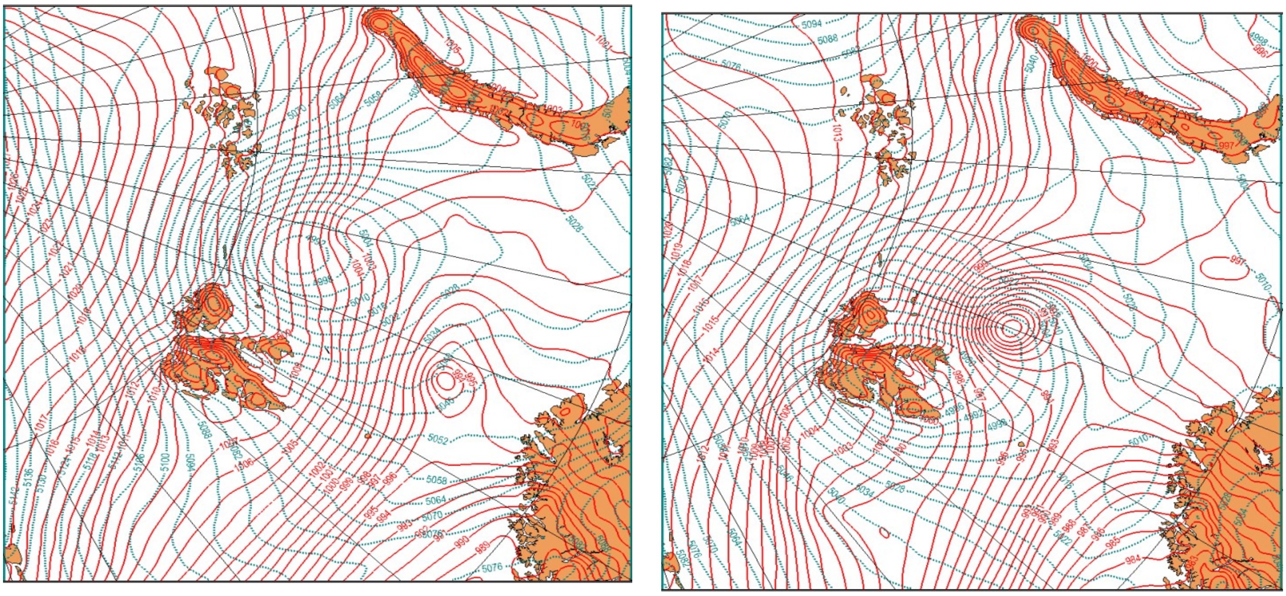


Figure 1. NOAA image, at 12 UTC on 29th February 2008, showing the AF. Surface winds measured by ASCAT and QuickSCAT are shown in the form of wind barbs. Red contours indicate model simulated sea-level pressure patten. Green symbol and the blue curve are the surface analyses.

The strong baroclinicity seen on the 29th of February was associated with a low-level reverse shear flow (where the mean flow is opposite to the direction of the thermal wind) as indicated by the strong northeasterly flow that brought the arctic air over to the ice-free surface. Conceptually, this situation must lead to deepening of the surface vortex and development of a PL provided there is an upper-level forcing in the form of an upper-level trough/low with positive potential vorticity anomaly (Rasmussen and Turner, 2003).

In Figure 2, 500 hPa geopotential height distribution is plotted alongwith the sea-level pressure pattern. (a) indicates the flow pattern for 12 UTC on 29th February whereas (b) indicates the same, but for 06 UTC on the next day. An upper-level cyclonic flow was seen over the ice-covered surface and found steering the surface low towards ice (a). Following this, the upper-level flow and surface vortex moved over Spitsbergen terrain after 06 UTC on the 1st of March (b).



(a) CNTL – run : 12 UTC, 29 February 2008 (b) CNTL - run : 06 UTC, 01 March 2008

Figure 2. CNTL - run: 500 mb geopotential height contours (green, dashed contours with 6m interval) and sea-level pressure contours (blue, continuous contours with 1hPa interval).

A weak trough had formed at 500 hPa near the center of the cyclonic flow (Figure 2a). The upper-level trough and surface low were exactly in phase. The trough persisted until the 500 hPa disturbance moved over the Spitsbergen terrain and the surface vortex that was found directly below this trough was deepening. Just before the 500 hPa disturbance entered the Spitsbergen terrain, the surface vortex was at its maximum intensity (figure 2b). But thereafter the surface low had filled up resulting in the decay of the cyclonic circulation (not shown). A satellite image of the situation seen on the 1st of March at 06 UTC is shown in figure 3 where the weakening of both the AF and surface winds (by 6 to 7 ms^{-1}) can be seen.

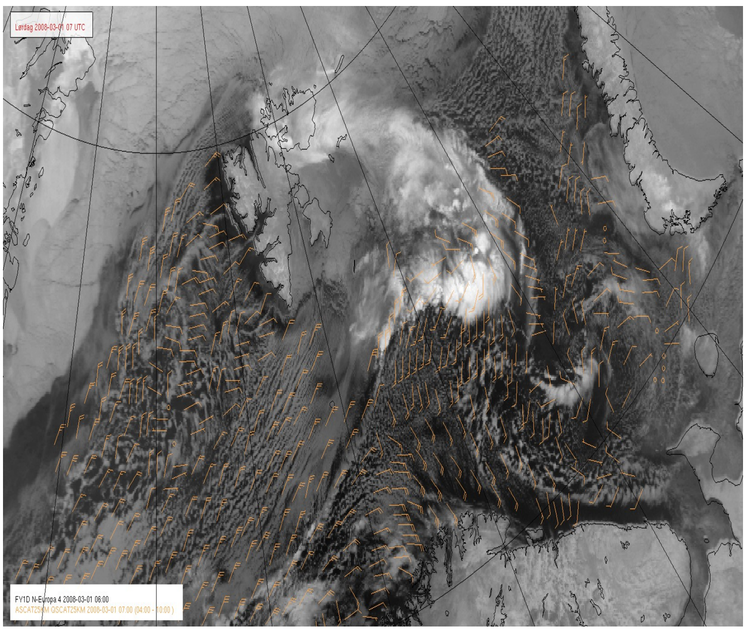


Figure 3. Image taken by NOAA on 1st March, 06 UTC. Surface winds measured by ASCAT are also shown.

Sensitivity cases:

From the analysis of the control run, it is clear that steering of the low-level vortex, towards the ice-covered surface and later on towards the Spitsbergen terrain, by the upper-level cyclonic flow resulted in the decay of the low-level cyclonic flow. To address if the low-level disturbance is able to spin up into a PL in the absence of parameters like the ice-cover and terrain, two sensitivity experiments were performed. In the first, sea-ice has been removed and the SST values have been increased by 5K from that of control run. This test is called SSTP5 hereafter. For the second experiment, Spitsbergen terrain is also removed in addition to the ice-cover. SST values are kept same as that in the SSTP5 test. The second case is termed NT_SSTP5 hereafter.

Figure 4 shows the difference between SSTP5 case and CNTL case, in-terms of wind speed (ms^{-1}) and sea-level pressure (hPa). It indicates that the surface low deepens by around 10 hPa and the wind speed increases by 7 to 8 ms^{-1} for SSTP5 case. The magnitude of the heat fluxes raises roughly by 200 Wm^{-2} (not shown).

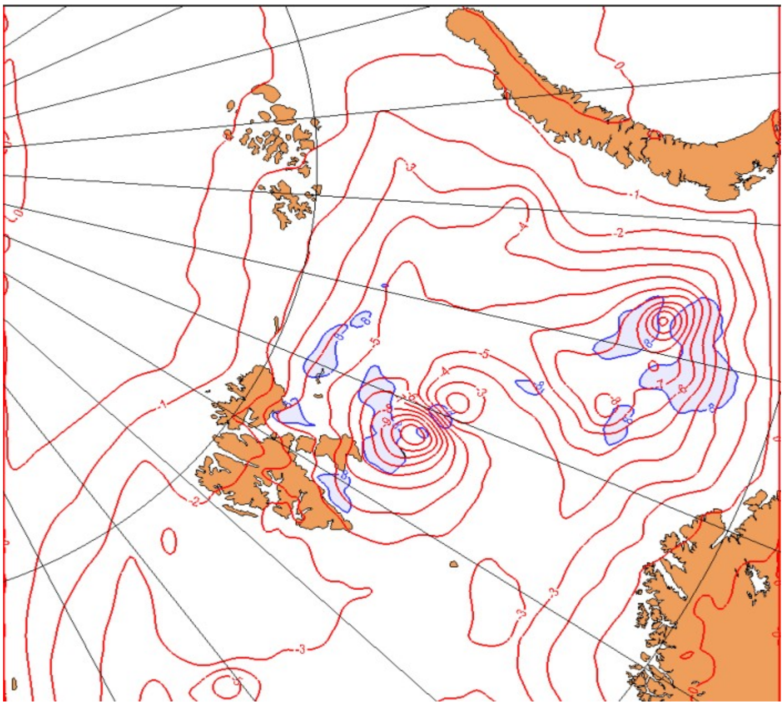


Figure 4. Difference between SSTP5 and CNTL for sea-level pressure (red contours with interval 1hPa) and wind speed (filled contours, maximum difference 8 ms^{-1}) at 06 UTC on 1st of March.

As in the control experiment, the low-level cyclonic circulation had the maximum intensity at 06 UTC, 1st March. Later on, the low-level vortex was steered onto the Spitsbergen terrain where the upper and lower-level vortices were exactly in phase. But the cyclonic flow disappeared in this case too as in the control run(not shown).

In the case of NT_SSTP5, the vortex (in-phase upper and lower-level vortices, combined into a single vortex) turns into a PL with winds of the magnitude 25 to 30 ms^{-1} at 500 hPa level as shown in Figure 5. This magnitude is roughly 10 ms^{-1} stronger than CNTL case and 5 ms^{-1} stronger than SSTP5 case. The surface pressure falls by approximately 4 hPa in the NT_SSTP5 case. The PL remains fixed in position for roughly 24 hrs and then stagnates.

The development of PL could be attributed to the stronger and deeper convection in the troposphere which is a direct effect of the warmer surface in the sensitivity experiment. These results are too preliminary to conclude that the convective phase is more important than the baroclinic phase in the development of PLs. However, for the case investigated here it seems that strong convection can trigger PLs in spite of weak or no baroclinicity in the initial stages of the development.

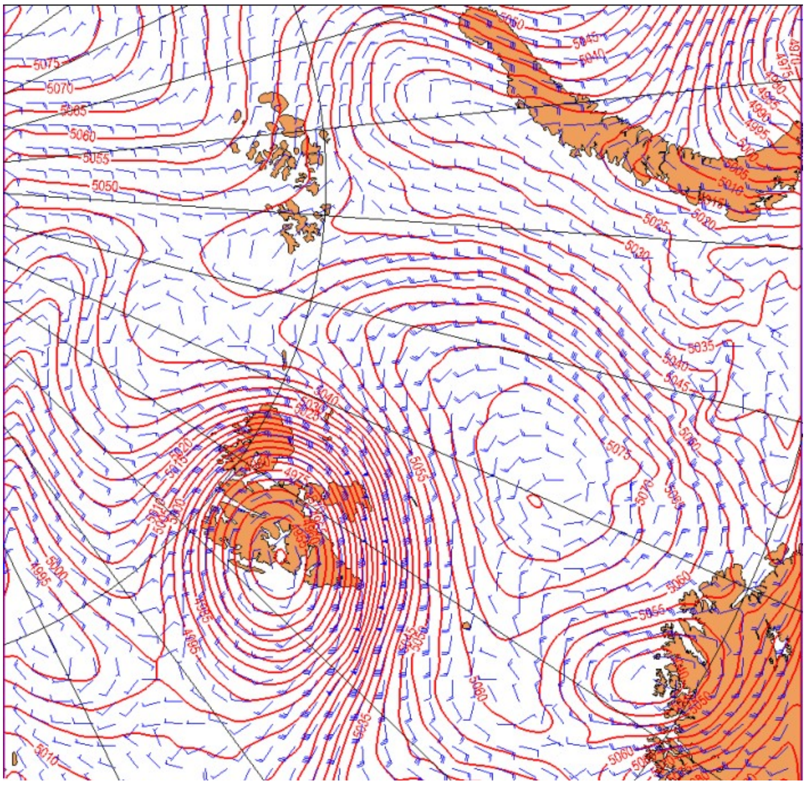


Figure 5. NT_SSTP5 case: Geopotential height contours at 500 mb (red contours with 5m interval) and wind barbs at 12 UTC on 2nd of March,2008. (This case has no terrain. Land-sea symbols are used in the domain for the clarification)

Conclusions and future work:

The case presented in this study had the initial conditions favourable for the development of a polar low (PL). However, no PL developed. We have analysed the case in order to address the possible causes for the hampering of the system. From the control run of the case, the decay of the system could be attributed to two reasons:

1) The upper-level flow was present over the ice-covered surface and hence the lower-level stability was too high to provide sufficient energy to the upper-level system.
2) The upper-level flow steered the surface vortex onto the Spitsbergen terrain.

Sensitivity studies were performed to examine above points. When the terrain and ice were removed, the upper-level cyclonic flow does not decay as was the case in the control run. However, it is too weak to be termed as a PL. But when the SST was increased by 5 K in order to provide more energy to upper-level perturbation, it turns into a PL. In the latter case, the wind speed around the cyclone increases by 7-8 ms^{-1} from the control run and the fluxes are stronger by a magnitude of around 200 Wm^{-2} than that in the control run.

During the campaign, aircraft observations had been made for the corresponding case. In this preliminary report of the investigation, the aircraft observations are not presented. We plan to make use of these observations for the future studies.

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