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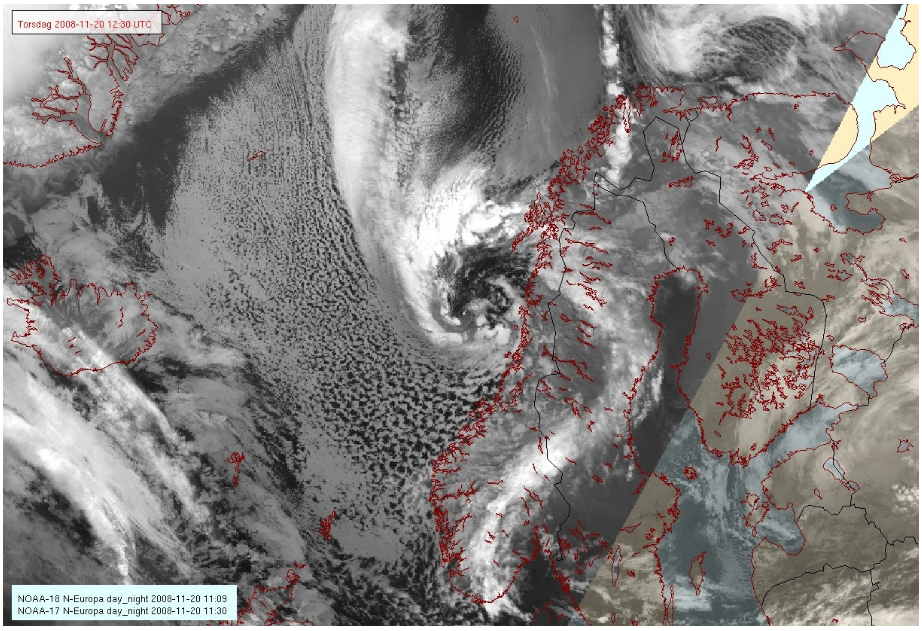
4/2009
Meteorology

A polar low named Vera
- dynamics and model performance

Thor Erik Nordeng



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Abstract
20th November 2008 the Norwegian Meteorological Institute issued an extreme weather warning for Trøndelag county. A storm was expected in the afternoon. The storm, a polar low, was named "Vera". Vera was the second of two polar lows that developed along a wedge of warm air at the rear of a synoptic scale low that moved north-eastwards into Northern Norway. The dynamical development of both lows may be explained by classical dynamical theory; low level warm air seclusion and shallow secondary circulation in frontal zone which couples to transient upper level disturbances. We have studied the performance of the models and found that even "coarse resolution" operational models (resolution higher than 8 km) were capable of forecasting the development of the precursors of the low as well as the polar low itself. We also show that the low was predictable with a lead time of approximately 36 hours as forecasts issued from the morning (00 UTC) on the 19th of November 2008 and later successfully forecasted the development. Forecasts from the day before gave strong winds, but not a correct polar low development. There were only small differences between the models, but the UM4 model was slightly superior to the others. The deterministic forecasts were supported by met.no's limited area ensemble prediction system

Keywords
Polar low dynamics, potential vorticity, model

Disiplinary signature	Responsible signature
Knut Helge Midtbø	Øystein Hov

Background

20th November 2008 the Norwegian Meteorological Institute issued an extreme weather warning for Trøndelag county. A storm was expected in the afternoon. The storm, a polar low, was named “Vera”.

The forecast was (translated from Norwegian): *Intensifying wind, reaching full storm 30 m/s at the coast north of the Trondeim fiord. Tonight reducing to gale force. Strong winds and snowfall will give difficult driving conditions. Significant wave heights of 10-12 m is expected along the coast this evening and maximum wave height above 20 m. The strongest winds coincide with high tides.*

Later the same day (20th November at 2000) the forecast was updated to (translated from Norwegian): *Tonight strong and full storm at the coast of Trøndelag county north of the Trondheim fjord is observed. Sklimma and Nordøyan lighthouses observe the strongest winds at 1900 local time with 55 kts. Buholmsråsa has around 45 kts. Max mean wind during the last six hours is observed at Nordøyan lighthouse (62 kts), while Sklinna has 58 kts. Buholmsråsa 49 kts. Strong winds in combination with snowfall will give difficult driving conditions. It is expected significant wave heights of 10 – 12 meters along the coast tonight and maximum wave heights above 20 m. From tonight northwest gale with significant wave heights reaching 8 to 10 meters*

Observations proved that the forecast was right; the wind force became strong (see figure 1 below). This report consists of two parts. Part I contains a description on the lows precursors and the dynamical processes that contributed in making the low particularly strong while Part II describes the performance of the numerical models used to forecast the low.

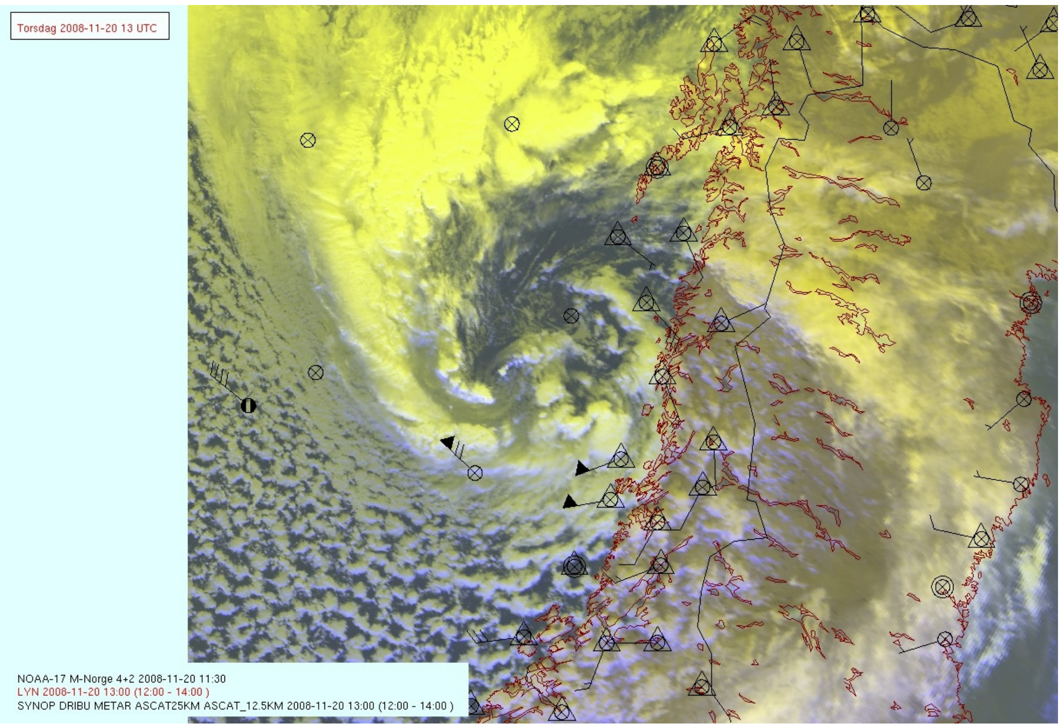


Figure 1. Some wind observations 20th November between 1200 to 1400 UTC together with satellite picture (NOAA 17) taken 20th Nov 2008 1130 UTC

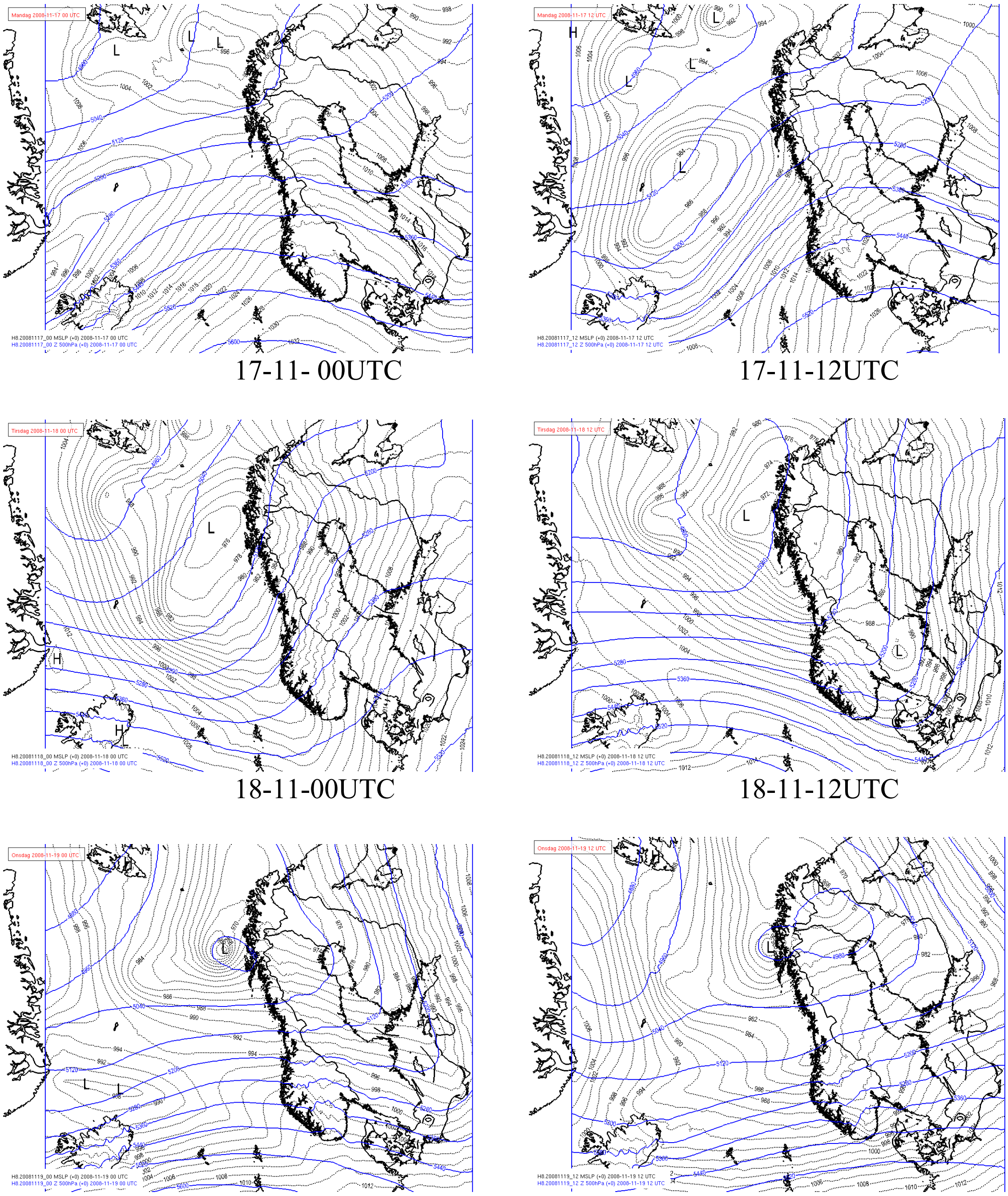
Part I: Dynamical development

a) The precursors of Vera

Vera was the second of two polar low which formed along a wedge of warm air combined with strong baroclinicity at the rear flank of a synoptic scale low (sometimes described as a redevelopment on the trailing occlusion). This synoptic scale low ("the mother low") came from the Denmark Strait, crossed the northern part of the Norwegian Sea heading towards Northern Norway and the coast of Troms county. See Figure 2.

Of special concern is the small-scale low outside the coast of Troms county (lower row), which developed strongly in the evening of 18th Nov. This was the first of two polar lows (Vera was the second) and it formed at the boundary between the relatively calm inner part of the mother low and a much stronger north-easterly wind further west. This configuration sets up a strong differential temperature advection creating a reversed shear baroclinic zone. In a reversed shear flow, wind and thermal wind are in opposite directions and the flow weakens with height. The area will in addition have strong (shearing) vorticity. To some respect this initial phase is similar to the development of "A Most Beautiful Polar Low" as described by Nordeng and Rasmussen (1992). In its early phase we find no indications of a development induced by a disturbance aloft. A combined low level barotropic/baroclinic development, reinforced by the release of latent heat, is a plausible explanation for the initiation of the low. A necessary condition for barotrop instability is that the vorticity has a maximum in the interior of the flow (The Raleigh/Fjørtoft criterion). The baroclinic counterpart to this is that the potential vorticity has a maximum in the interior; see e.g. Holton, 2004, pp. 253-257. This is the case here.

During the strong development in the evening of 18th Nov, however, the low is clearly influenced by an upper level disturbance. An IPV maximum is advected in from west and becomes coupled to the low level disturbance (see figure 3a and b).



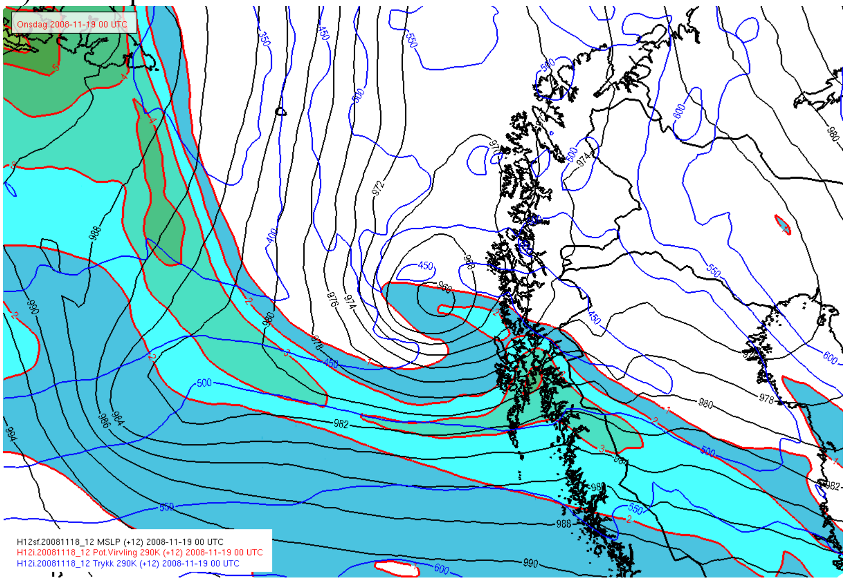
17-11- 00UTC 17-11-12UTC

18-11-00UTC 18-11-12UTC

19-11-00UTC 19-11-12UTC

Figure 2. Mean sea level pressure at contour intervals of 2 hPa and geopotential height of 500 hPa at contour intervals of 80 m. Upper row from left: 17th Nov 00 UTC and 17th Nov 12 UTC; middle row from left: 18th Nov 00 UTC and 18th Nov 12 UTC; lower row: 19th Nov 00 UTC and 19th Nov 12 UTC. The plots are taken from the analyses of HIRLAM 8.

a) Isentropic surface 290K



b) Isentropic surface 285K

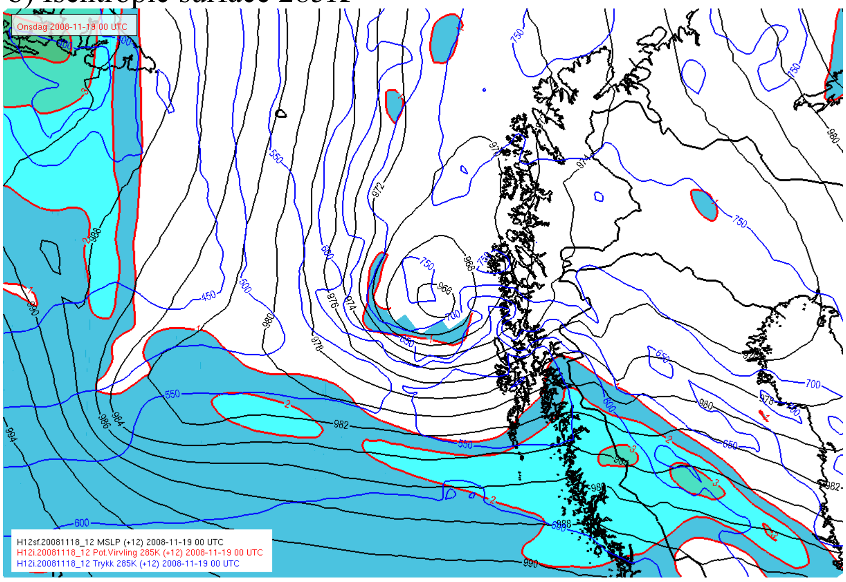


Figure 3. MSLP at contour intervals of 2 hPa (black lines), pressure in units of hPa (blue lines) and Isentropic Potential Vorticity (IPV) in units of 1 PVU valid at 00 UTC 19th Nov 2008. a) Isentropic surface 290K and b) isentropic surface 285K.

We notice the characteristic "hook-pattern" and that the low level (~700 hPa) IPV maximum is found in a ring (the "eye-wall") of the developing low. The low level IPV maximum is probably caused by the release of latent heat from condensation as it coincides with areas of heavy precipitation from the simulation (not shown).

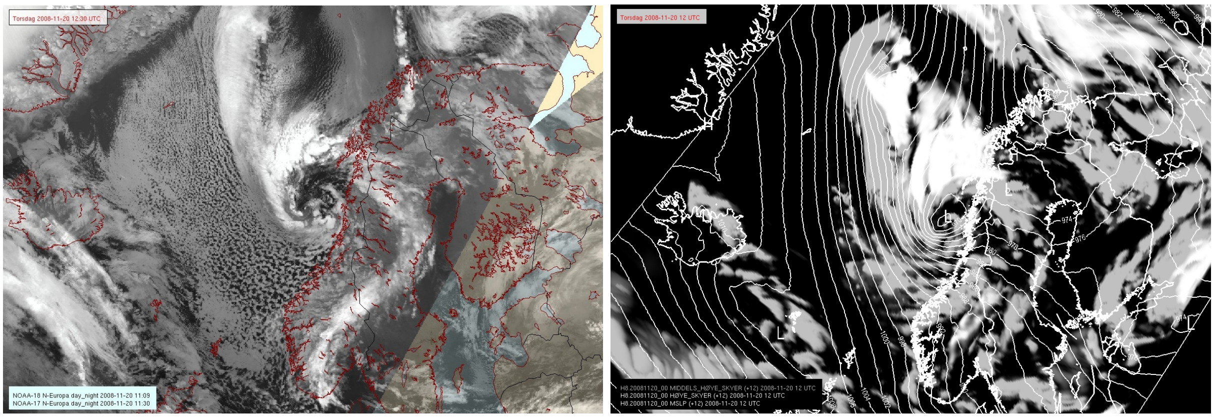


Figure 4. Satellite picture taken 20th November 2008, 1230 UTC (left panel) and simulated mean sea level pressure at contour intervals of 2 hPa (right panel) together with medium and high clouds from the model HIRLAM8 (12 hour forecast from 20th November 2008, 0000 UTC).

b) The development of Vera

It should however be noted that it was **not** the small scale low just described outside the coast of Troms (figure 3) that developed into Vera. That polar low just ashore in the Vesterålen area and diminished shortly after 12 UTC 19th November (figures 2 and 3). The wedge of warm air, however, remained and was advected southwards. Vera developed on this low level structure in many ways similar to "her older sister". Figure 4 shows Vera in its mature stage outside the coast of Nordland county as seen from satellites and in HIRLAM8. It is noteworthy that HIRLAM8 apparently did an excellent job in simulating the event (this will be focused in part II); making it possible to understand the dynamics of the system by studying the model output.

As the wedge of warm air moved southwards, it was squeezed in between approaching colder air masses at both its northern and southern side. There is (again) a clear contrast between cold Arctic air in the western part of the Norwegian Sea and much warmer air along the Norwegian coast and over Scandinavia. The strongest relative vorticity is found as narrow vorticity filaments (bands) along the frontal zone. Due to strong cold air advection from north-west at the southern side of the mother low a wedge of warm air is formed from the Scandinavian peninsula into the Norwegian Sea as the cold air has penetrated towards the coast of Nordland. According to Hoskins et al. (1985) a warm (cold) temperature anomaly at the surface will have the same effect as a potential vorticity anomaly setting up a cyclonic (anticyclonic) circulation. Release of latent heat will in addition create potential vorticity below the heating maximum and reduce potential vorticity aloft; (in reality within a material volume, potential vorticity is not created nor destroyed but rather redistributed). All in all, as for its older sister, a potential vorticity anomaly is formed at low levels due to release of latent heat connected to the secondary circulation along the frontal zone. The frontal zone developed due to cold air advection west of the mother low. In addition, the warm surface air in the centre of the mother low acts as an additional PV source.

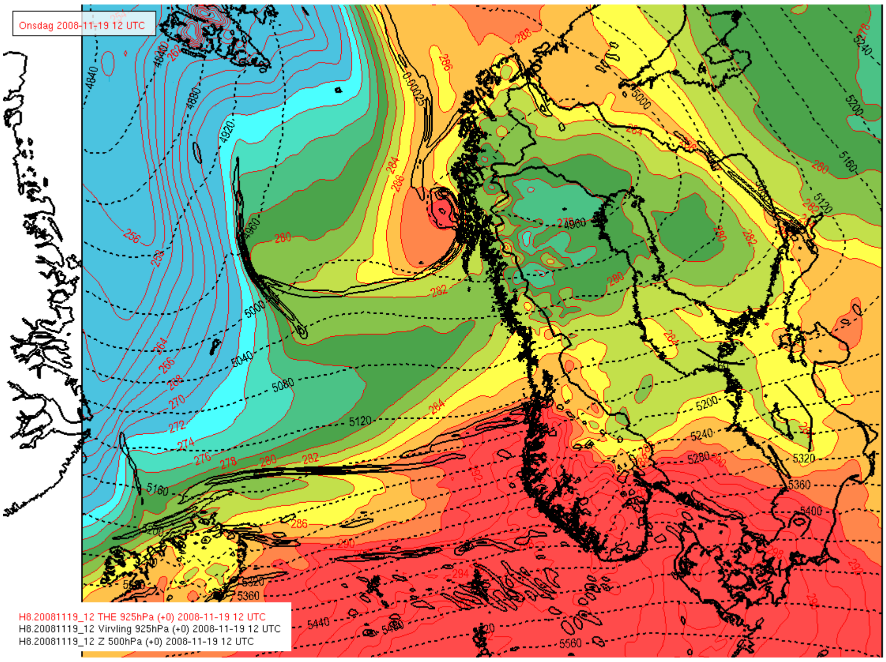
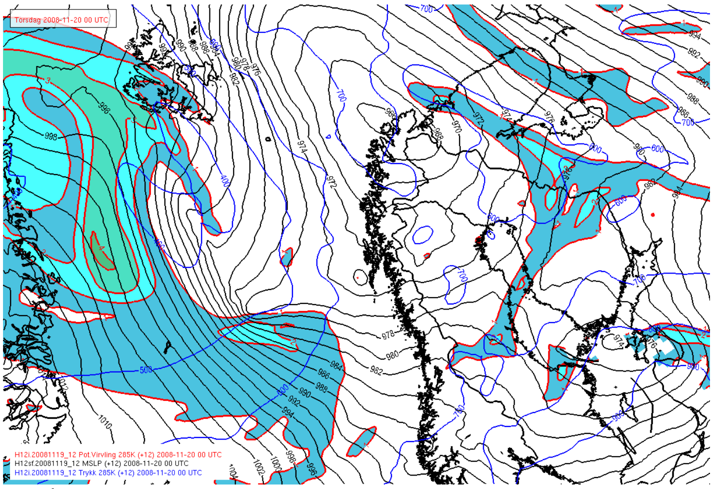
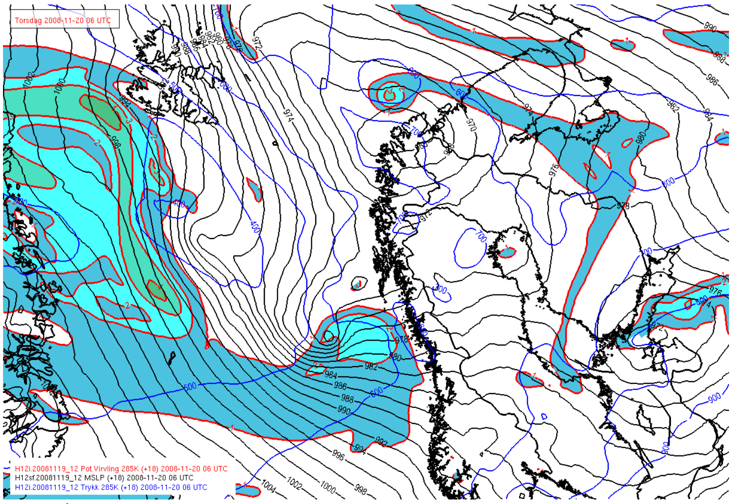


Figure 5. Full lines in black are relative vorticity in 925 hPa (only positive values are plotted) at contour intervals 2.5 10^{-4} s^{-1}. Red contour lines (with colour scale) are equivalent potential temperature at contour intervals of 2K also in 925 hPa. Dotted black lines are geopotential heights of 500 hPa at contour intervals of 40m. 19th Nov 1200 UTC.

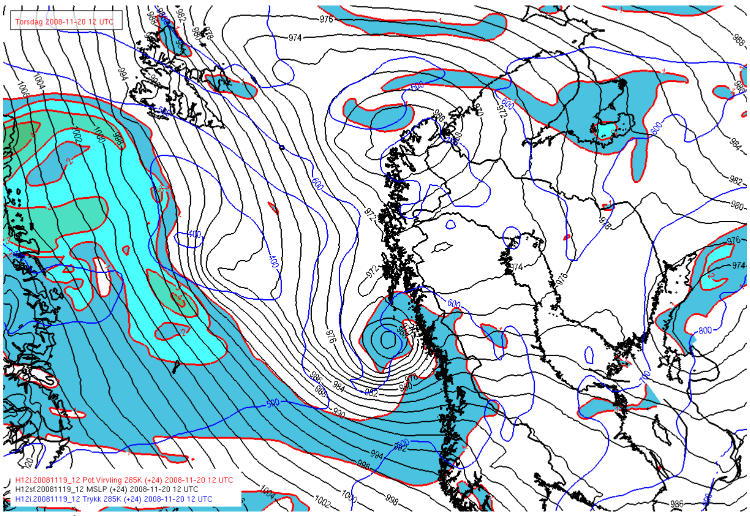
This configuration alone may spin up the cyclone as shown by Montgomery and Farrel (1992) and they name it "self-induced development". We have investigated if the low level dynamical structure acts on its own or whether it interacts with upper level transient disturbances. Figure 6 shows IPV and pressure at the 285K isentropic surface 00 UTC, 06 UTC and 1200 UTC 20th Nov 2008. There is strong advection of air with high IPV values downwards along the 285K isentropic surface ahead of the cyclone bringing high IPV air down to low levels. (*Note that since this is reversed shear development, everything is mirrored as compared to a "standard" positive shear development. The "warm front is trailing the low and the cold front is in front. Strong developments are expected, as for ordinary shear lows, when air is descending on the cold side of the cold front. This clearly takes place here*). As for its older sister there is dynamical coupling between high PV air from aloft and the low level circulation making the system more vulnerable for development than the low level self-induced part could do alone.



a) 20th Nov 00 UTC



b) 20th Nov 06 UTC



c) 20th Nov 12 UTC

Figure 6. MSLP at contour intervals of 2 hPa (black lines), pressure in units of hPa (blue lines) and Isentropic Potential Vorticity (IPV) in units of 1 PVU at isentropic surface 285K valid a) 20th Nov 00 UTC, b) 20th Nov 06 UTC and c) 20th Nov 12 UTC.

Part II. The performance of the NWP models operated by the Norwegian Meteorological Institute

Since the low developed close to the Norwegian coast with a number of available data from SYNOP stations, it is possible to evaluate in some depths how well the operational numerical weather prediction models performed during the event.

At the Norwegian Meteorological Institute 4 numerical weather prediction models were operated during the event (HIRLAM12, HIRLAM8, HIRLAM4 and UM4, where HIRLAM12 was running with 12 km horizontal resolution, HIRLAM8 with 8 km resolution and so on….). We had in addition access to the ECMWF model which had a horizontal resolution of approximately 25 km. It should also be mentioned that the UM-model with 1 km resolution was run in a test bed once a day, but that its results was not readily available for the statistics shown. All models are hydrostatic except from the UM-model which is non-hydrostatic.

Figure 7 shows the performance of the various models with respect to wind strength for some chosen stations along the Nordland and Trøndelag coast.

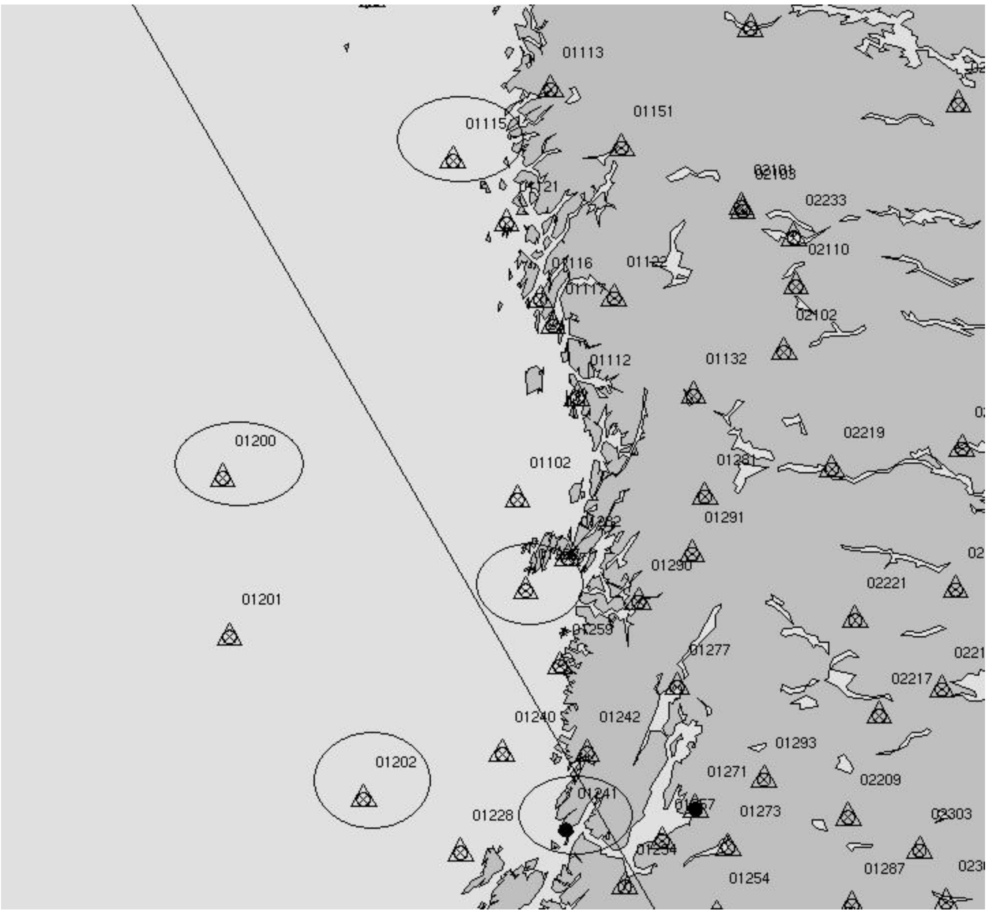


Figure 7. Observational sites used to evaluate the models for Figure 8. Myken (01115), Norne (01200), Nordøyan light house (01262), Draugen (01202) and Ørlandet (01241). Norne and Draugen are oil production platforms.

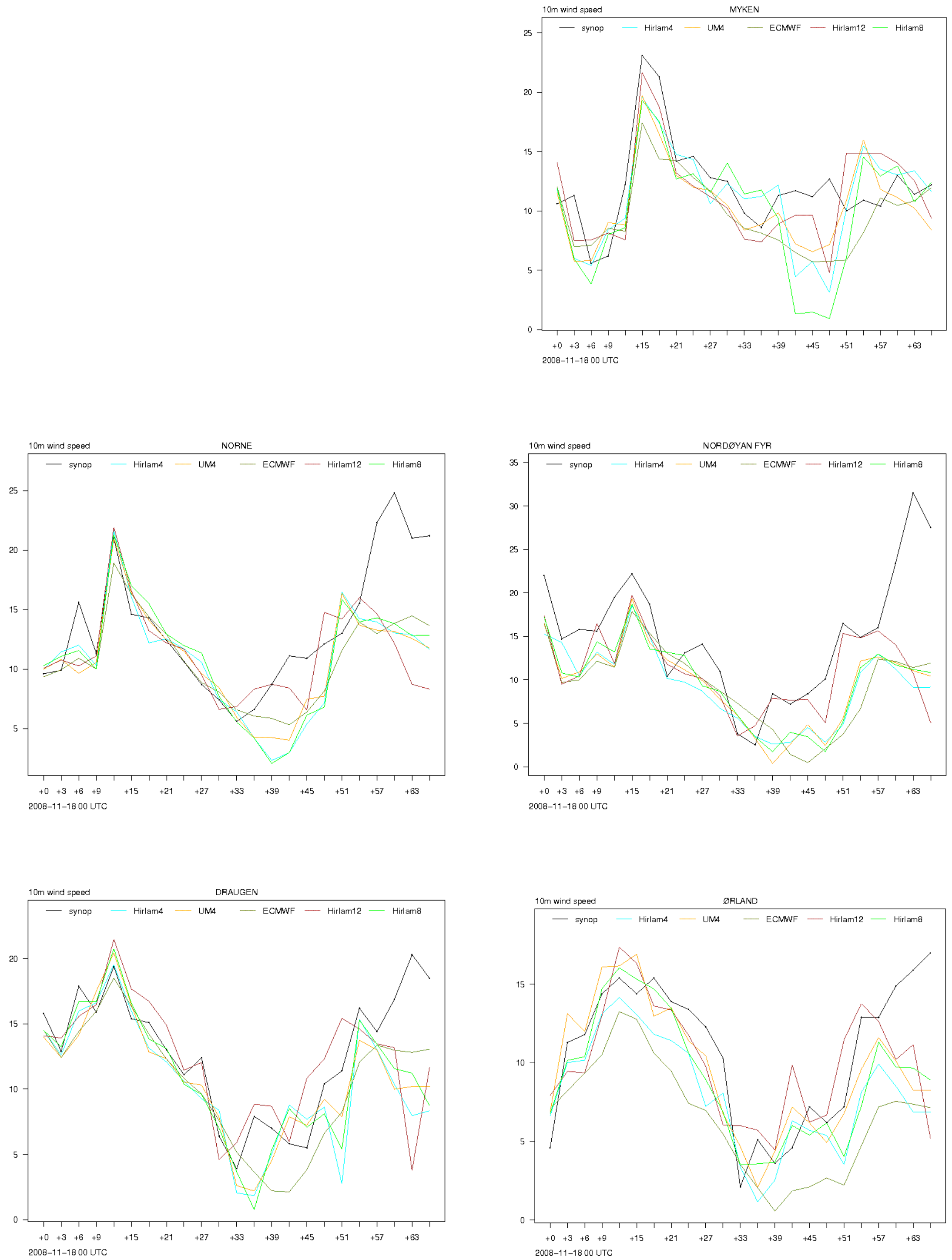


Figure 8a. Wind speed at various observational sites for forecasts starting at 00 UTC 18 Nov 2008. Left column are sites in the open sea while right column are corresponding sites at the coast (see figure 7). Vera reached the southernmost sites around 60 hours into the forecast.

Figure 8b. Wind speed at various observational sites for forecasts starting at 12 UTC 18 Nov 2008. Left column are sites in the open sea while right column are corresponding sites at the coast (see figure 7). Vera reached the southernmost sites around 50 hours into the forecast.

Figure 8c. Wind speed at various observational sites for forecasts starting at 00 UTC 19 Nov 2008. Left column are sites in the open sea while right column are corresponding sites at the coast (see figure 7). Vera reached the southernmost sites around 40 hours into the forecast.

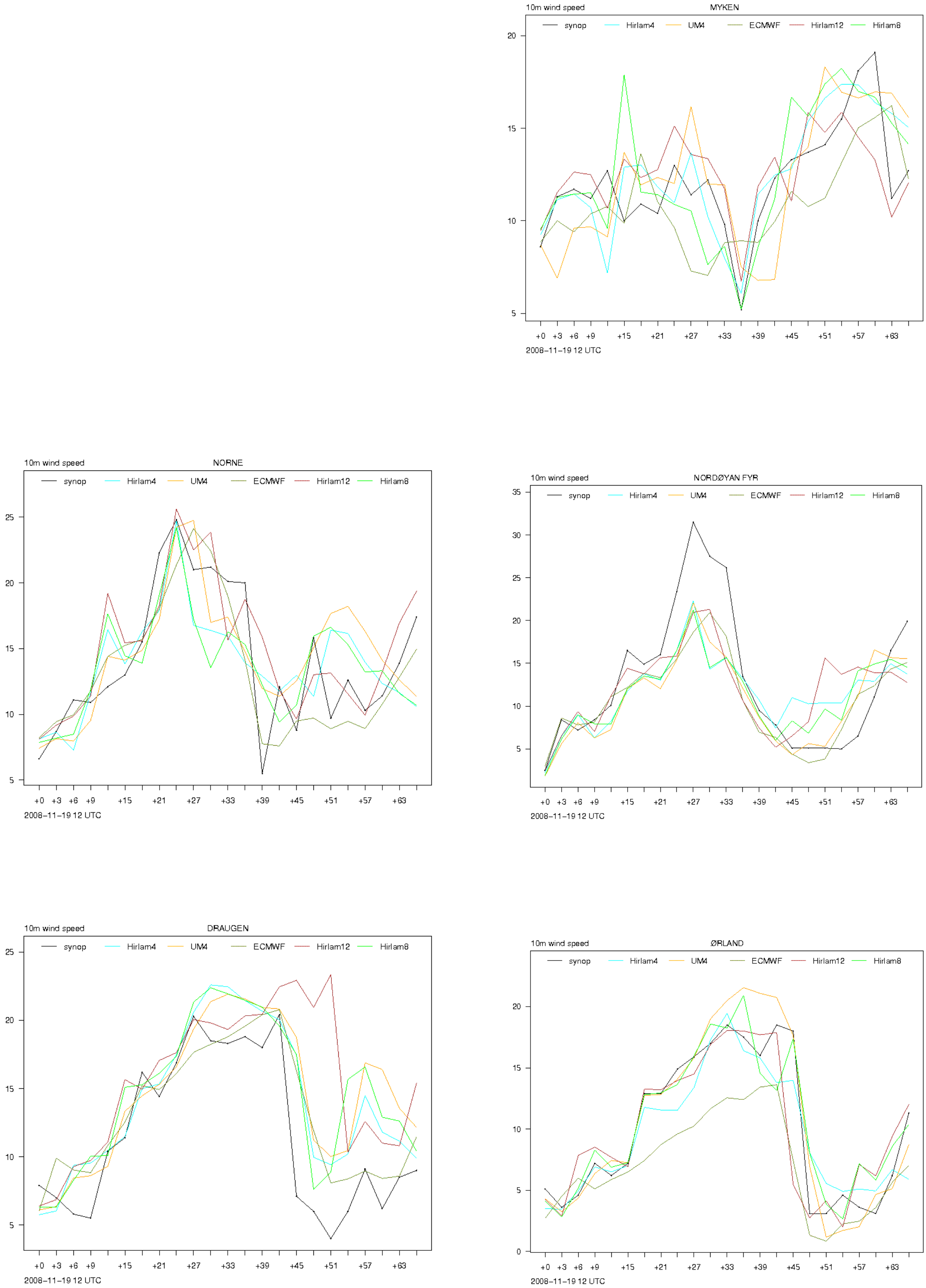


Figure 8d. Wind speed at various observational sites for forecasts starting at 12 UTC 19 Nov 2008. Left column are sites in the open sea while right column are corresponding sites at the coast (see figure 7). Vera reached the southernmost sites around 30 hours into the forecast (27 hours for Nordøyan lighthouse)

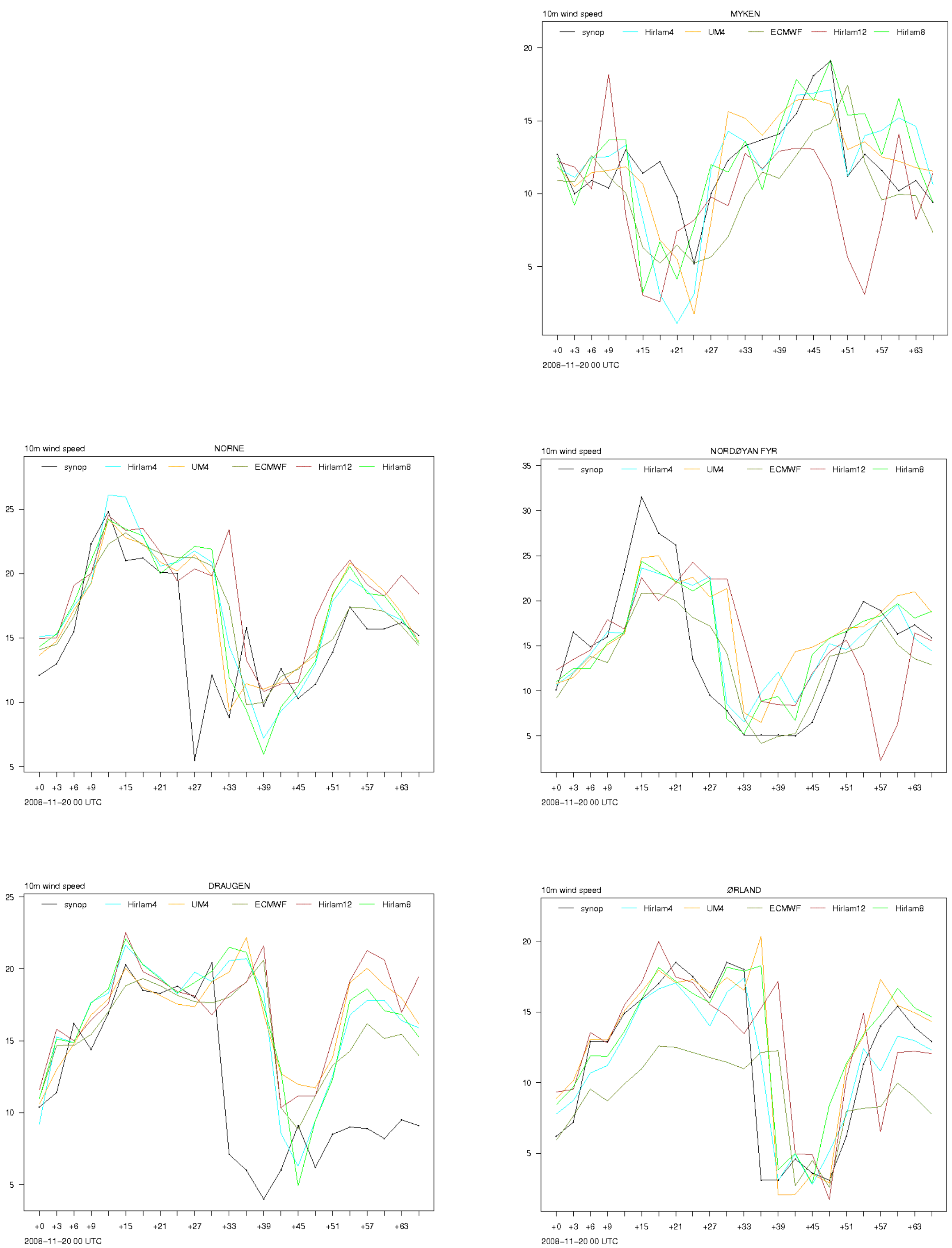


Figure 8e. Wind speed at various observational sites for forecasts starting at 00 UTC 20 Nov 2008. Left column are sites in the open sea while right column are corresponding sites at the coast (see figure 7). Vera reached the southernmost sites around 15 hours into the forecast.

Strongest winds were observed at Nordøyan lighthouse at 15 UTC 20th Nov with 33 m/s (mean over 10 mins). It is interesting to see that even forecasts issued at 12 UTC 18th Nov gave a decent warning for the storm (lead time ~48 hours), but with the coarsest resolution models only (HIRLAM12 and ECMWF), particularly so in the open sea (oil platforms Norne and Draugen) (figure 8b). However, already 12 hours later, the fine scale models caught up and managed to some extent to forecast the strong winds (figure 8c). The fine scale models were however unsuccessful in simulating the weakening of the wind after the storm. Forecasts launched 12 UTC 19th Nov (lead time approximately 27 hours; figure 8d) were in general good for all models (an exception is HIRLAM12 which tended to keep strong winds too long). Max wind is simulated well in the open sea but somewhat too week at the coast (Nordøyan). This could be related to local effects not resolved in even the highest resolution models. The last forecasts (issued at 00 UTC 20th Nov; figure 8e) were successful in simulating wind increase, but delayed the weakening of the storm by roughly 6 hours. In general we may conclude that all models did a decent job in forecasting the event and that the coarse resolution models (25 km in the ECMWF model, 12 km in HIRLAM12) apparently were sufficient to forecast the storm.

Wind speed may be related to local as well as large scale phenomena and in order to obtain some information on how the models simulated the passage of the polar low and its strength we have also looked at forecasted versus observed mslp pressure for the same SYNOP stations as for wind speed. The results for oil production platform Norne are shown in Figure 9.

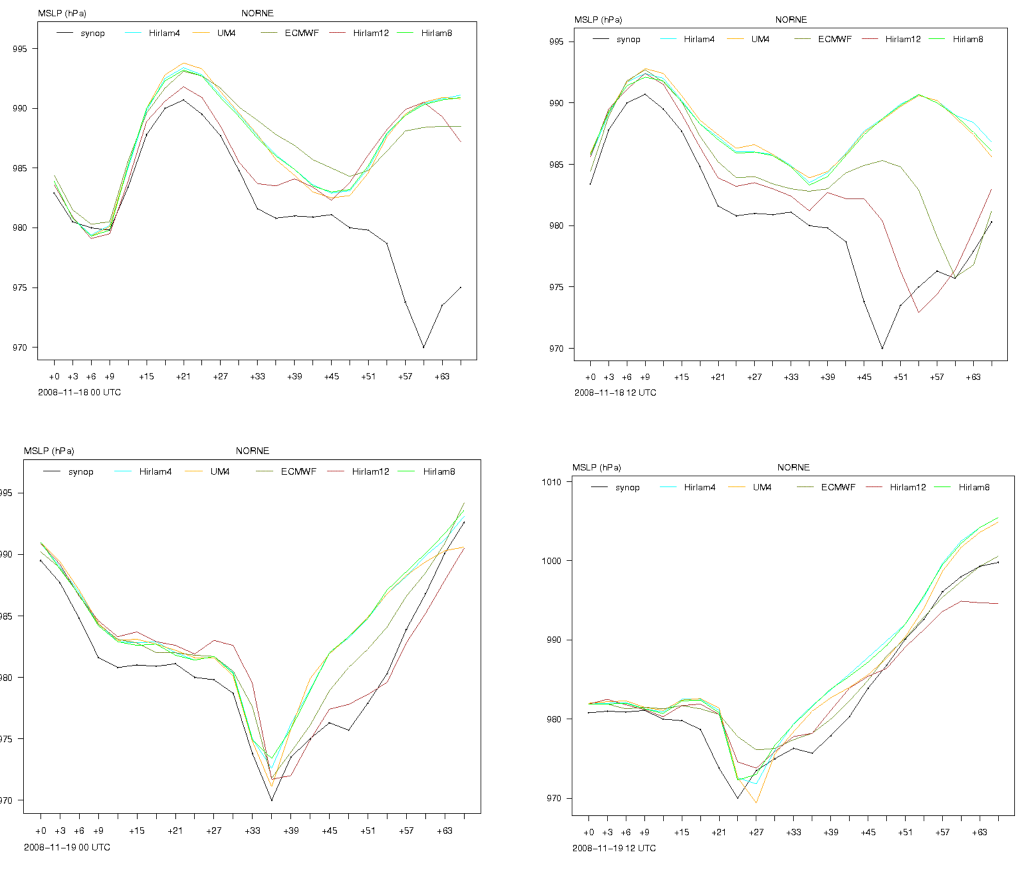


Figure 9. mslp for Norne as observed and forecasted with the models for forecasts issued at 00 UTC, 18th Nov; 12 UTC, 18th Nov; 00 UTC, 19th Nov; and 12 UTC, 19th Nov respectively.

Note the change in scale for the last panel (forecast from 12 UTC 19th Nov) as compared to the others. Forecasts issued on the 18th November (top panels) were out of phase with the small scale system and the decent wind enhancement forecasts (see figure 8) have apparently little relevance to the developing polar low. Forecasts with lead time ~36 to ~24 hours (issued on the 19th Nov) were in general good and showed the characteristic “v-shaped” structure in the barograph which is often observed for polar low passages (Rabbe, 1987). Interestingly, the longer of these (from 00 UTC 19th Nov) were better in describing the timing of the low than the latter. UM4 seems to perform slightly better than the other models.

In order to try to obtain a quantitative measure of the models performance, we computed model statistics as compared to observations for some chosen stations along the coast. The stations used have been highlighted in figure 10.

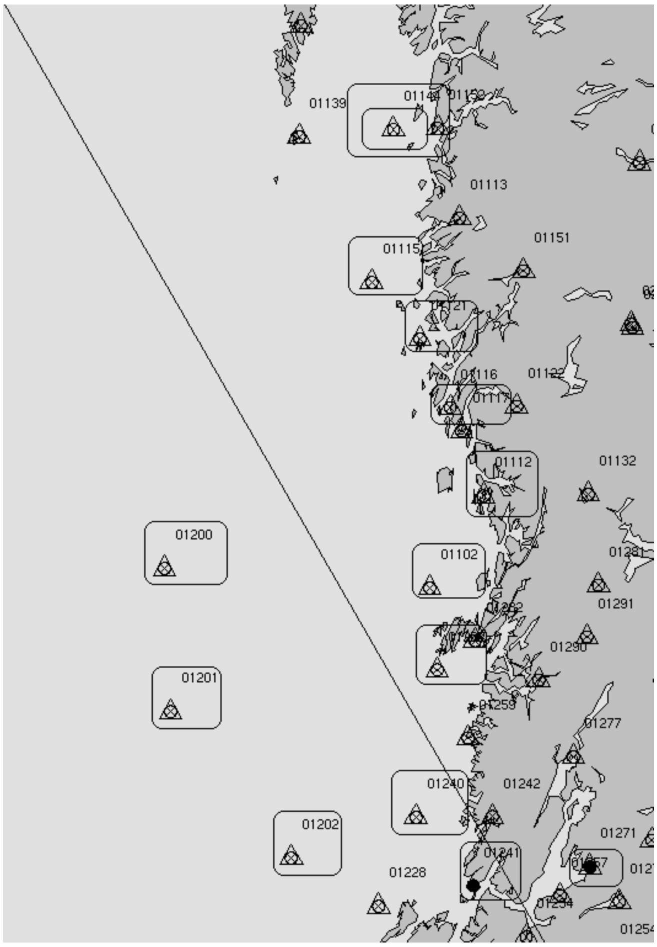
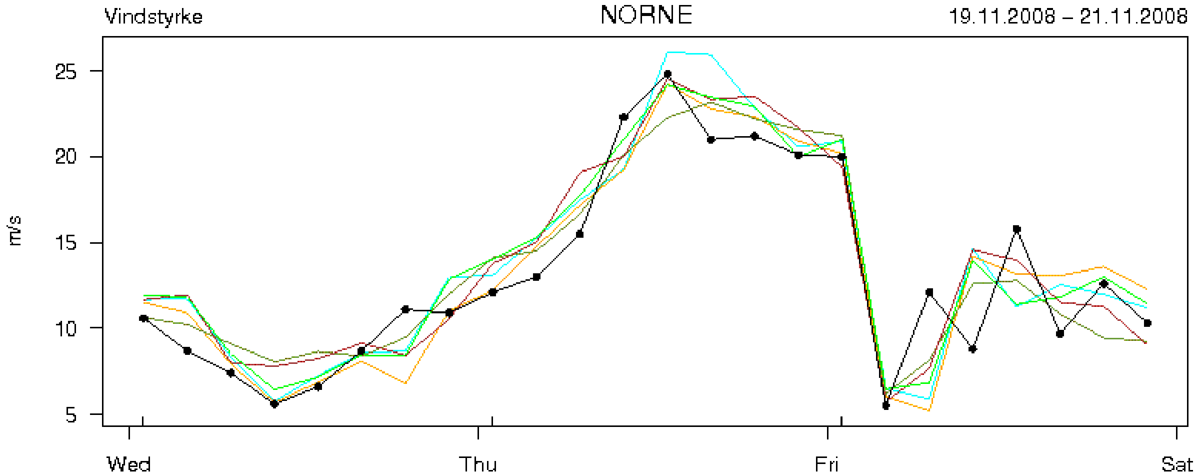
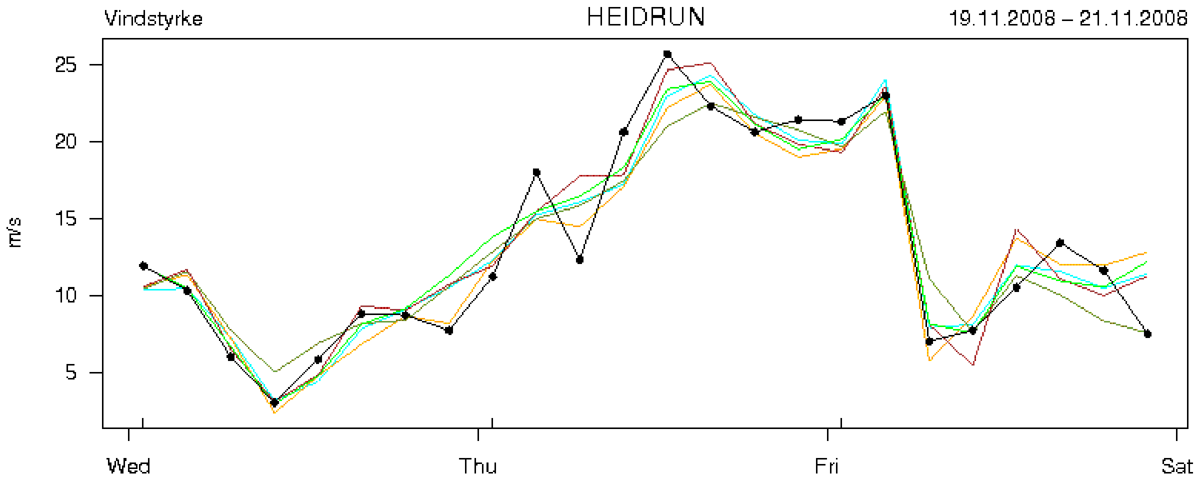


Figure 10. SYNOP sites used for the verification statistics of figure 10.

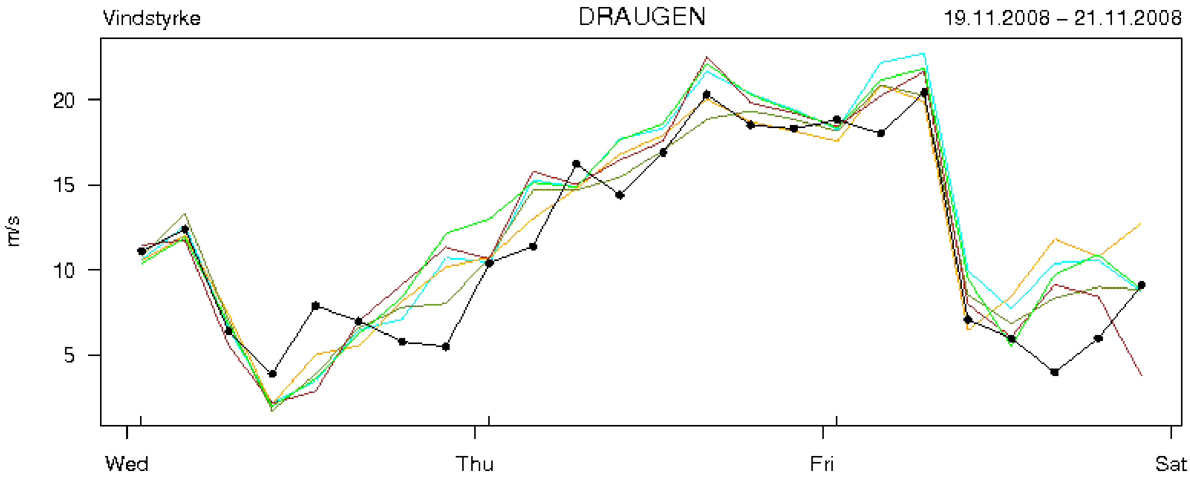
The data is based on all those individual forecasts that verify during the period 19th Nov 03 UTC (Wednesday) until 22nd Nov 00 UTC (Saturday), i.e. forecasts of individual lengths from 3 to 48 hours.



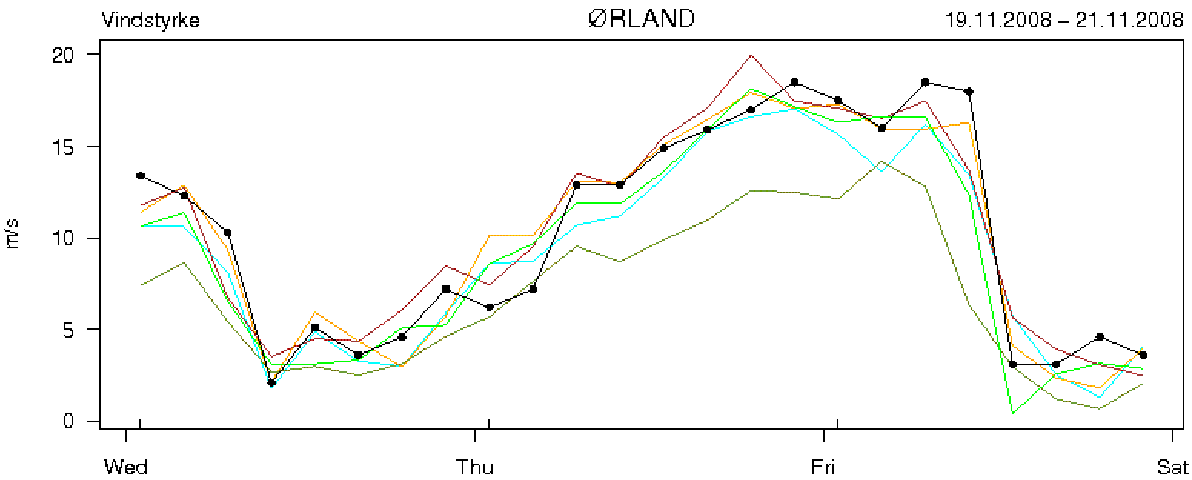
	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	0.7	2.7	2.8	2.1	6.2	24
UM4 – synop	0.2	2.5	2.5	1.7	6.9	24
ECMWF – synop	0.3	2.1	2.1	1.8	4	24
Hirlam12 – synop	0.6	2.3	2.4	1.9	5.8	24
Hirlam8 – synop	0.7	2.3	2.4	1.9	5.3	24



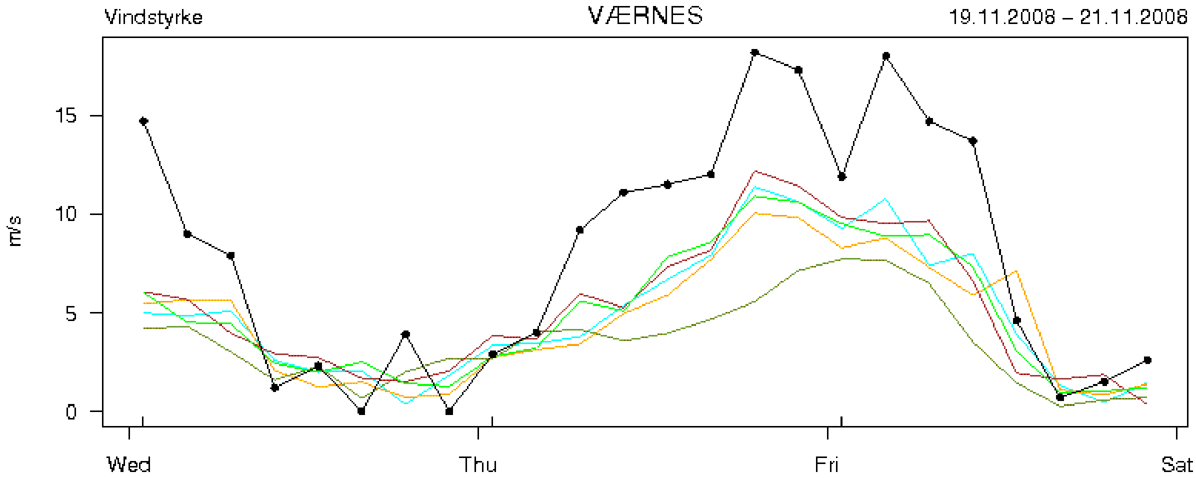
	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	0.1	2	2	1.6	3.9	24
UM4 – synop	–0.2	2.1	2.1	1.6	5.3	24
ECMWF – synop	–0.1	2.3	2.3	1.8	4.7	24
Hirlam12 – synop	0.2	2.3	2.3	1.8	5.4	24
Hirlam8 – synop	0.2	2	2	1.5	4.7	24



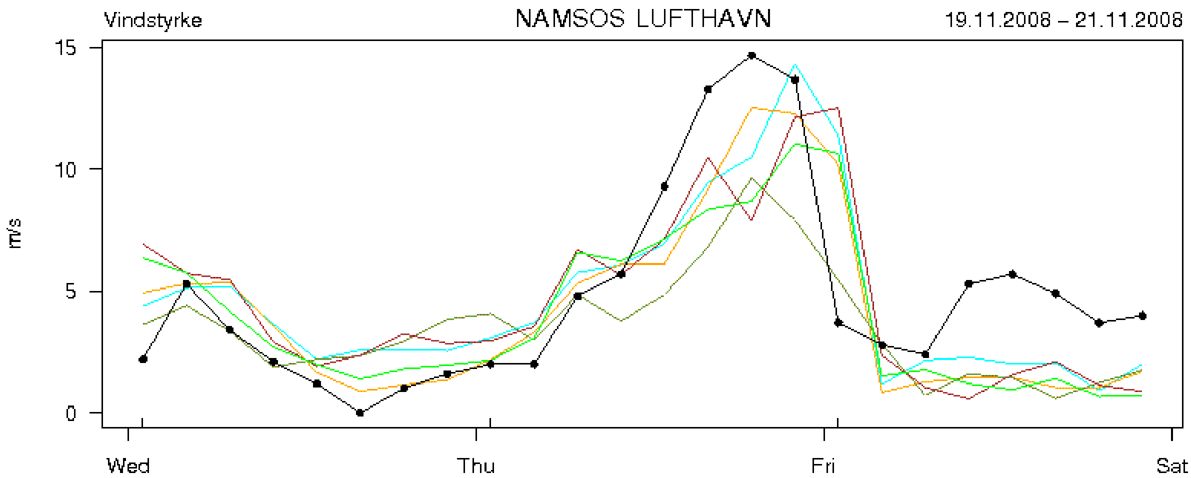
	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	1.4	2.5	2.8	2.1	6.4	24
UM4 – synop	1	2.5	2.7	1.9	7.8	24
ECMWF – synop	0.6	1.9	2	1.5	4.3	24
Hirlam12 – synop	0.8	2.6	2.8	2	5.8	24
Hirlam8 – synop	1.4	2.5	2.9	2.2	6.6	24



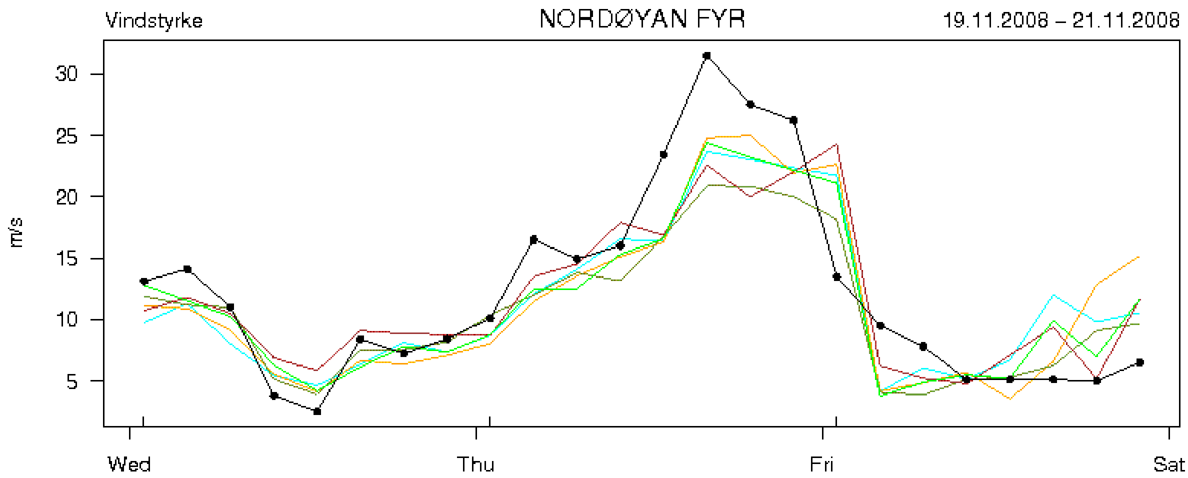
	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	–1.1	1.7	2	1.7	4.5	24
UM4 – synop	–0.1	1.6	1.6	1.2	4	24
ECMWF – synop	–3.4	2.7	4.3	3.5	11.6	24
Hirlam12 – synop	0.1	1.8	1.8	1.4	4.3	24
Hirlam8 – synop	–0.9	1.8	2.1	1.6	5.6	24



	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	–3.1	3.3	4.5	3.6	9.7	24
UM4 – synop	–3.4	3.7	5	3.9	9.3	24
ECMWF – synop	–4.5	4.4	6.3	4.8	12.6	24
Hirlam12 – synop	–2.8	3.3	4.3	3.5	8.6	24
Hirlam8 – synop	–3	3.2	4.4	3.5	9.1	24



	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	–0.1	2.7	2.7	2.1	7.7	24
UM4 – synop	–0.6	2.5	2.6	2	6.5	24
ECMWF – synop	–1.2	2.8	3	2.4	6.5	24
Hirlam12 – synop	–0.2	3.3	3.3	2.5	8.8	24
Hirlam8 – synop	–0.7	3	3.1	2.3	7	24

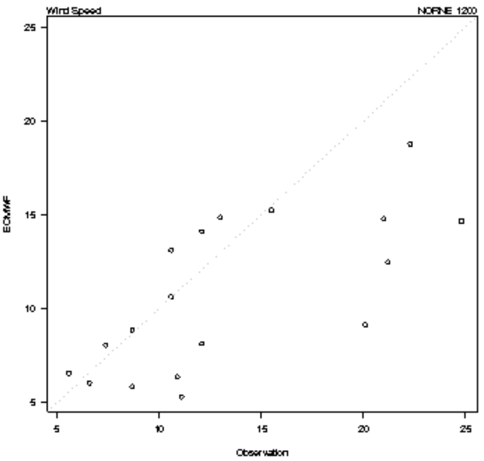


	Middelfeil	Std.feil.	RMSE	MAE	Maks.abs.feil	N
Hirlam4 – synop	-0.8	4.1	4.2	3.3	8.2	24
UM4 – synop	-0.8	4.3	4.4	3.4	9.1	24
ECMWF – synop	-1.5	3.7	4	2.9	10.6	24
Hirlam12 – synop	-0.4	4.3	4.3	3.2	10.8	24
Hirlam8 – synop	-0.9	3.7	3.8	3	7.6	24

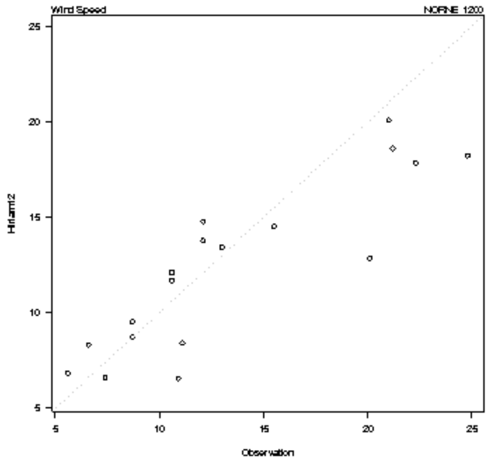
Figure 11. Verification statistics of wind speed for individual SYNOP stations for the period the period 19th Nov 03 UTC till 21st Nov 00 UTC

We note that in general the highest resolution models, and in particular UM4, did the best job, but that there were small differences between them. The ECMWF model in particular, gave in general very good RMSE scores, but too weak winds at costal stations. This is probably related to poor coast/sea description due to its coarse resolution. Theoretically, it is easier to obtain good RMSE scores for smooth (as from coarse resolution models) fields than for detailed fields (high resolution models)

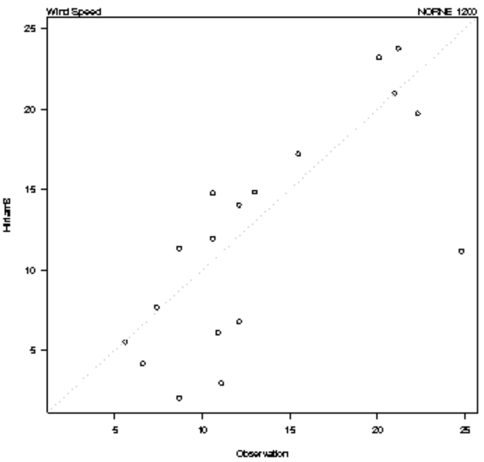
Similarities and differences between the models are also revealed through scatter plots of observed versus forecasted wind speeds. We have chosen Norne in the open sea (figure 11) and Nordøyan lighthouse (figure 12) further towards the coast (a group of small islands quite exposed to the open sea). For Nordøyan lighthouse winds strengths up to gale force (20 m/s) are relatively unbiased, while higher wind speeds are underestimated. This is true for all models. Further into the open sea however, at Norne oil production platform, there is no such tendency for the high wind regime; at low wind speeds however, the models underestimate wind strengths. This can not be explained by coastal or any other local effects and one is left with the suspicion that it may have to do with the parameterization of drag at low wind speeds. We also notice that for Norne the highest resolution models (HIRLAM4 and UM4) were better as compared to the low resolution models (ECMWF and HIRLAM12) at high wind speeds with UM4 slightly superior to HIRLAM4.



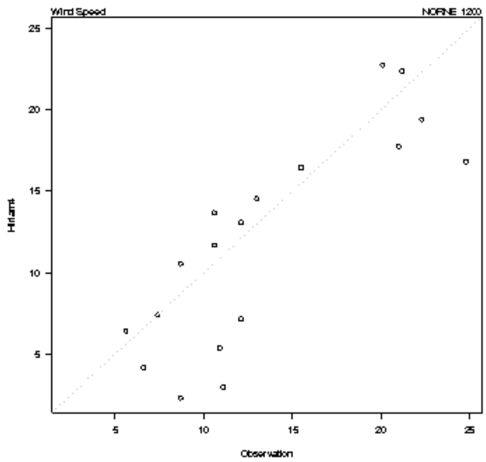
ECMWF



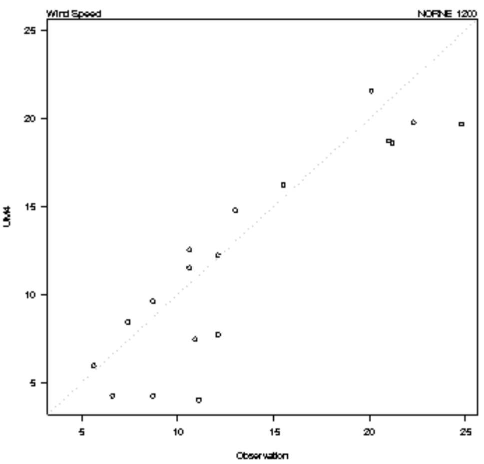
HIRLAM12



HIRLAM8

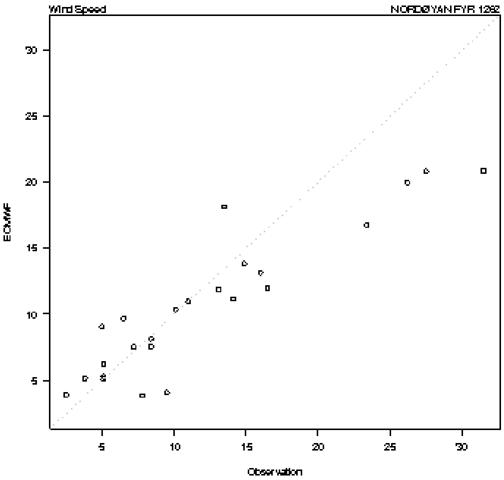


HIRLAM4

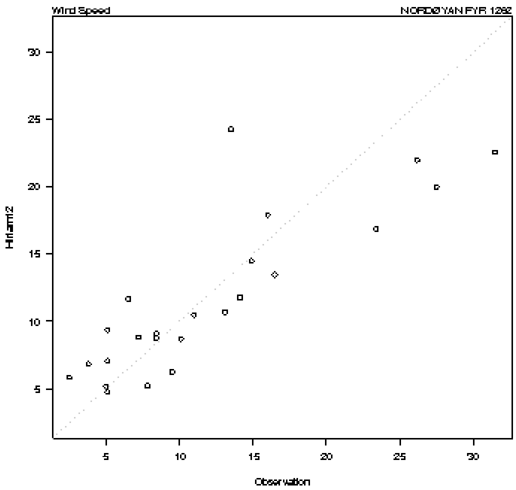


UM4

Figure 12. Scatter plots of observed versus forecasted wind speed for Norne oil drilling platform for forecasts issued at 00 and 12 UTC 19th Nov 2008 and verified between 00 UTC 20th Nov 2008 and 00 UTC 21st Nov 2008.



ECMWF



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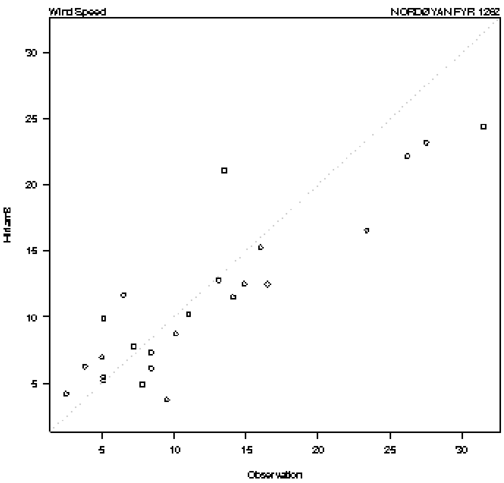
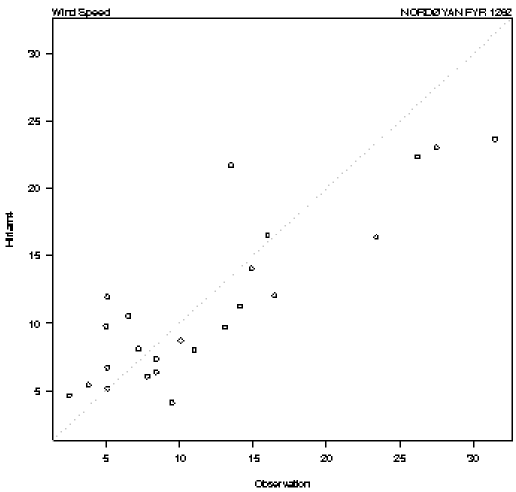
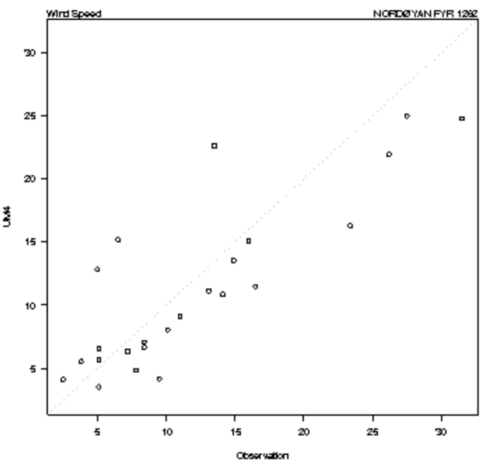


HIRLAM8



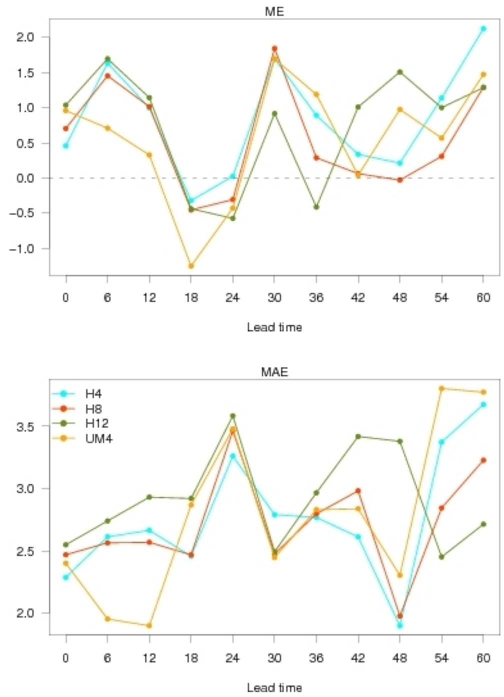
HIRLAM4



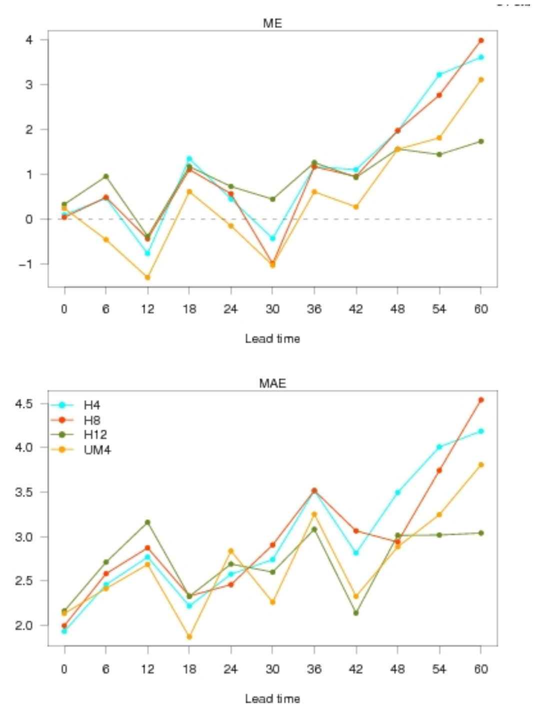
UM4

Figure 13. Scatter plots of observed versus forecasted wind speed for Nordøyan lighthouse for forecasts issued at 00 and 12 UTC 19th Nov 2008 and verified between 00 UTC 20th Nov 2008 and 00 UTC 21st Nov 2008.

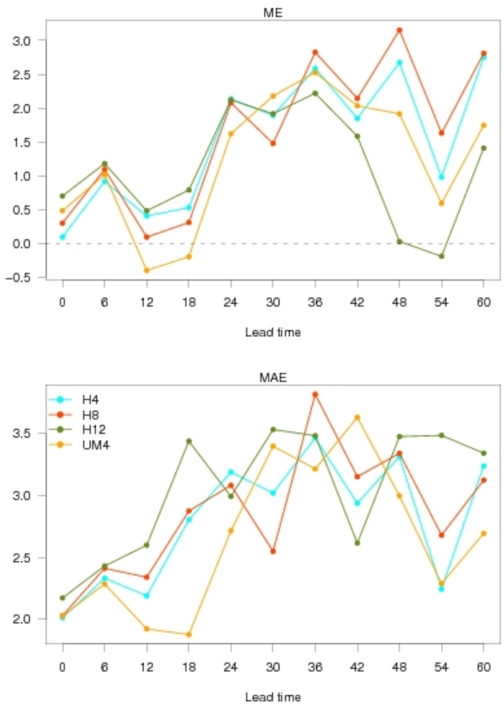
We have also computed some statistics of model performance for the region as a whole. For this statistics we have taken all available Norwegian SYNOP stations between Trondheim and Senja and calculated verification statistics based on forecasts starting every 12 hour from 00 UTC 19th Nov to 12 UTC 20th Nov.



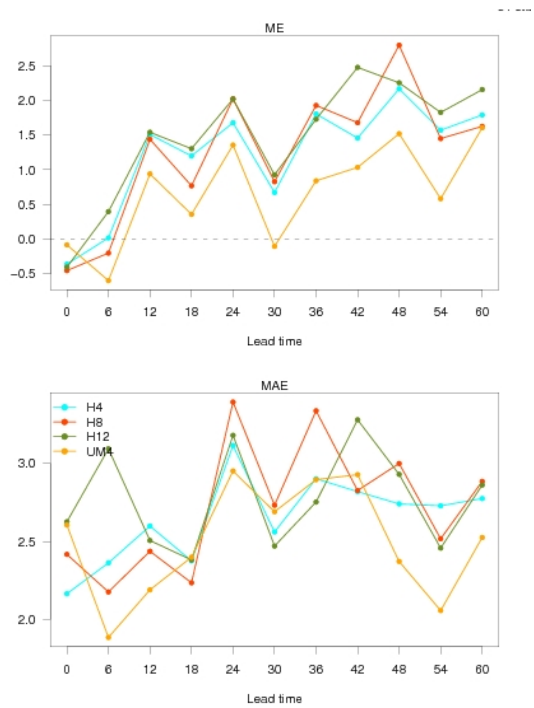
a) Forecasts from 00 UTC 19th Nov



b) Forecasts from 12 UTC 19th Nov



c) Forecasts from 00 UTC 20th Nov

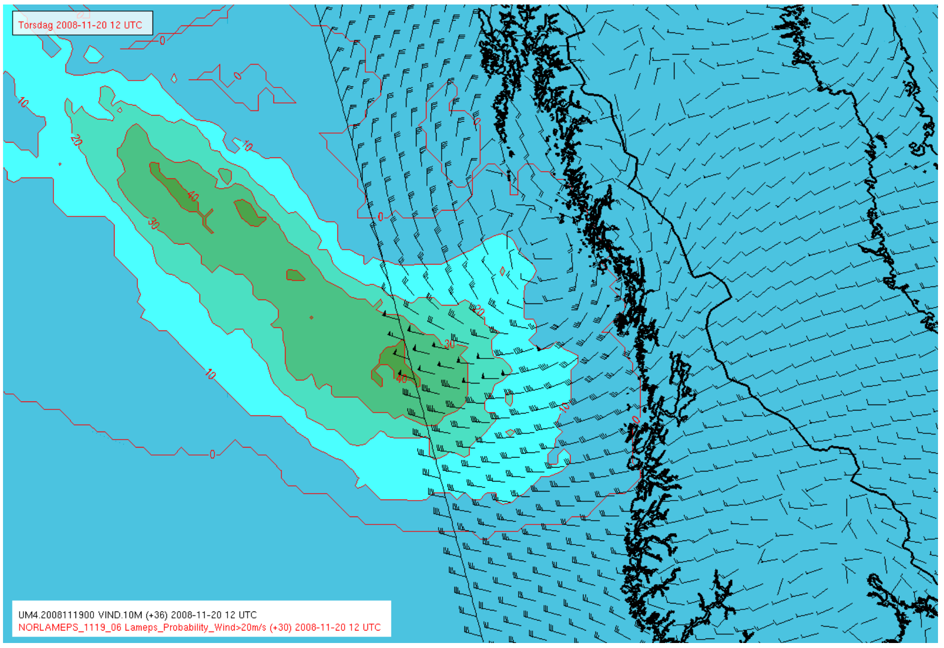


d) Forecasts from 12 UTC 20th Nov

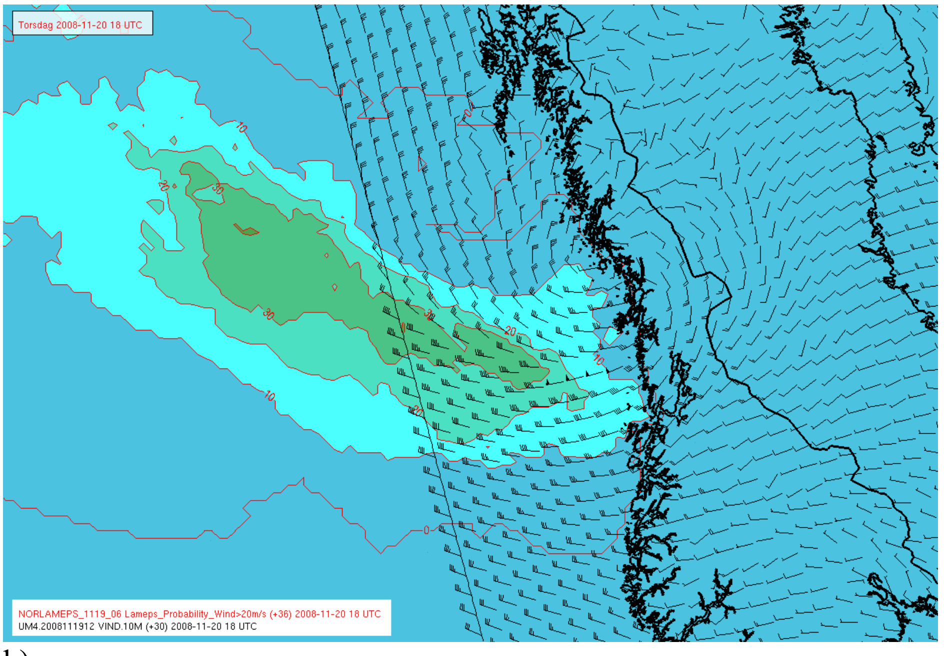
Figure 14. Mean error and mean absolute error of wind speed for forecasts starting from a) 00 UTC 19th Nov, b) 12 UTC 19th Nov, c) 00 UTC 20th Nov, d) 12 UTC 20th Nov.

There are no major differences between the models, but UM4 has slightly better error characteristics than the others with smallest bias as well as mean absolute error.

Finally, to make the work complete we have checked how well the limited area ensemble prediction system could guide duty forecasters. Figure 15 and 16 show plots of forecasted winds from UM4 together with probabilities for winds stronger than 20 m/s.

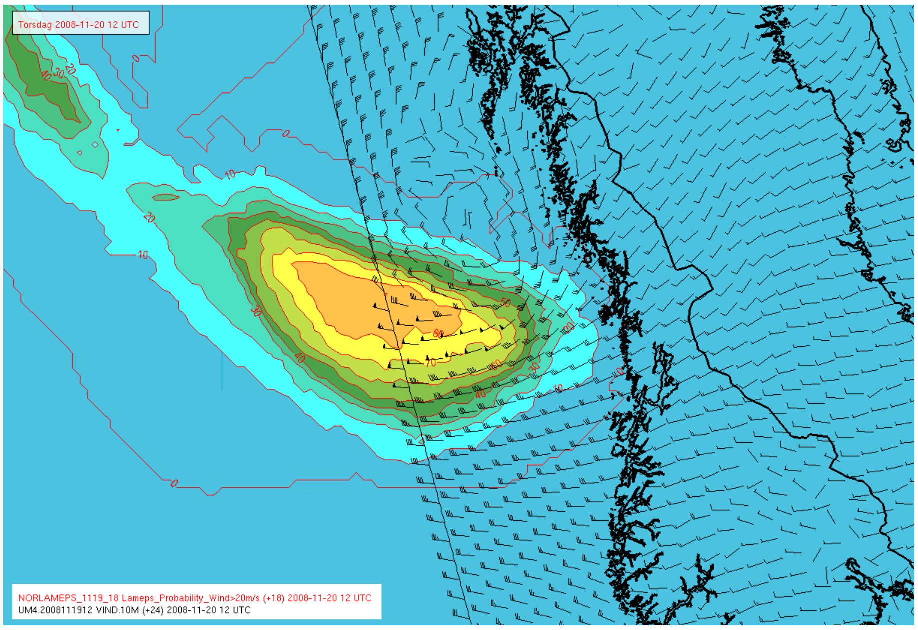


a)

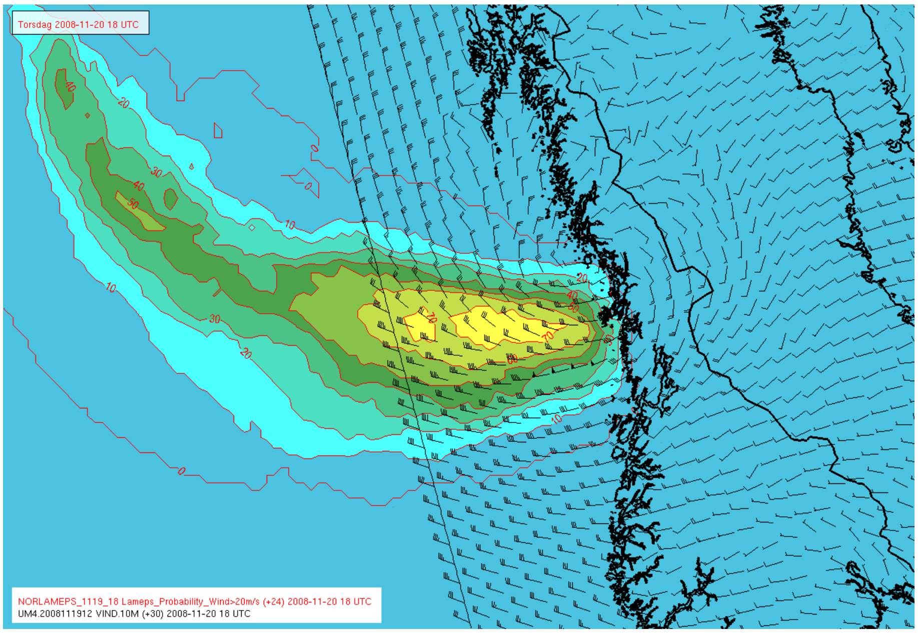


b)

Figure 15. Arrows are 10 m winds from UM4 (a full barb is 5 m/s and a half barb is 2.5 m/s). Contour lines are probabilities (%) for 10m wind speed exceeding 20 m/s based on the NORLAMEPS-ensemble system. Valid at a) 12 UTC 20th Nov 2008, i.e. a 36h forecast with UM4 and a 30h forecast with the ensemble system and b) valid at 18UTC 20th Nov 2008, i.e. a 30h forecast with UM4 and a 36h forecast with the ensemble system.



a)



b)

Figure 16. Same as figure 15, but a) valid at 12 UTC 20th Nov 2008, i.e. a 24h forecast with UM4 and a 18h forecast with the ensemble system and b) valid at 18UTC 20th Nov 2008, i.e. a 30h forecast with UM4 and a 24h forecast with the ensemble system.

Probabilities for stronger winds than 30 m/s were zero. We note that in particular the 18 UTC forecasts from 19th Nov with the ensemble system gave a very good signal in the range 18 to 24 hours ahead of the incident.

Conclusion/summary

The polar low Vera was the second of two polar lows that developed along a wedge of warm air at the rear of a synoptic scale low that moved north-eastwards into Northern Norway. The dynamical development of both lows may be explained by classical dynamical theory; low level warm air seclusion and shallow secondary circulation in frontal zone which couples to transient upper level disturbances.

We have studied the performance of the models and found that even the “coarse resolution” operational models (resolution higher than 8 km) were capable of forecasting the development of the precursors of the low as well as the polar low itself. In this respect it should be mentioned that Vera was a relatively large scale polar low. We have also seen that the low was predictable with a lead time of approximately 36 hours as forecasts issued from the morning (00 UTC) on the 19^{th} of November 2008 and later successfully forecasted the development. Forecasts from the day before gave strong winds, but not a correct polar low development. There were only small differences between the models, but the UM4 model was slightly superior to the others.

Duty forecasters issued a “weather warning”based on information from the numerical models. This analysis show that their background information all pointed in the correct direction; not only did all available deterministic forecasts point in the same direction, but they were also supported by the ensemble prediction system.

The two lows were spectacular but their developments may easily be explained by standard dynamical theory. Of more fundamental interest is how and why the large scale structures that make the seas outside the Norwegian coast a favourable place for polar low developments. We have observed that similar structures as observed here; wedges of warm air extending like arms into the cold air northerly flow, frequently develop in cold air outbreaks and become birthplaces for polar lows. Why and how these structures are generated will be focus for further research.

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