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Predictability of very high resolution operational weather models in complex terrain

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Predictability of very high resolution operational weather models in complex terrain

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Abstract

In this paper we investigate the forecasting skill of two operational very high resolution modeling systems consisting of nested limited area models down to 1 km horizontal resolution. The models used in the study are MM5 and MC2, and the model domains cover parts of northern Norway with complex terrain.

We concentrate on the predictability of wind and temperature, and the purpose is to investigate how high resolution models verify compared to models with coarser resolution. The verification is performed against conventional surface observations, and against Synthetic Aperture Radar images which generate high resolution wind fields with resolution less than one kilometer.

Our results show that a horizontal resolution of at least 1 km is required to realistically reproduce wind fields along the Norwegian coast, and that high resolution models are far superior to models with coarser resolution. The predictability studies show that the errors grow very slowly in a 48 hour forecast, and hence indicate that high resolution models with a resolution of approximately 1 km can indeed be useful, and better than reported in previous works in the literature.

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1 Introduction

For several years real-time numerical weather prediction has spread rapidly from operational centers such as the ECMWF (European Centre for Medium Range Weather Forecast) to universities, governmental agencies and private companies. Increased computer power combined with lower hardware costs have made real-time forecasting at very high resolution possible. Unfortunately, model verification is not always performed for such forecasting systems. Hence, many forecasters have little or no understanding of how models with high resolution perform relative to synoptic scale models. Furthermore, as the resolution and physics of operational models change, the forecaster's experience in interpreting model results may no longer be useful. Therefore, it is imperative that objective verification of high resolution models is done routinely so that forecasters and model developers can extend their skills.

In this paper we communicate a case-study on predictability of numerical weather predictions based on two different models, MM5 and MC2, with horizontal resolution down to 250 m. Predictability is evaluated using standard statistical measures and a new high resolution Synthetic Aperture Radar (SAR) wind product. The fields we focus on are wind and temperature in complex Norwegian terrain.

There are several sources of forecast errors, including physical process parameterizations, initial conditions, see e.g. Tribbia and Baumhefner [1988], numerical algorithms and surface forcings. A number of studies, see e.g. Warner et al. [1997] for details, have demonstrated that the lateral boundary conditions (LBCs) of limited area models (LAMs) may have a significant impact on the evolution of the fields through the propagation of boundary errors into the interior of the domain. The boundary conditions for LAMs are normally obtained from coarser mesh models, such as the ECMWF model with 0.5 degrees horizontal resolution we use in this study. Tribbia and Baumhefner [2004] investigate show different scales in the atmosphere interact and what implications that have on the error growth. This study also shows how errors in the initial conditions can be a limiting factor on the accuracy of fine scale LAMs.

There have been several studies of predictability of models with various resolutions. Anthes [1986], Baumhefner [1984] and others have focused on the growth of synoptic scale errors and their impact on predictability. Results from Baumhefner [1984] indicate that the typical error doubling time is about 2 days for the synoptic scale and that it may decrease with decreasing scale. Tennekes [1978] suggests that the error growth in mesoscale models are caused by the transfer of energy from smaller scales to larger scales by backscatter, which further constraints the predictability.

However, for mesoscale phenomena whose spatial spectrum do not resemble the spectrum of turbulence, this rate of energy transfer and thus the forecast error may be quite different. Warner [1994] suggests that some mesoscale phenomena may be more predictable than others, especially those forced by strong fixed surface features such as the mesoscale terrain. This statement has not been widely checked and many efforts in mesoscale numerical forecasting are based upon this assertion.

Predictability of LAMs is examined in Elía and Laprise [2002] by comparing the results from models using high resolution on the outer model, and models using the nesting strategy. The rather pessimistic result in Elía and Laprise [2002] is that inner models are not capable of improving the predictions of the coarser scales as well as producing accurate results on finer scales. Predictability is obviously dependent on the model domain, resolution, topography and weather situation, so one can not relate the results in Elía and Laprise [2002] directly to our case-study. Other case-studies e.g. Holstad et al. [2001], have shown very good predictability of very high resolutions models due to the strong influence by the topography. An interesting result from Elía and Laprise [2002] is that if the initial condition in the inner model contain elements of the finer scales, the predictability will be much better for all scales, despite that the boundary conditions contain only coarse scales.

A growing number of verification studies evaluating model forecasts have been performed. The studies by e.g. Colle et al. [1999], Mass and Kuo [1998], Mass et al. [2002], White et al. [1999] and Nutter and Manibianco [1999] have been using the MM5 model. Both subjective and objective evaluations have found clear benefits in increasing the model resolution in regions where orographic flows or diurnal circulation are important. Rao et al. [1999] used two-way nesting procedure with 1.6 to 0.1 km horizontal grid spacing to show that less than 1 km was required to realistically simulate the diurnal circulation of the Cape Canaveral region of Florida using the ARPS mesoscale model. Davies et al. [1999] demonstrated that reducing the grid spacing in the MM5 forecasts from 10 to 1.1 km helped to improve the simulation of the diurnal circulations over Utah produced by the variable surface conditions and topography. Hauge and Hole [2003] showed that high horizontal resolution was essential to capture the break-up of a temperature inversion over Norwegian inland topography. Other studies, such as Mass et al. [2002] have shown that higher horizontal resolution improved the realism of the forecasts, but not necessarily the objectively scored forecast skill.

Verification of real-time forecasts at fine scales over Norway have up to now been few. Berge et al. [2002] investigated a 1 km MM5 setup for the city of Oslo, for air pollution purposes with mostly weak winds.

The remaining of this paper is organized as follows: Section 2 describes the model configuration used for MM5 and MC2, respectively. In section 3 we present verification for the Melkøya site from November 1 2005 to January 10 2006. Section 4 contains verification using the new high resolution SAR wind product which provides both wind speed and direction over a large area. Finally, we give a conclusion and recommendation for further work.

2 The MM5 and MC2 model configurations

In this section the MM5 and MC2 model configurations for the case-study are described in detail. We use nested models, which means that a model of comparatively coarser resolution and larger model domain provides initial conditions (ICs) and boundary conditions (BCs) to a model with higher resolution and smaller model domain. As will be described below, both in the MM5 and MC2 model configurations there are several levels of nesting.

Processes that are not resolved explicitly by the models are calculated with parameterization schemes. This can be parameterization of turbulence, the soil surface, radiation, explicit moisture or cumulus clouds. Different parameterizations are used in the different levels of the nesting. A detailed discussion of the parameterizations is beyond the scope of this study. We focus on those that may contrast the models and those that will be commented on in the discussions.

2.1 Model configuration for MM5

MM5 is an extensively used numerical weather prediction system for operational weather forecasting and research. The model has a flexible configuration system making it easy to setup a nested model system. In our case-study we use a nested configuration of MM5 where the ICs and BCs come from ECMWF at 0.5 degrees horizontal resolution and with update of the BCs every 6 hours. To obtain the 1 km horizontal resolution MM5 predictions, the ECMWF data are nested in three steps:

- ECMWF 0.5×0.5 degrees $\rightarrow$ MM5 9km
- MM5 9km $\rightarrow$ MM5 3km
- MM5 3km $\rightarrow$ MM5 1km

This is done with a 1-way nesting, see figure 1, which means that the 9km domain provides ICs and BCs for the 3km model and the 3km model output provides data for the 1km model. In contrast to the MC2 model (see section 2.2), this nesting is done in the same model simulation. An advantage of this is that the BCs for the finer grid (3 and 1km) are updated every time step. The grid dimensions for the 9, 3 and 1km domains are all 100×100 grid points. In the vertical 29 unevenly spaced full-sigma levels[1] are used, with 12 layers below 1 km and model top at 50 hPa. The forecast length is 48 hours, initialized twice daily at 00 and 12 UTC. Initialization is made by the +12 to +60 hours forecasts from the ECMWF model. This is due to the delay of the forecasts and the need for running the MM5 configuration in an operational mode.

[1] The 29 full sigma levels were $\sigma = 1.00$,0.995,0.993,0.989,0.985,0.98,0.97,0.96,0.945,0.93,0.91 ,0.89,0.85,0.80,0.75, 0.70,0.65,0.60,0.55,0.50,0.45,0.40,0.35,0.30, 0.25,0.20,0.15,0.10,0.05,0.00

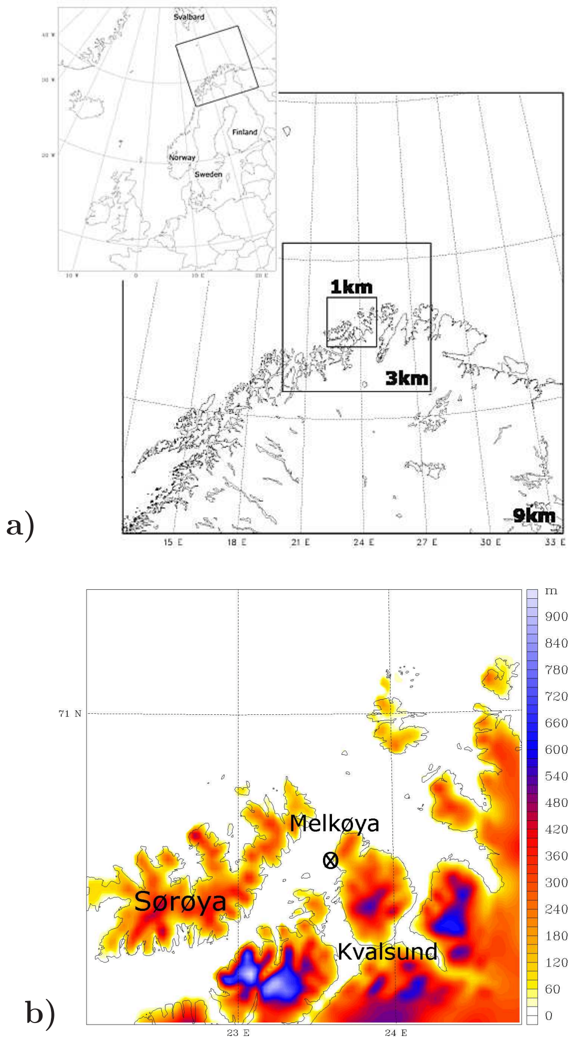


Figure 1: **The MM5 9km, 3km and 1km domains used in the study are showed in a). b) shows the 1 km model topography. The location we use in the case-study is Melkøya, marked with a cross.**

In the MM5 configuration file one of the most important parts is the specification of the parameterization schemes. These schemes may affect the model results near the surface quite significantly, and there is an ongoing discussion on their resolution dependency.

In this configuration a turbulence parameterization scheme based on Hong and Pan [1996] is used.This scheme is suitable for high resolution in the Planetary Boundary Layer (PBL) and is numerically very efficient. The vertical diffusion uses an implicit scheme to allow longer time steps in the integrations. It is based on Troen-Mahrt representation of the counter-gradient term and a diffusion coefficient profile in the well mixed PBL, for details see Hong and Pan [1996]. This parameterization is strongly coupled to the description of the surface which is described by a five layer soil model. In this model the temperature is predicted by solving a one-dimensional diffusion equation in the vertical direction, assuming fixed substrate below the surface. The thermal properties are taken from the global 1 km USGS dataset, see Eidenshink and Faundeen [1998]. The surface scheme takes the diurnal temperature variation into account, allowing for more rapid responses of the surface temperature.

A mixed phase explicit moisture scheme, the so called Reisner scheme, see Reisner et. al (1996) , describes condensation. It has prognostic equations for cloud water, rain, ice, water vapor and super cooled water. The outer 9km domain, also has cumulus parameterization to take cumulus clouds into account. This is necessary at such a coarse grid since cumulus clouds are not directly resolved in the model. The scheme uses a sophisticated cloud-mixing scheme to determine entrainment/detrainment, and also removes all available buoyant energy in the relaxation time. For details see Kain and Fritsch [1993]. Further information on the MM5 modeling system can be found in Grell et al. [1994] or at http://www.mmm.ucar.edu/mm5.

2.2 Model configuration for MC2

The ICs and BCs for the MC2 modeling system are results from a MM5 model with 12 km horizontal resolution on a domain covering Scandinavia and the Norwegian Sea using ICs and BCs from ECMWF, initialized twice daily at 00 and 12 UTC. The nesting principle is the same as for MM5, 1-way nesting, but the MC2 runs consist of a sequence of model runs. The MC2 model configuration is:

- MC2 3km on a relatively large domain, see figure 2. The number of grid points is $150 \times 130 \times 26$ with model top at 20 km. Ten of the vertical levels are below 1 km. Forecasting periods are 03 UTC: +24 hours, 15 UTC: +24 hours, with output of weather predictions every 3 hours and nesting data for MC2 1km every hour. The time step in the computations is 45 seconds.

Figure 2: **The MC2 3km 1km and 250m domains, respecitvely. The magenta dot indicates Hammerfest, the town southeast of Melkøya.**

- MC2 1km on a smaller domain, see figure 2. The number of grid points is $75 \times 85 \times 50$ with model top at 20 km, with 20 vertical levels below 1 km. Forecasting periods are 05 UTC: +6 hours, 05 UTC: +19 hours, 11 UTC: +6 hours, 17 UTC: +6 hours, 23 UTC: +6 hours, with output of predictions every hour and nesting data for MC2 250m every 30 minutes. The three first periods use ICs and BCs from the 03 UTC MC2 3km simulation, while the two latter ones use data from the 15 UTC MC2 3km simulation. By dividing a MC2 1km simulation into four periods of 6 hours we obtain a 24 hour forecast. The reason for the short runs is the assumption that the accuracy of such high resolution models decreases relatively fast with time. The very purpose of the 05 UTC: +19 hours run is to investigate the validity of this assumption. The time step in the simulations is 24 seconds.

- MC2 250m on a still smaller domain, also shown in figure 2. The number of grid points is $91 \times 91 \times 60$ with model top at 15 km, with 10 levels below 100 m and 30 below 1 km. Forecasting periods are 07 UTC: +1 hour, 19 UTC: +1 hour, with output of weather predictions every 15 minutes. The time step in the computations is 3 seconds.

There are several turbulence schemes available in MC2. In the 1km configuration we have used an advanced scheme which takes moisture into account. For the 3km and 250m configurations we have chosen a simpler scheme. The

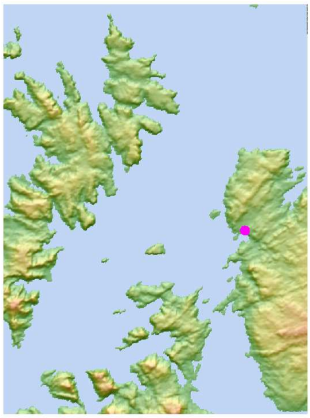


Figure 3: **A 100 m model topography of the Melkøya area. The magenta dot indicates Hammerfest. Melkøya is the small island northwest of this town. The panel is useful in understanding how the topography influences the wind at Melkøya.**

surface scheme is a simple "Force-Restore" scheme, we do not have enough data to use a more sophisticated scheme like ISBA. There are also several condensation schemes suitable for high resolutions available in MC2. In the 3km we have used a sophisticated scheme with one ice phase, whereas in the 1km we have used a simpler scheme. As the simulation period is only one hour for MC2 250m, we neglect radiation. We also decided to neglect any moist processes, as we question how well these are represented at such a high resolution.

For more information about MC2 see Benoit et al. [1997] or http://collaboration.cmc.ec.gc.ca/science/rpn.comm.

2.3 Verification methods

In the verification, the model results are compared to convential observations (corrected for any obvious errors) every hour in the test period.

The the case of MM5, the model values at the lowest σ-layer were reduced to an elevation of 10 m for wind, using a logarithmic profile. In MM5 the winds and temperature were then interpolated at the observation location by Cressman interpolation , see Cressman [1959], while in MC2 bilinear interpolation was used.

Error statistics for the model runs are presented in terms of the mean error

(ME) and the absolute mean error (MAE) defined by

$$ME = \frac{1}{N}\sum_{n=1}^{N}(x_n - y_n)\,, \qquad MAE = \frac{1}{N}\sum_{n=1}^{N}|x_n - y_n|, \tag{1}$$

where x_n is a forecast value, y_n is the corresponding observation, and N is the number of forecast-observation pairs that were compared.

The ME and MAE are also used as measures of the predictability, discussed in the next section.

3 Verification of the MM5 and MC2 models

Verification of models at high horizontal resolution is a challenging task, see Mass et al. [2002]. . This task is even more difficult in our case-study since the observation network in Norway is relatively sparse. The conclusions we can draw from a verification at a single point are limited, but it does provide useful insights. Moreover, the high resolution in time of the observations we use gives an opportunity to investigate sudden changes of wind and temperature. Melkøya is an island shown on figure 1, or more detailed in the 100m topography model displayed in figure 3. The island is close to the city of Hammerfest at 70 degrees north. In the 1 km MM5 and MC2 topography the Melkøya island is not directly resolved in the models. The island is small and has negligible topography so the influence of the island on the wind measurements are believed to be limited. The observations and the model results are therefore reasonably representative for the wind conditions over the sea in the nearby area. Moreover, the weather conditions in the Melkøya area are strongly affected by the topographic forcing and the weather conditions upstream, for example drainage wind from the inland winter-time and synoptic scale weather phenomena coming from the west.

As a measure of forecast improvement we compare the model output from MM5 and MC2 with the ECMWF 0.5 degrees global data interpolated to the Melkøya site. Data are only used when both observations and results from the two models are present, giving a sample size of 896 hourly forecasts. The period investigated in this study is from November 1, 2005 to January 10, 2006. We compare the model results to SAR wind speed and wind direction in next section.

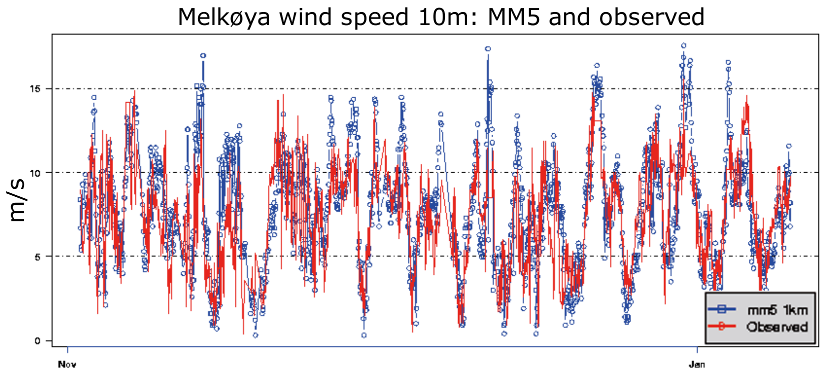
3.1 MM5 verification

In the verification we primarily focus on wind speed and temperature. Unfortunately precipitation was not observed at Melkøya, but other studies have shown that precipitation verification for very fine scale models is poor. This is mostly due to deficiencies in the model microphysics which are tuned for other resolutions than the ones used in this study.

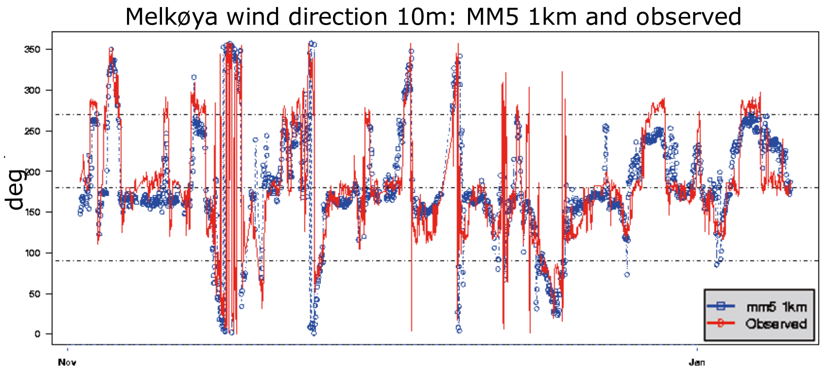
As seen on figure 4a, there are large fluctuations of the wind speed and direction during the test period. The figure shows forecasts from both cycles from forecast hour 6 to 18, to be consistent with the MC2 runs.

The ME of the forecasted MM5 wind speed for this period is (defined in section 2.3) 0.20 ms^{-1} and the MAE is 2.00 ms^{-1}, see table 1. This shows that the results are reasonable on the average, but somewhat disappointing for weak winds. MM5 captures the larger variations of wind speed quite well, but some of the smaller fluctuations seen in the observations are not present in the model results.

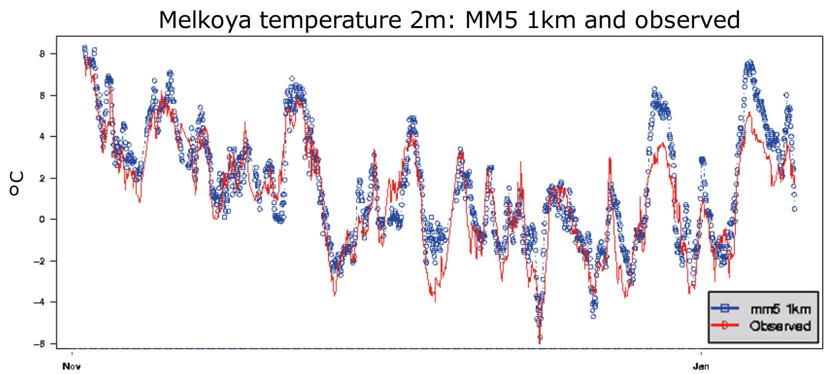
Figure 4 shows that southerly winds occur relatively often in the period.



a)



b)



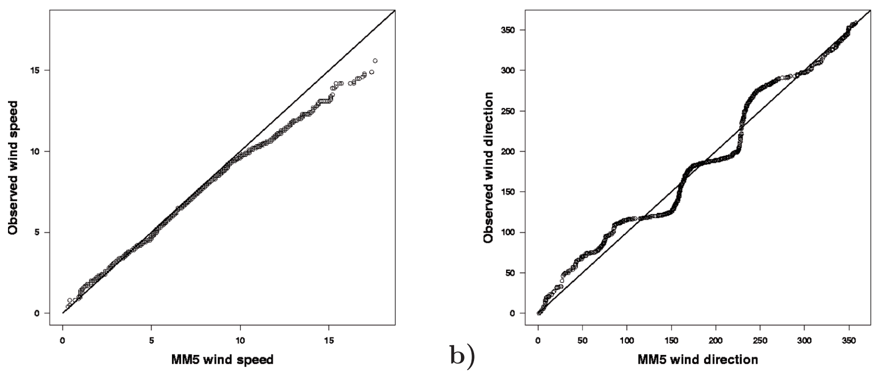
c)

Figure 4: **Time series from November 1, 2005 to January 10, 2006 at the observational site. The blue line is the MM5 1km values from forecast hour 6 to 18. The red line gives the observations. a) shows the 10 meter wind speed, b) the wind direction and c) the temperature in 2 meter, $\mathbf{T}_{2m}$.**

This implies that phenomena such as topography dominated drainage flows will affect the wind conditions at Melkøya. Such phenomena are not well predicted by MM5, partly due to model topography.

There are also indications that MM5 has problems in predicting correct wind speeds in case of northerly winds. It is difficult to explain this model deficiency. The quantile-quantile plots on figure 5, reveal that the model wind speed is overestimated for observed winds larger than 10 ms^{-1}. It has been discovered that the instruments may have had problems with measuring strong winds in our test period, so the overestimation is not necessary a model deficiency.

The wind direction has larger fluctuations in the error, mainly in directions around south-southeast. The MAE for the wind direction in figure 4 is 27.9 degrees. This error is mainly caused by the lack of small scale fluctuations around southerly wind directions in the model results. The errors in northwesterly wind directions may be related to the large island (Sørøya) west of Melkøya.



a) b)

Figure 5: **Quantile-quantile plots of the wind speed and wind direction for the forecast hours 6 to 18. a) shows the wind speed, and b) the wind direction. The data used in this plot are the time series displayed in figure 4.**

The two meter temperature, T_{2m}, is reproduced very well with a ME of $-0.60°C$ and MAE of only $1.06°C$. An interesting feature is however the larger errors seen in the temperature forecasts in late December and early January. It is an open question whether this is due to errors in the wind direction or deficiencies in the model.

3.2 MC2 verification

The quality of the MC2 forecasts are similar to those of MM5, both for wind speed, wind direction and temperature despite the fact that the model configurations are different and the nesting strategy is different.

For example, the MAE for wind speed is 2.00 ms^{-1} for MM5 and 2.02 ms^{-1} for MC2, see table 1. Corresponding numbers for the ME in wind speed are 0.20 ms^{-1} and -0.78 ms^{-1}. A marked difference in the wind speed predictions between the two models is seen in November where the large peaks in the MM5 results are not seen in the MC2 results. In the period November 12 to November 21 the wind direction was mainly from the north-northwest, and it seems that MC2 has less problems with this wind direction than MM5 has.

The MC2 temperature forecasts are slightly better than for MM5, with MAE 0.91°C, which we consider as fairly good. The bad predictions in late December and early January are also seen for MC2, but are not so pronounced.

There are far fewer model results from the MC2 250m model than for the 1 km models. This is due to operational constraints. The results from the MC2 250m show a slight increase in forecast skill compared to the 1 km models, particularly for wind speed. This is probably due to better model topography near the observation site. It is difficult to draw conclusions based on this limited material whether the 250m model will be an improvement than can justify the extra computational cost. However, it is encouraging to see that there is an improvement in forecast skill for wind speed since we may not have used the optimal configuration of the model, and there is a room for improvement in the parameter fields, e.g. the surface roughness and the sea surface temperature.

	Wind speed		**Wind direction**	$\mathbf{T}_{2m}$	
	ME	MAE	MAE	ME	MAE
MM5 1km	0.20	2.00	27.91	-0.60	1.06
MC2 1km	-0.78	2.02	28.65	-0.42	0.91
MC2 250m	-0.45	1.87	27.53	-0.36	0.91

Table 1: **ME and MAE of wind speed, wind direction and $\mathbf{T}_{2m}$ for the MM5 1km, MC2 1km and MC2 250m models in the test period. The errors are averages from forecast hour 6 to 18 where the forecasts are expected to be best.**

3.3 MM5 predictability as a function of forecast length

There are different measures of predictability used in the literature, see e.g. Lorenz [1982], Simmons et al. [1995], Anthes et al. [1985] or Tribbia and Baumhefner [2004]. In this study we use ME and MAE in order to investigate the predictability of our forecasting system. We investigate the predictability for wind speed, wind direction and temperature as a function of forecast length.

In our definition of predictability, MAE is the best measure since ME can have compensating errors. This is very different compared to the standard verification of for instance the ECMWF model which uses the 500 hPa geopotential height anomaly as the measure of predictability. Our predictability measure is strongly coupled to the short time scales associated with winds in complex terrain, where the local variability of temperature and especially winds are large.

We have calculated ME and MAE for every hour in the test period. A distinction between the cycles has also been made to see possible effects of diurnal variations. This gives approximately 65-70 quality controlled observations for each forecast hour. So, the sample is somewhat limited, but large enough to be used for an evaluation of the winter time predictability of the model configuration at this site.

Figure 6 shows that the MM5 model needs approximately 3 hours in order to generate its own circulation patterns. This is seen most clearly in the 00 UTC run which has a large ME the first hour of the verification. Both model cycles give a positive bias on the average of the wind speeds. It is also seen that there is a possible diurnal variation of ME during the first 24 hours of a simulation. In the morning, between 6 and 9 UTC, the ME changes from positive to slightly negative. This may be caused by the underestimation of surface drainage winds coming from the inland.

For the wind speed, the ME has little or no amplification during the model runs, but the MAE seen on the right panel of figure 6 shows a near linear increase of the forecast error after 18 hours. The error growth is however quite small, the MAE is only increased by 0.5 ms^{-1} from forecast hour 18 to 48.

Similar results are seen for the errors in the wind direction where there is slower error growth the first day of the forecast. The errors in the wind direction have a near linear increase during the 48 hour forecasting period. As discussed, the errors are associated with northwesterly and southerly winds.

The temperature patterns are quite similar with a slow error growth. The ME is negative, meaning that the MM5 temperatures on the average are too low. MAE has a slow linear increase. In both 00 and 12 UTC model runs the errors seem to have a minimum early in the morning.

There seems to be no significant diurnal variation in the temperature errors. Since our test period is during winter and the site is at 70 degrees north, there is no distinct diurnal variation of the temperature at the coast where our site is located. Hence, the lack of diurnal variation in the temperature error is to be expected.

3.4 MC2 predictability

For MC2 we have chosen the following experiment in order to investigate short term predictability: We want to compare two short term (6 hour) 1 km runs based on the most recent 3 km runs (00 UTC and 12 UTC), to a long 1 km run

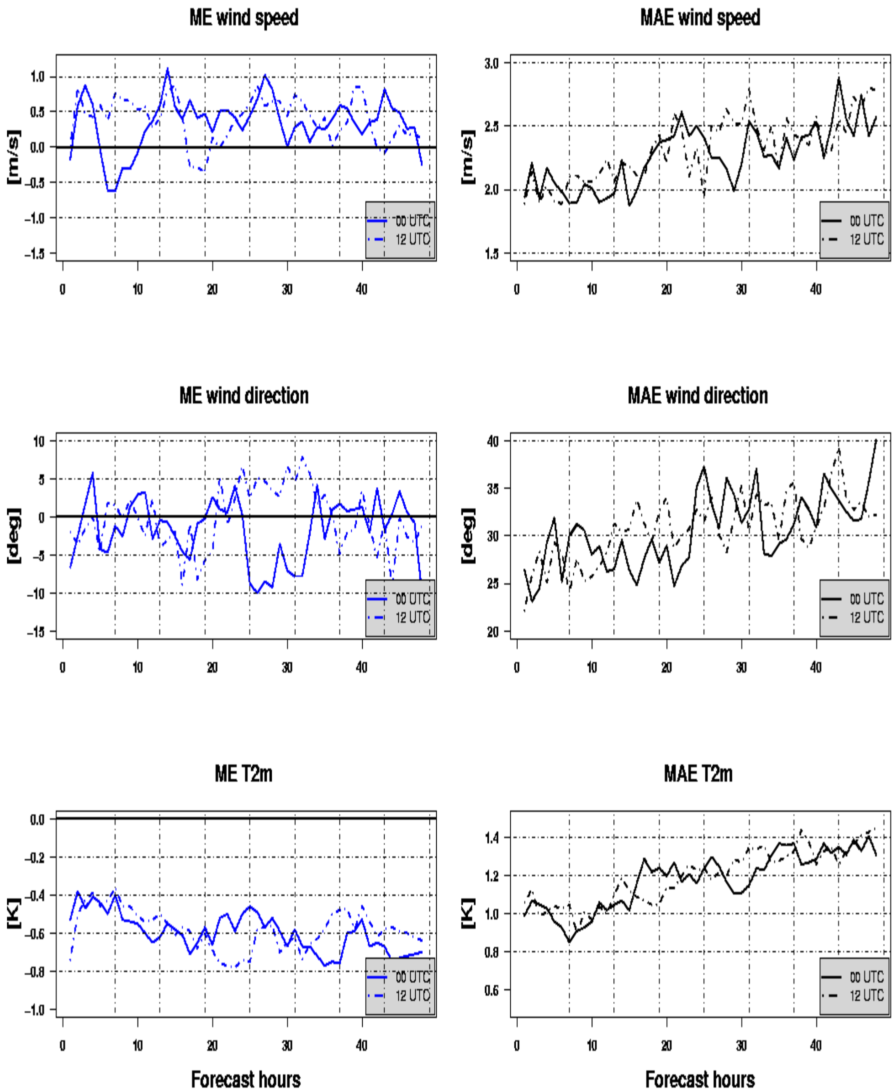


Figure 6: **ME and MAE for wind speed, wind direction and temperature from the MM5 model runs at 00 and 12 UTC as a function of forecast hour.**

(19 hours) based on the 12 UTC-based 3 km run. By this we want to investigate if there is a benefit in using the latest available 3 km run for nesting. In this configuration, the results of the first 6 hour run and the first 6 hours of the 19 hour run should coincide. As described in the previous subsection, the error growth for MM5 is quite small, and this is what we may expect for MC2 too. We use the period from February 13 to February 20, 2006 since there were some interesting weather changes in that week.

Figure 7 shows a plot of the model results and observations of T_{2m} at every hour, from 18 UTC to 12 UTC the following day, for every day in this week.

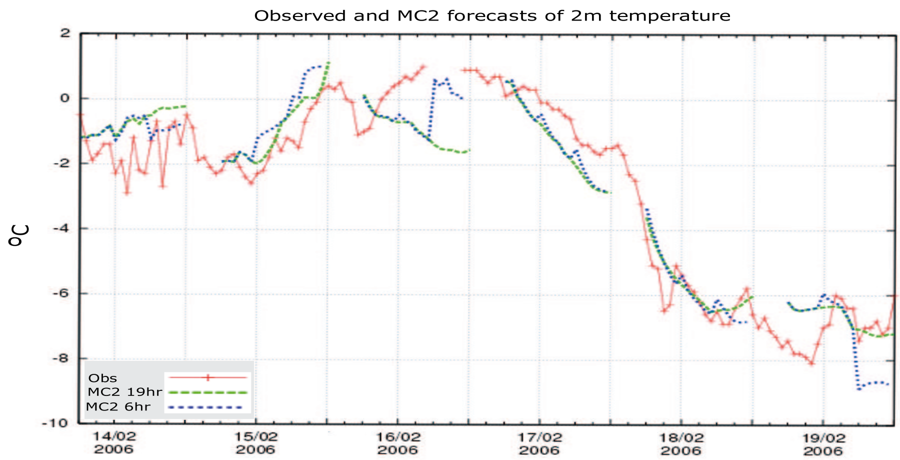


Figure 7: **MC2 6 and 19 hour forecasts of T_{2m} compared to observations, February 14-19, 2006.**

From the figure we can identify two characteristics which should be fairly obvious, but still important to verify:

- In periods where the temperature changes fast the 19 hour run is not capable of following the development, see in particular February 16. However, it is not always the case that the 19 hour run is worse, e.g. February 19. The difference between the results of the 19 hour run and the 6 hour runs can be significant, we see that at the end of February 16 the difference is about 2°C, only after 6 hours.

- In periods where there is a more or less steady change in the temperature, the 19 hour run and the 6 hour runs differ very little.

As our experiment is only based on data for a week and in the winter, it may not be representative for all seasons. However, we assume that the results also will be valid for all seasons since the location is so far to the north that atmospheric phenomena like strong convection evolving over a short time, which may lead to bad predictability for fine-scale models, will be rare events.

3.5 Forecast skill of the ECMWF model

To evaluate the forecast gain of the model configurations studied here, we have calculated ME and MAE for the ICs and BCs provided by the ECMWF model. This is done every 6 hour when the BCs for MM5 correspond to the ECMWF data. Table 2 shows the ECMWF error statistics for the wind speed, the wind direction and the temperature.

ECMWF Error statistics				
Forecast hour	**Wind speed**		**Wind direction**	$\mathbf{T}_{2m}$
	ME	MAE	MAE	MAE
18 (6)	-3.5	3.5	22.2	3.2
24 (12)	-3.2	3.3	19.4	3.3
30 (18)	-2.7	3.2	25.2	3.1
36 (24)	-2.9	3.3	21.0	3.0
42 (30)	-3.2	3.5	30.2	3.3
48 (36)	-3.1	3.3	25.3	3.5
54 (42)	-3.2	3.5	32.8	3.5
60 (48)	-3.1	3.7	34.8	3.6

Table 2: **ME and MAE for wind speed, wind direction and $\mathbf{T}_{2m}$ for the ECMWF model in the test period. Forecast hours are the actual forecasted hours of the ECMWF model, and the numbers in parenthesis are the corresponding forecast hours of the MM5 model.**

Compared to the results presented in subsection 3.3 and 3.4 it is evidently a strong underestimation of the wind speed at the observation site. The MAE is between 3.2 and 3.7 ms^{-1}. This is probably due to the fact that the land use in the ECMWF model at Melkøya is land, hence the roughness at the site may be too high. The wind directions in the ECMWF data are similar to the ones from the MM5 and MC2 runs. The large scale pressure gradient is much the same in MM5 and ECMWF, giving approximately the same errors for the two models for the wind direction.

It is also clear that the increased resolution by MC2 and MM5 have much greater capability to forecast the temperatures. The inland air masses are in many occasions cold, and the temperatures are strongly coupled to drainage winds coming out the fjords. Since these effects are absent in the ECMWF it is clear that the temperature errors will be large.

Errors in LAMS are in many cases strongly limited by the quality of the boundary data used. It is however interesting to see that the forecasts produced by the MM5 1km model contains its own wind structures with a considerably better statistical score. The largest forecast errors of MM5 1km are strongly linked to large errors in the boundary data, even if the forecasts in most cases produce significantly better forecasts than the ECMWF model itself.

4 Application of SAR images for wind field verification

AA major problem with evaluation of very fine scale atmospheric models in Norwegian terrain is the lack of spatially distributed observations. In order to investigate how the wind fields verify for the MM5 and MC2 models, we have used the same model configurations as described in section 2. The model runs were initialized at 00 UTC with hourly output of the fields. We have chosen to investigate winds at February 15, 2006, a day which was dominated of winds from southeast over land, and with a warm frontal zone coming in from the west. Such a weather situation results in channelling of the wind fields from the fjords. Traditional forecasts made from coarser resolution models such as MM5 9km presented in figure 10a, hardly show any such effects from the fjords. However, for many of our 1km model runs we find large wind gradients in the model results. Further, it is well-known that predicted winds can change dramatically within 10 km from the Melkøya site.

Several works have shown that high resolution wind fields derived from SAR are useful for validation of modeled wind fields, see e.g. Furevik and Sandvik [2002] or Furevik et al. [2002]. In this paper we therefore also verify the wind fields from our models against SAR wind fields to demonstrate this capability.

Figure 8: **Envisat ASAR image from 09.21 UTC 15 February 2006. Courtesy of Nansen Environmental and Remote Sensing Center and ESA**

4.1 Derivation of wind speed from SAR images

The methods for estimating wind speed from SAR imagery are similar to the ones used for scatterometers: resonant scattering of radar waves (typically of 5 cm wavelength) from wind induced sea surface waves. These waves are strongly correlated to the near surface wind speed. The direction of the wind relative to the satellite look direction must however be taken into account when retrieving the wind speed, since the resonance is much stronger for waves traveling in or opposite the radar look direction. For scatterometers this is done by looking at the same pixel from various directions as the satellite is passing. A SAR, on the other hand, has only one side-looking antenna, and thus only one measurement of a given location is possible. Therefore, to estimate the wind speed without ambiguity, the wind direction must be taken from an external source, usually from numerical models or from scatterometers covering the same area at approximately the same time. However, in some cases the wind direction can be inferred directly from the SAR image itself, if there are streaks in the image due to boundary layer rolls, which are normally aligned with the wind direction. The accuracy of SAR-derived wind speed is comparable to the accuracy from scatterometers, about 1-2 ms^{-1} standard deviation when compared to buoy measurements see Monaldo and Kerabaol [2004] for details, but at a resolution of less than one kilometer, compared to 25 kilometers for scatterometers. The higher resolution makes SAR able to resolve mesoscale wind phenomena like e.g. fjord jets and sharp fronts. In our case, an Envisat SAR scene from February 15, 2006 at 09:21 UTC (figure 8) is combined with wind directions from the 9 hour ECMWF 0.25 degrees forecast at 09:00 UTC to estimate the wind speed, see figure 9.

4.2 Verification of the wind at 09 UTC February 15, 2006

The MM5 forecasts, see figure 10a-10c, reveal many interesting features - ranging from mesoscale phenomena to complex local scale wind patterns. As seen on figure 9a there is a sharp warm frontal zone present on the west side of the coast. In association with this front a strong wind shear is seen where the wind speed drops from 16-18 ms^{-1} to almost no wind and the wind direction changes from southwesterly to easterly. In the coastal areas, see figure 9b, the complex local scale wind patterns are evident with strong winds coming out from the fjords. It is also seen that there are strong channelling effects giving local maxima of approximately 20 ms^{-1}. The wind gradients are very large - the lee-side wind wakes are easily seen on the SAR derived wind images.

The MM5 forecast presented in figures 10a-10c show the mesoscale structures described above. The position of the frontal zone seems reasonably good, but is somewhat further north than seen on the SAR image. One should however note that different map projections are used on the SAR image and in the MC2 and the MM5 configurations. The MM5 9km, figure 10a, shows little or

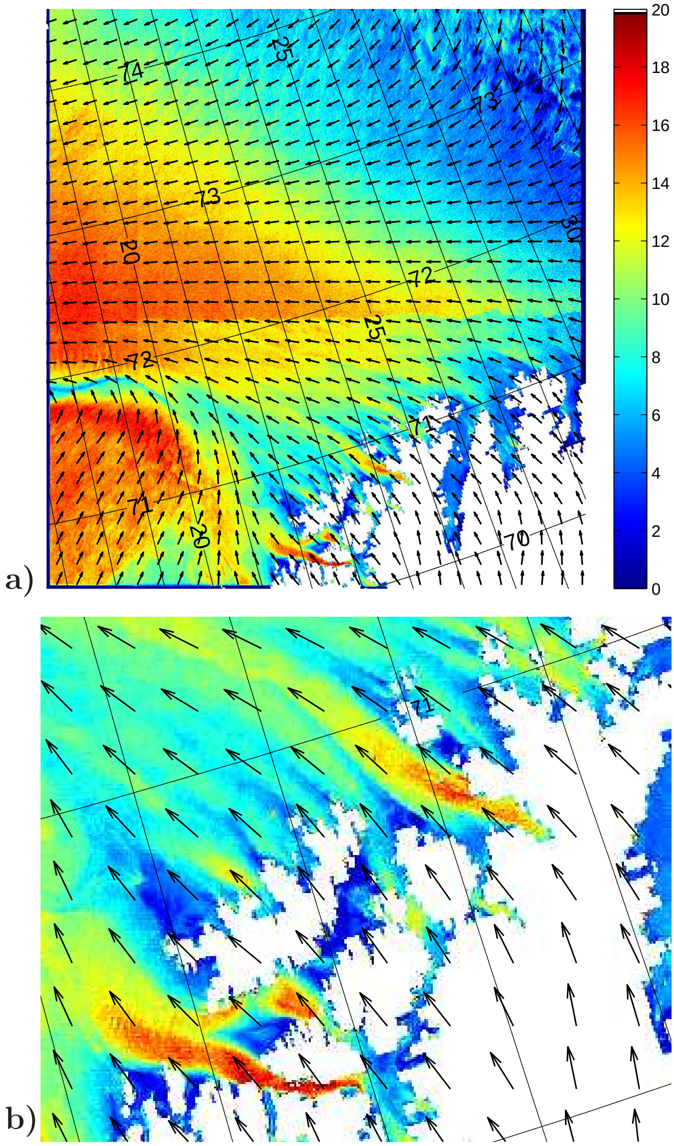


Figure 9: **SAR derived wind speeds observed at 09.21 UTC February 15, 2006. a) shows the entire area covered by the satellite. b) shows a close-up of an area around Melkøya.**

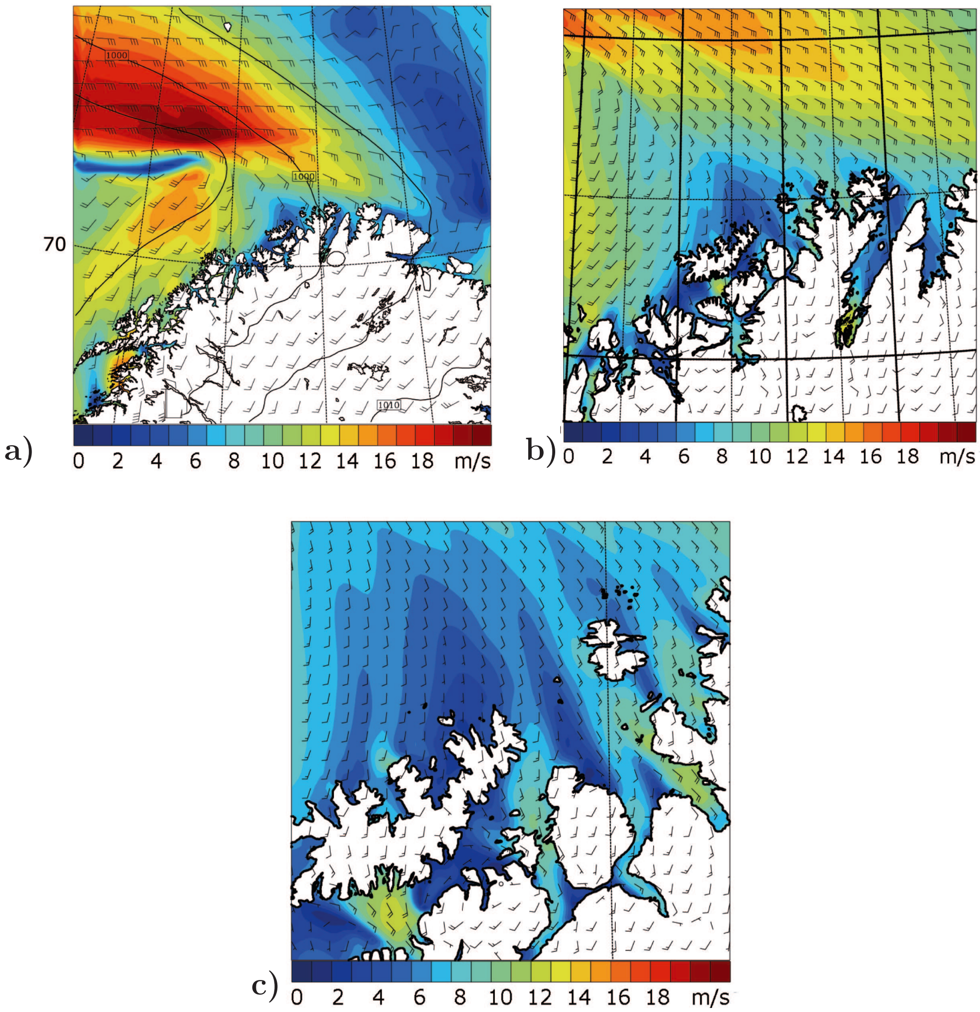


Figure 10: **a) the MM5 9km, b) 3km and c) 1km forecasts at 09 UTC February 15, 2006. Long barbs on the wind arrows denote 5 ms^{-1} and short denote 2.5 ms^{-1}**

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no effects of the channelling seen on figure 9b. For the MM5 3km there are indications of these effects but not very clear, see figure 10b. The really clear local effects are seen when the model resolution is increased to 1km. The jet north of Kvaløya, which is often seen in MM5 1km forecasts over the island is clearly present, see figure 10c. The maxima in the observed SAR-jets are stronger than what the MM5 1km is showing. This may be caused by too high roughness over land and sea.

For MC2 we have compared the results from the 3km and 1km models with the SAR wind. In the 3km results the location of the front is rather accurate, but the wind to the south of the front is 1-2 ms^{-1} too weak, which also is the accuracy of SAR derived winds. The wind speed pattern to the north of the front is more accurate in terms of magnitude and location, but there are no visible jets from the fjords, similar to what we saw in the MM5 results. The results from the MC2 3km run and 1km are presented in figure 11a and 11b. We see very similar wind patterns to the SAR winds in figure 9b. The jet north of Kvaløya (the island on which Hammerfest is located) is clearly seen but is more smoothed out and located more to the south than on the SAR image. The regions with stronger winds west of Melkøya and in Kvalsund are clearly visible. The wind speed is slightly lower in the model than on the SAR image. The jet on the southeast side of Sørøya is also seen, but the wind direction over Sørøya in the model results are different (and probably more realistic) from the SAR winds where the wind direction is taken from a large scale model, which is not able to take such fine scale wind patterns into account. The frontal zone is also very clear on the MC2 run at 3km (see figure 11a).

There are marked differences between the wind field from the MM5 and MC2 models over land, but this cannot be verified by SAR images. Some fine scale features are seen in the SAR derived wind, not visible in the MM5 and MC2 model results. Our 1km models have high resolution, but there are details we do not see in the results due to the 1km topography. As we have pointed out in section 3 our model configurations do depend on the ICs and BCs which may not be sufficient accurate for the 1km models to produce a highly accurate wind field. For the purpose of creating very fine scale wind forecasts for this region the 1km horizontal resolution seems to be necessary in order to capture the essential part of the wind patterns.

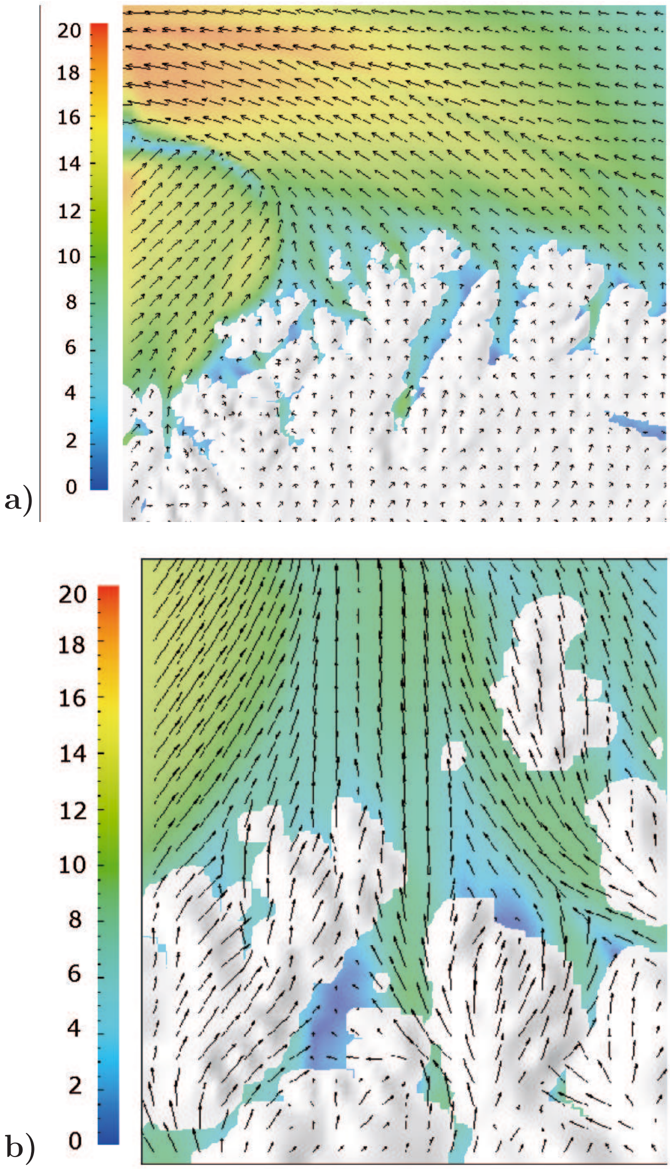

Figure 11: **a) MC2 3km winds and b) 1km at 09 UTC February 15,2006.**

5 Conclusion

I In this study we have investigated the forecasting skill of two operational very high resolution model systems using limited area nested models, MM5 and MC2, down to 250 m horizontal resolution. Our primary goal has been to study the applicability of such high resolution models in short term forecasting. Operational forecasting systems using models down to 1 km resolution are not common, and this is due to lack of suitable parameterization schemes, lack of good parameter fields and to some extent computer resources. It is therefore of interest to investigate the forecasting skills of current high resolution models, also in the context of the improved quality and resolution of global models.

In this study we have seen that the high resolution models verify considerably better than the initial and boundary conditions coming from the ECMWF global model. Hence there is a real value in the high resolution forecasting system. Moreover, the high resolution models produce realistic spatial wind fields in the complex terrain surrounding the test site. In addition to classical verification we have applied SAR images to derive high resolution wind fields. Such wind fields do unfortunately not have high resolution in time, but gives a high resolution wind field over a large area. Our model systems are able to predict fine scale wind patterns like jets from the fjords in a very satisfactory way as well as larger scale patterns seen in the SAR images.

We have seen that the high resolution models in some cases perform not so satisfactorily, so there is room for improvement. It is expected that data assimilation producing realistic fine scale structures and improved physical parameterizations will improve the quality of the model results in the 1 km resolution range.

The predictability studies we have performed show that the errors grow slowly over a 48 hour period. This is encouraging and we may infer that if we had better initial conditions, the forecasting skill would be improved over the entire forecasting range. There may be several explanations for the slow growth in fine scale forecasting studies. As suggested by Anthes et al. (1985) and others, both the BCs and surface forcing, e.g. topography and land/water contrasts, constrain error growth. There are strong indications that such constraints exist in this study. The orographic forcings dominate for fine scale models in complex terrain, and the fine scale structures in the fields caused by these forcings, change slowly. Moreover, the strength of these fine scale structures is not large enough to be propagated to the larger scales. Hence the total error is controlled by the slow error growth of the larger scales.

In this paper we have pointed out several ways that high resolution models can be improved in order to produce high quality forecasts. The research and development required for such improvements are significant, but we think such a development will greatly benefit the forecasting skill in notoriously difficult areas like in mountainous terrain.

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