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# Rapid Refresh Update Nowcasting with Harmonie-Arome

Roohollah Azad

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**Abstract**

Wind speed and direction can suddenly change due to local weather fluctuations. Forecasting such fluctuations days ahead in time is difficult for the current numerical weather prediction (NWP) models. It is mainly because the NWP is an initial value problem and very small errors in the initialization of NWP model will result in large forecast errors after a few days.

To provide weather forecasts for such conditions a few hours ahead in time one needs a NWP model that runs more often than the current prediction systems. In the current NWP models the short range forecasts are updated every 6 hours and have a delay of several hours. This means that forecasts are 2-7 hours old. In this study, a high resolution NWP system is provided tailored towards fast delivery of high quality and very short term weather forecasts. The high resolution NWP model is updated hourly but in order to avoid delays it is restricted to the use of observations which are quickly available. Forecasts have lead time of only up to 9 hours, are updated more often and thus available within one hour after the analysis time. The NWP system is first tested for a small domain in a research mode and the preliminary results are presented for two different periods. It is shown that for the 10m wind the nowcast NWP scores better in the first 2 hours and that for the 100m wind it provides better wind change forecasts compared to the short range NWP system.

**Keywords**

NWP model, nowcasting, data assimilation, rapid refresh update

Disiplinary signature

Responsible signature

[1] The report summarizes the main outcome of work package H1 NWP based nowcasting.

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# 1 Introduction

Weather forecasting with the aim of numerical weather prediction model (NWP) has gained promising achievements in the recent decades. This is in part due to the ever-increasing resolution of such models which represent the weather features with smaller but more accurate details. Another factor that has contributed to the improved forecast quality is the data assimilation which provides better initialization for the NWP model.

NWP models are capable of simulating larger atmospheric scales. The regional high resolution models infrastructure is developed for lead times of around 2 to 3 days. NWP models have a shortcoming for very short term forecasts in that the updating and delivery framework is delayed by 4 to 7 hours. Even for the first hours the spin-up problems related to data assimilation schemes are problematic. This has lead end-users to seek statistical approaches based on observations as the reliability and skill of NWP forecast is considerably reduced for the very short lead times. Therefore, further research is needed to develop novel NWP based nowcast systems in order to deliver high quality very short range wind forecast.

Precise and frequently updated forecasts are of paramount importance for users dealing with intraday markets at the power exchange. The energy amount originating from wind energy sources cannot be fully controlled. In fact, wind energy production sometimes results in very large fluctuations. Therefore, NWP has been playing a crucial role in planning for wind energy production and the purpose of this study is to improve upon the existing very short range weather forecasting capabilities with the aim to support the wind energy production .

# 2 NWP model set-up

Nowcasting for weather applications has generally been pursued with two approaches, one based on observations and the other based on NWP models (see e.g. Huang et al, 2012). This study concerns the second approach.

## 2.1 Harmonie-Arome and MetCoOp

The limited area NWP model used in this study is the version 38h1.2 and 40h1.2 of a branch of the Harmonie-Arome (Bengtsson et al., 2017). Norway, Sweden and Finland collaborate around the NWP production through the MetCoOp (Meteorological Co-operation on Operational Numerical Weather Prediction) project which covers large part of the Scandinavia (Fig. 1) and is called MetCoOp domain (see Müller et al., 2017). This model has a horizontal resolution of 2.5 km where the horizontal grid (739 × 949 grid points) is defined by a Lambert projection with the center at 63°N and 15°E. In the vertical, sixty five levels are used by a general pressure based and terrain following vertical coordinate, with the model top at 10 hPa and the lowest level around 12 m. The model is forced by the ECMWF model at the lateral and upper boundaries, which has approximately 16 km horizontal resolution and 137 vertical levels. In order to simulate operational runs, ECMWF lateral boundaries used in this study are at least 6 hours old.

Harmonie–Arome uses a non-hydrostatic dynamical core and is based on the fully compressible Euler equations. These equations are discretized in time and space using a two-time-level, semi-Implicit, semi-Lagrangian advection scheme on an A grid. We refer readers to Bengtsson et al. (2017) and Seity et al. (2011) for a complete description of the model physics. However, several modifications is included for the high latitudes to reduce the 2m temperature bias in winter and to improve the low-level cloudiness (Müller et al., 2017). It should be mentioned that deep convection is explicitly represented by the model's nonhydrostatic dynamics at 2.5 km resolution and therefore there is no parameterization of deep convection in the model. Meanwhile, shallow convection is not resolved at this resolution and needs to be parameterized. Achievement of more accurate performance of the Harmonie-Arome especially for the surface parameters is realized through an online coupling with the SURFEX (Surface Externalisée) mode (Masson et al. 2013)l. The reader is referred to Bengstsson et al. (2017) and Müller et al. (2017) for more details regarding the dynamic, physics and surface part of the Harmonie-Arome model.

The upper-air data assimilation in the Harmonie-Arome model is a 3D variational (3DVAR) assimilation scheme (Fischer et al. 2005 and Randriamampianina et al. 2019) based on a three-hourly rapid update cycle (RUC) to analyze wind, temperature, specific humidity, and surface pressure fields. The background-error covariances are calculated from ensemble global perturbed analyses downloaded to the regional domain and projected to a 6-hour forecast. The balances are purely statistical as they are estimated through multivariate linear regression. Moreover, the Harmonie-Arome uses a climatological representation of the background-error without taking into account the time dependency and heterogeneous information in space.

## 2.2 Rapid refresh update

It is essential for a nowcasting system to provide forecasts more often and with much less delay than the short and medium range NWP systems. For example, the MetCoOp operational NWP system is issuing forecasts every three hours but the longest forecasts up to 66 hours are only provided four times per day. The current setup in the Harmonie-Arome is such that the analysis can be updated down to every hour. However, due to spin-up issues in the hydrometeor prognostic variables the hourly update cycling would score worse than the three hourly updating especially for the precipitation. The solution has been to update the analysis every hour but use the first guess (FG) from a host model, so no cycling of FG, an approach called rapid refresh update (RR). As the host model FG is at least 2 hours old the spin-up is less problematic for precipitation (see Auger et al., 2015).

## 2.3 Data assimilation window

To collect the observation for the data assimilation one needs to define a time interval with the analysis time at its centre. How long this time interval should be depends on two factors. First, there is a question whether each observation should be used more than once in the data assimilation. The common practice is to choose the length of data assimilation window to be equal to how often the analysis is updated so that each observation is only assimilated once in the system. Another factor is the timeliness which will be explained further in the subsection 2.5. The analysis is updated every three hours in the Harmonie-Arome version implemented in this study and the data assimilation window is three hours. For the operational MetCoOp system this window is reduced to two hours and 15 minutes for the resean explained in the subsection 2.4. However, in a nowcasting mode the window should be even more reduced so that the forecast is available before one hour after the analysis time. The decision has been to reduce the data assimilation window to one hour while updating the analysis every hour.

## 2.4 Cut-off time

Due to the delivery time limit in a nowcasting application the model run should start sooner than the short-range NWP systems. In the MetCoOp the time it takes after the analysis time to collect observations and start the data assimilation and forecast model run is around one hour and 15 minutes (cut-off time) giving a data assimilation window of 2 hours and 15 minutes, but not three hours. This cut-off time is chosen to be 15 minutes in the nowcasting system which gives a data assimilation window of 45 minutes. The cut-off time can be tuned later depending on how many more observations are collected if one increases the window. Not to forget when choosing the cut-off time is also how many different types of observations are available for the data assimilation. The main challenge for the 15 minutes, or even 20 minutes for that matter, is the absence of radiosonde, called TEMP in the NWP community, observations meaning that the only source of upper air direct observations are aircraft data.

## 2.5 Timeliness and forecast length

Several choices so far have been made to construct a more timely NWP system that produces forecast in the nowcasting range. Having set up hourly update with 15 minutes cut-off time in a one hourly data assimilation window are the basis for such a system. On the other hand, the forecast model run should also take less than 45 minutes so that the whole model run could finish in less than one hour and products are available for users within one hour. The whole idea behind a rapid refresh update is also to provide weather forecast in the nowcasting range, which according to the feedbacks from wind energy community is up to 12 hours. Based on the available high performance computational machines the nowcasting product could be available in less than one hour if the forecast model runs up to 9 hours. Meanwhile the first test runs showed that the gain from the rapid refresh system is limited to up to 6 hours, and forecast behind 6 hours have the same or worse quality than the short-range NWP system. Generally, nowcasts are 2-7 hours more timely than the three hourly short range NWP (see Fig. 2 and 3).

### 2.6 Lagged verification

It is expected that the RR nowcasting would score better than the short-range NWP mainly for two reasons. Firstly, because fresher observations are assimilated more often and secondly nowcasting products are delivered more frequently and with less delay. To demonstrate the latter the lagged verification method is used to show to the users the benefit from the nowcasting forecasts. In the traditional verification method the forecasts with the same lead time from different models are compared to each other to find the model with the best forecast quality. However, the nowcasting products are available sooner than the short-range NWP products. Taking this into account, the lagged verification compares the forecast of different lead time but valid at the same verification time. Table 1 compares which lead times of that from the nowcasting is compared with the short-range NWP. Clearly, the lead time for the nowcasting is less than that from the short range NWP and therefore it is expected to have better quality.

# 3 TrønderEnergi test domain

The large MetCoOp domain covering Scandinavia is too expensive to test hourly RR experiments. In this work, the solution was to use a smaller domain than the MetCoOp domain. How small the test domain could be is also depending on what weather phenomena in terms of their time and spatial scale are considered to be important for wind situations. A too small domain for example will not be suitable to forecast wind conditions more than even one hour.

### 3.1 domain selection

The small test domain selected here covers TrønderEnergi wind park sites and called TE domain. Figure 1 shows both TE and MetCoOp domain. The TE and MetCoOp domains have both the same 65 vertical levels but the TE domain has only 240 × 240 horizontal grid points against the 739 × 949 in the MetCoOp domain.

### 3.2 structure function calculation

The 3DVAR method for data assimilation in Harmonie-Arome consists of minimizing the following cost function

$$\boxed{J(x)=\frac{1}{2}\left(\mathbf{x}-\mathbf{x}^{\mathbf{b}}\right)^{T}\mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}^{\mathbf{b}}\right)+\frac{1}{2}\left(\mathbf{y}^{\mathbf{o}}-H(\mathbf{x})\right)^{T}\mathbf{R}^{-1}\left(\mathbf{y}^{\mathbf{o}}-H(\mathbf{x})\right)}$$

where **B** is the background error covariance matrix, **R** is the observation error covariance matrix and *H* is the observation operator. For the TE domain one only needs to recalculate the **B** matrix and use the same **R** and *H* as in MetCoOp. In order to generate background error covariances (generally referred to as structure functions) the derivation within the Harmonie-Arome community has been based on data generated with ensemble

Harmonie-Arome forecasts downscaled from ECMWF ensemble runs. The Harmonie-Arome forecasts are run up to 6 hours to avoid the spin-up issues in the model. Then using the ECMWF lateral boundary conditions (LBCs), four Harmonie-Arome ensemble forecasts are initiated from ECMWF 6 hours forecasts from 00 UTC and 12 UTC. It is also recommended to run for one winter month and one summer month, in our case June 2015 and January 2016. Figure 4 compares the spectral density for unbalanced humidity and divergence between the TE **B** matrix and several other domains.

### 3.3 boundary condition strategy

As explained in subsection 2.2, the FG used in the data assimilation is coming from the host model, here the MetCoOp domain. Since the LBSc are used from the ECMWF deterministic runs there would be inconsistencies between the ECMWF LBCs and MetCoOp FGs, for example they would have different lead times. The TE domain is inside the MetCoOp domain and an interpolation method using the FULLPOS in the Harmonie-Arome is implemented to use the boundaries from the MetCoOp forecasts. It is found that even though such a nesting procedure is quite simple for the upper air FG files it is technically more problematic for the surface FG files used in SURFEX. The choice has been to only interpolate boundaries from MetCoOp for upper air forecast files but let the surfex file to come from the TE runs, an hourly update cycling by definition.

# 4 preliminary results

In this final subsection the verification results for the TE test domain is presented. Verifications are performed for the synoptic stations shown in Fig. 5 which are inside the TE domain as well as two wind masts at Hitra and Smøla wind parks.

### 4.1 Rapid refresh versus rapid update cycling

The first set of experiments are carried out to examine how the 1h and 3h RUC performs against the 1h RR method. Using a version of Harmonie-Arome 38h1.2 and assimilating only conventional and satellite microwave radiances in the 3DVAR method three sets of experiments are run where the boundary files are from ECMWF 6-18h deterministic forecasts for a period from 20150904 to 20151005. For the RR experiment the FG is from another 3h RUC experiment covering the MetCoOp domain. An example of 12h wind forecasts at 10m for 1h RUC, 3h RUC, and 1h RR is shown in Fig. 6.

Lagged verification of mean seal level pressure (MSLP) is shown in Fig. 7. The standard deviation is smaller in the 1h RR for the first 6 hours, a result also seen for 10m wind but rather in the first 2 to 3 hours (see Fig 8). The 3 runs are also verified towards both Hitra and Smøla wind mast stations. These observations are from 100m height so the model wind is interpolated to this height. As shown in Fig. 9, the persistence has better correlation with observations than forecasts up to 2 hours. But the forecasts is useful before that because it can give an indication of ramp up and ramp down (see Fig 10).

### 4.2 Rapid refresh with FGs and LBCs from the host model

The first guess (FG) for the RR method is used from a host model, the latter being a similar run but with the MetCoOp domain instead of the TE domain. However, as mentioned in subsection 3.3 the ECMWF LBCs may have different lead time than that for the MetCoOp FGs. Figure 11 shows an example where the LBC and FG used in the RR experiment are valid for the same time but are relatively different from each other. To use not only FGs but also the LBCs from the host model a version of Harmonie-Arome 40h1.2 is implemented. The period chosen here is from 20170513 to 20170520. Having both the FGs and LBCs from the host model with the same lead time would result in more consistent initial conditions for the model runs. The lagged verification in Fig. 12 shows that the RR forecasts have less bias and STDV for the first 3 hours than the 3h RUC while Fig. 13 confirms that the smaller root mean square error (RMSE) in RR forecasts are statistically significant up to one hour ahead in time. The same results are also found for 10m wind speed (see Fig 13 and 14), though here the biases are smaller for RR up to 6 hours while the significantly smaller RMSE are observed only at 2h forecasts. One of the main reasons that verifications are different between 1h RR and 3h RUC is that the 1h RR uses observations with 15 minutes cut-off time but 3h RUC assimilated observations with 75 minutes cut-off time.

## Concluding remarks

This study shows that there is a potential for using the Harmonie-Arome NWP model for the nowcast range with a setup that delivers fresher forecasts more frequently and more timely. Not only the wind energy community can benefit from such a system but also aviation meteorology could use the very short range forecast for example in En-route planning. To develop further such a nowcast system based on the Harmonie-Arome NWP model, one needs to consider how to tune the several components of the data assimilation system, to mention among them is the data assimilation window length and using more type of observations available before the cut-off time. In addition, it might be necessary to tune the **B** matrix and the weight given to the background error for the nowcasting range. Despite all the considerations mentioned here, one needs to remember that the main benefit from such a rapidly updated system is that the very short range weather forecasts are available less than one hour after the analysis time.

# Acknowledgement

The wind farm data for Hitra and Smøla were kindly provided by Statkraft and TrønderEnergi respectively. The lagged verifications for 100m wind masts are provided by Thomas Nipen. Malte Müller and Hilde Haakenstad also made important contributions in different parts of this work. I would like to thank Roger Randriamampianina for reviewing this report. This work is part of the project " Nowcasting for wind energy production -- an integrated modelling approach " funded by the Norwegian Research Council (project number 256399) and industry partners Kjeller Vindteknikk, Statkraft, TrønderEnergi, Vestas Wind Systems, and WindSim.

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# Figures

*Figure 1. TronderEnergi (TE, red) and MetCoOp (blue) geographical domain*

*Figure 2. Timeline for the weather forecast production*

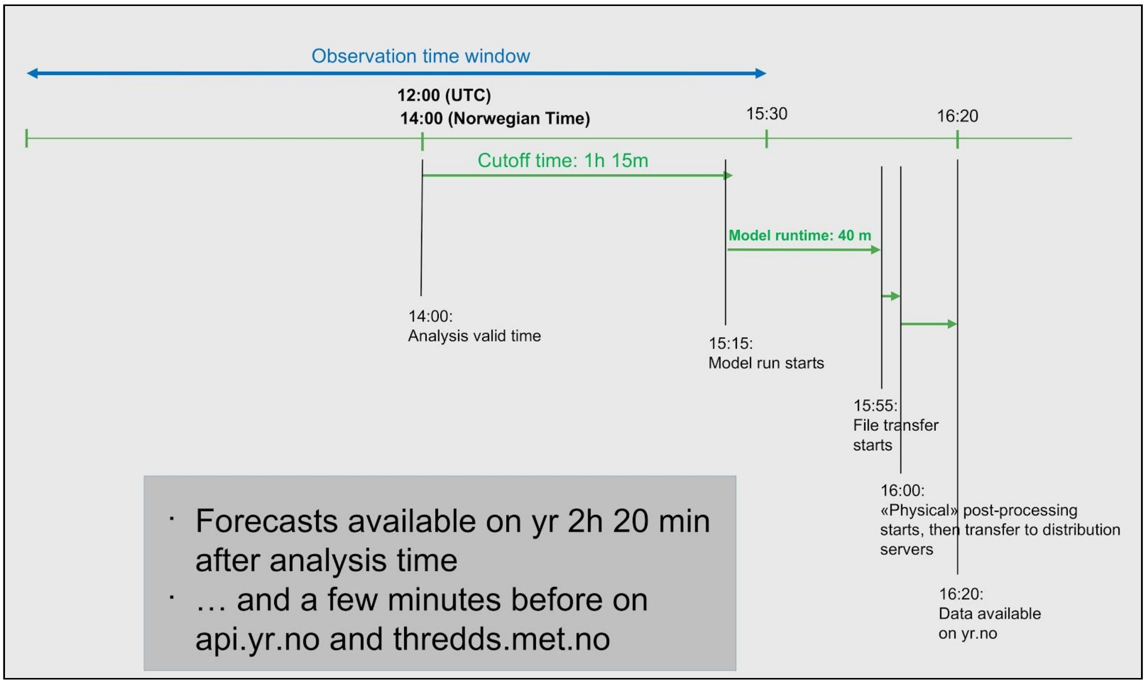



*Figure 3. Foreseen timeline for the nowcasting production*

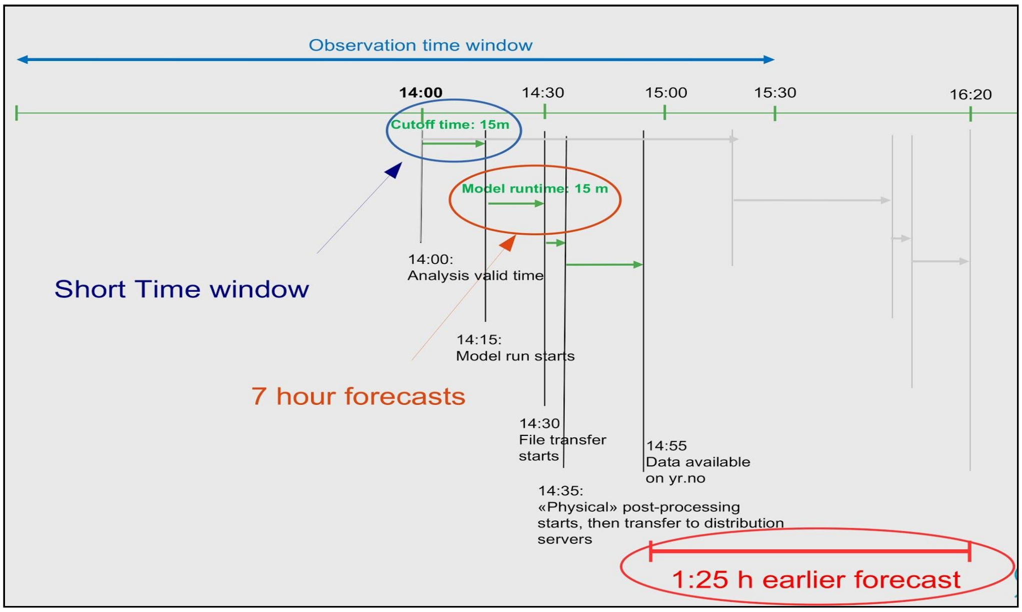


*Figure 4. Spectral density for unbalanced humidity and divergence showing the variances for different time scales in different domains, where the TE domain is in pink colour.*

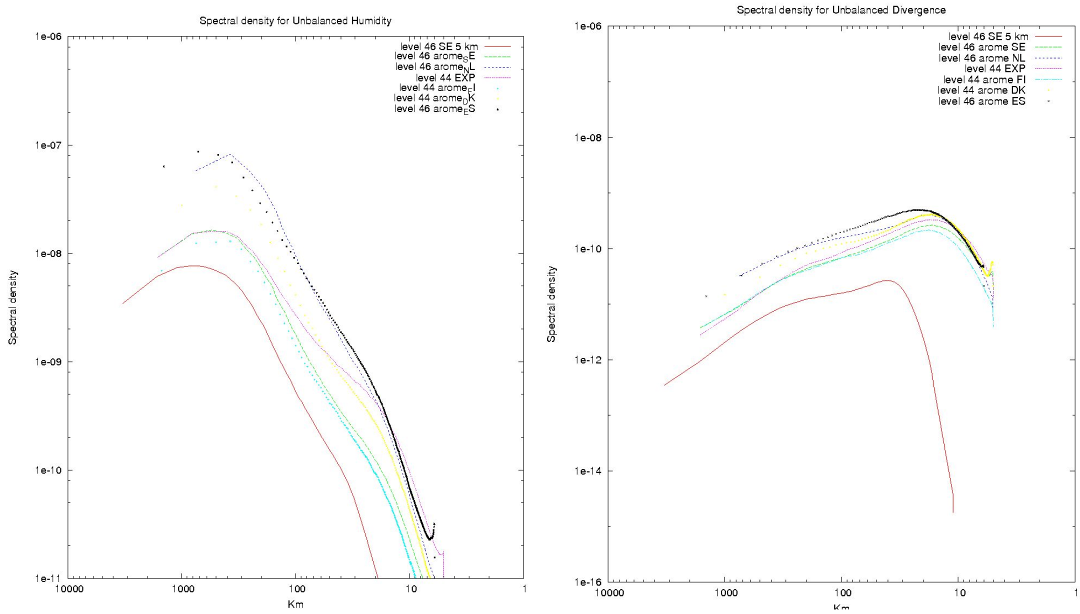



*Figure 5. geographical position of synoptic stations used for verification in dots*

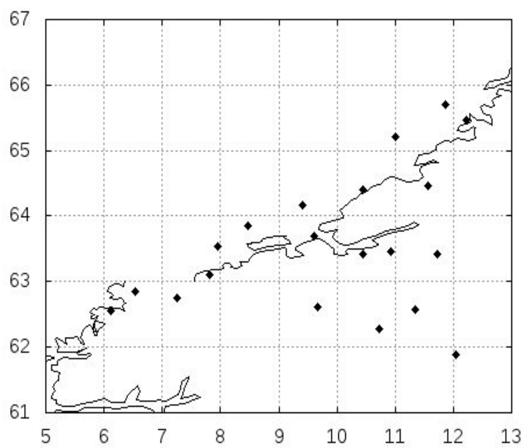


Figure 6. *12h wind forecast at 10m from 1h RUC (red), 3h RUC (green) and 1h RR (blue) valid at 2015091012*

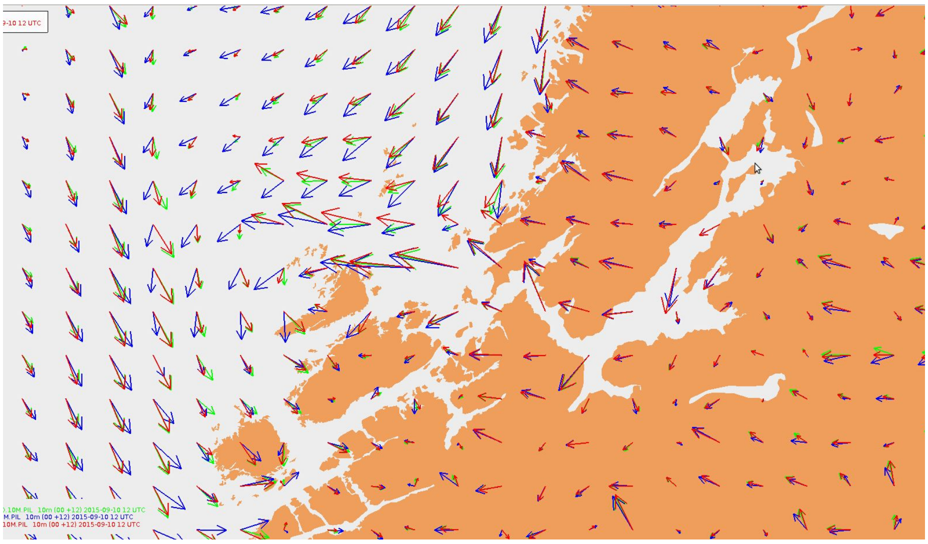


*Figure 7. Bias and standard deviation (STDV) for MSLP in 3h RUC (red), 1h RUC (blue), and 1h RR (green)*

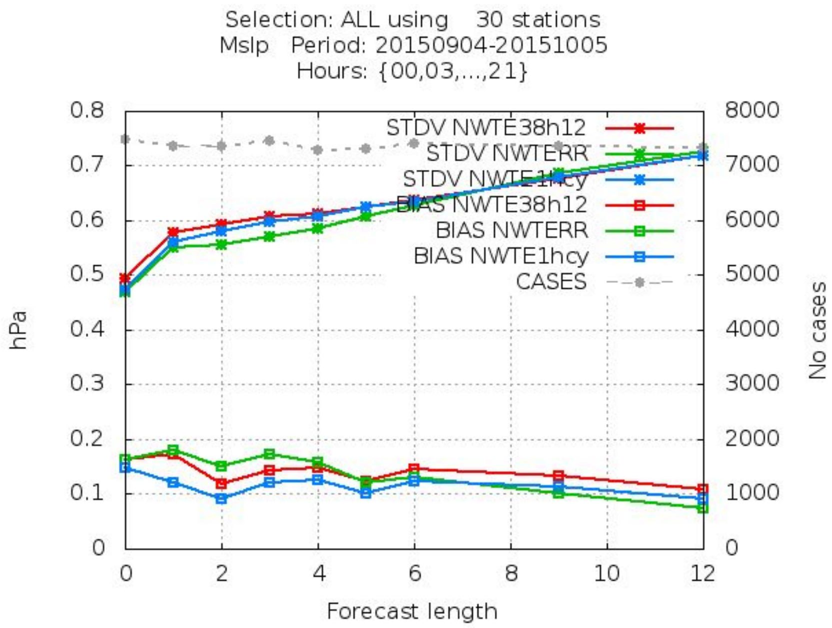


*Figure 8. same as Fig 7 but for 10m wind*

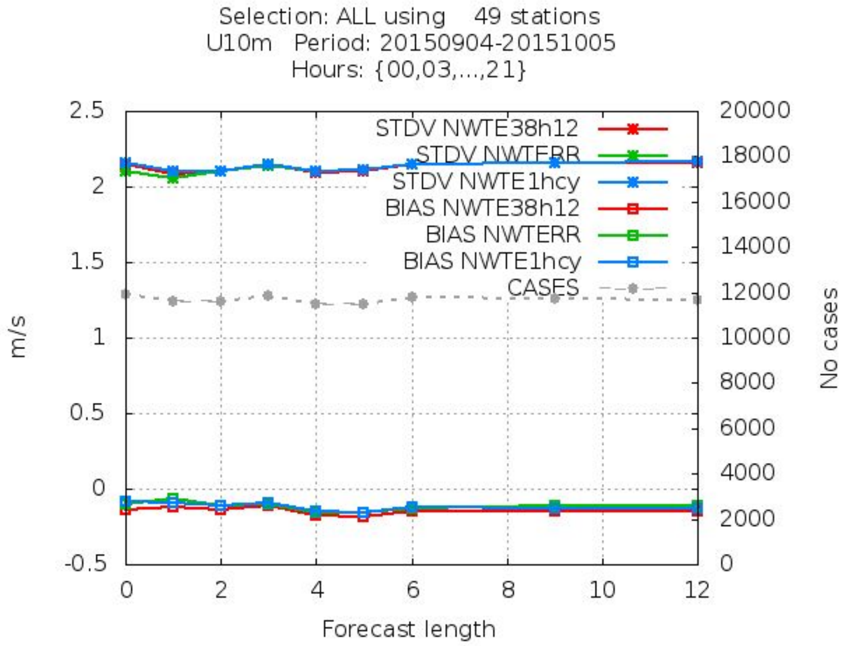



*Figure 9. Lagged verification for 100 m wind at Hitra and Smøla wind masts (by Thomas Nipen)*

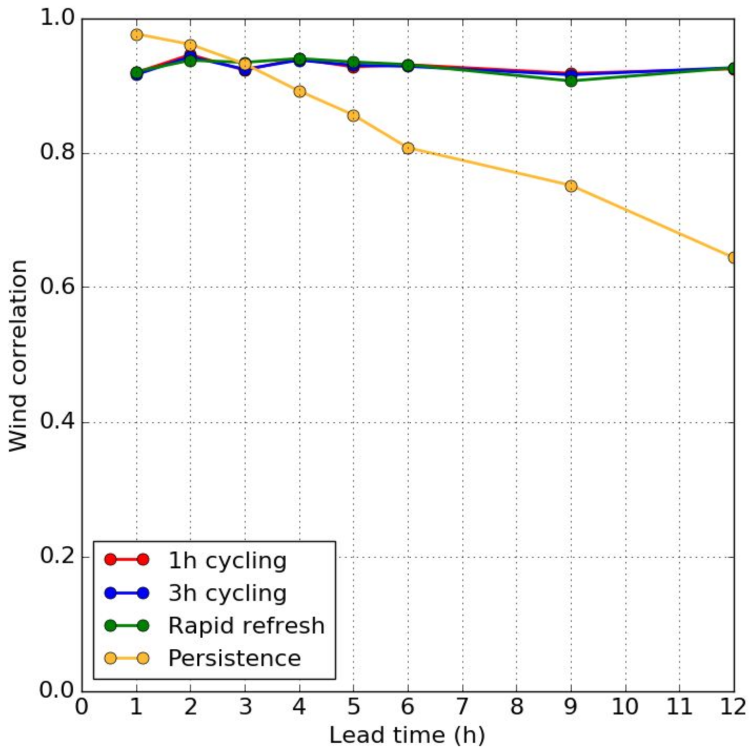


*Figure 10. same as Fig 9 but for wind change correlation (by Thomas Nipen)*

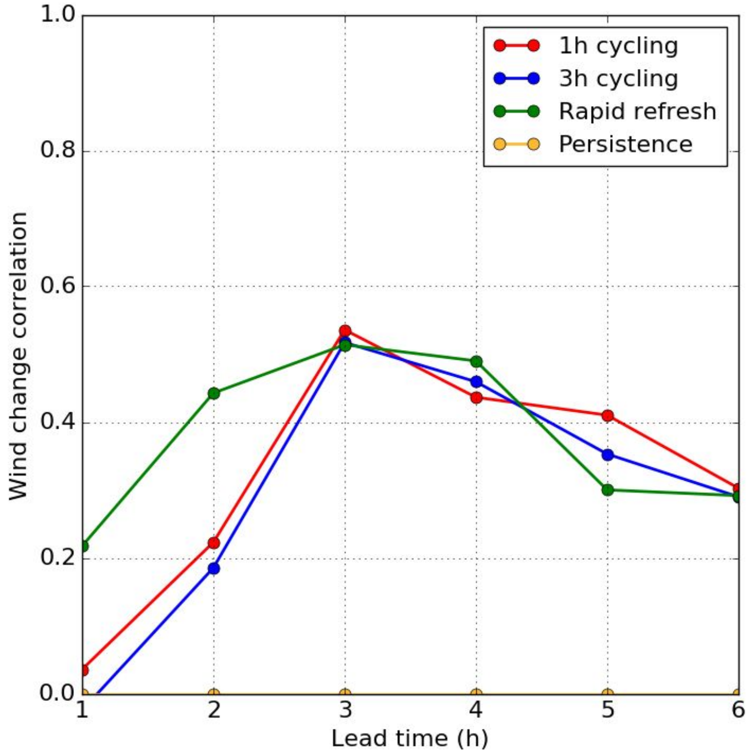



*Figure 11. MSLP First guess (+3h) from the host model (blue) and MSLP boundary conditions (+9) from the ECMWF deterministic forecast (red) both valid at 2018011103.*

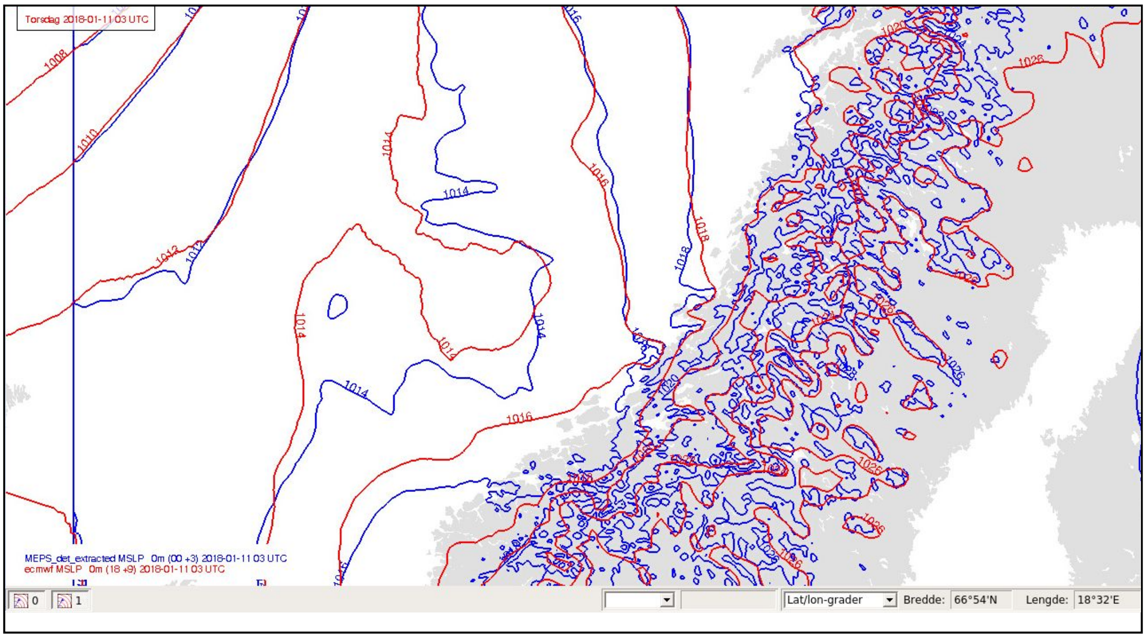


*Figure 12.  Bias and standard deviation (STDV) for MSLP in 3h RUC (green) and 1h RR (magenta). Both experiments are mimicking the operational MetCoOp runs but 1h RR is run for TE domian while the 3h RUC is run for MetCoOp domain.*

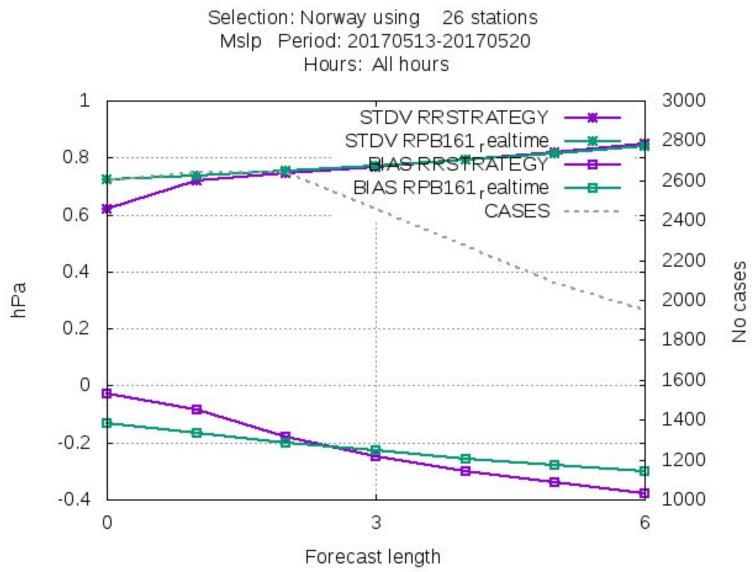



*Figure 13. Normalized root mean square error (RMSE) differences between TE 1h RR and MetCoOp 3h RUC. The bars show the confidence intervals at 95%.*

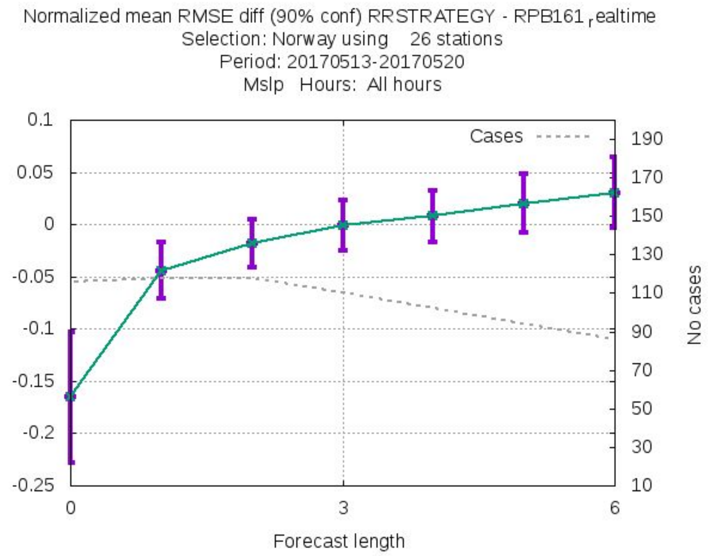


*Figure 14. Same as Fig 12 but for 10m wind*

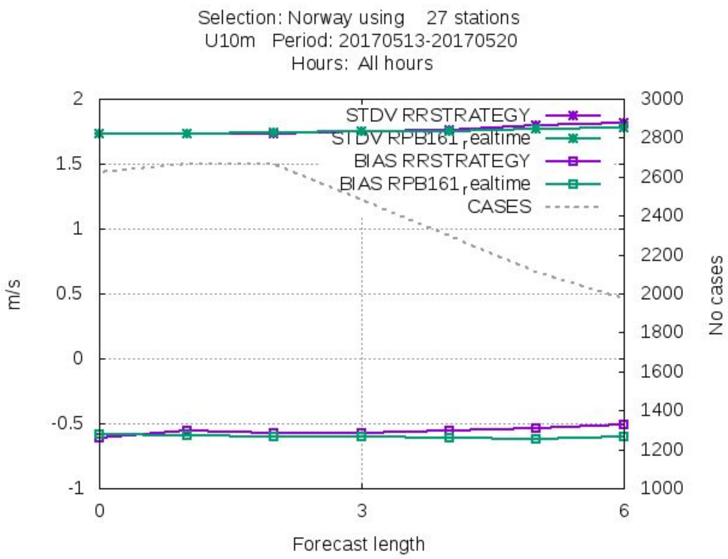
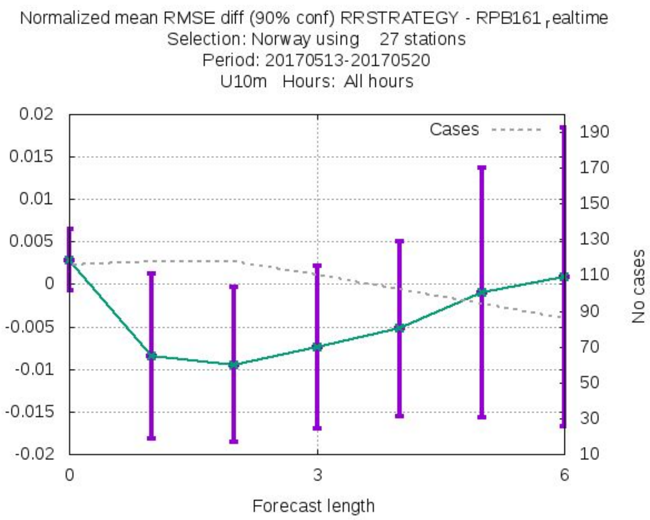



*Figure 15. same as Fig 13 but for 10m wind*



# Tables

*Table 1. First, second, third and fourth row below are analysis time (UTC), NWP forecast delay, NWP nowcast delay, and the difference between the NWP forecast and NWP nowcast delay. NWP nowcast is 2-7 hour more timely.*

| 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 7 | 8 | 3 | 4 | 5 | 6 | 7 | 8 | 3 | 4 | 5 | 6 | 7 | 8 | 3 | 4 | 5 | 6 | 7 | 8 | 3 | 4 | 5 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 6 | 7 | 2 | 3 | 4 | 5 | 6 | 7 | 2 | 3 | 4 | 5 | 6 | 7 | 2 | 3 | 4 | 5 | 6 | 7 | 2 | 3 | 4 |