Norwegian
Meteorological
Institute

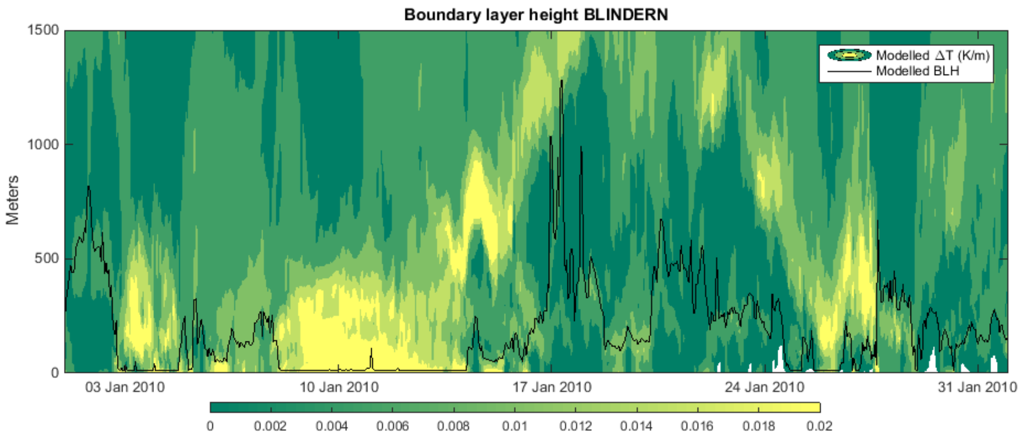
No. [x]/[xxxx]
ISSN 2387-4201
Numerical weather
prediction and air
pollution

METreport

NBV report on meteorological data for 2015

Deliverable 6, Work package 3

Bruce Rolstad Denby and Jakob Kristoffer Süld



Modelled inversion strength and boundary layer height in Oslo, January 2010.

METreport

Title NBV report on meteorological data for 2015	**Date** 2016-09-26
Section Klimamodellering og luftforurensning (KL) and Numerisk værvarsling (NM)	**Report no.** No. [x]/[xxxx]
Author(s) Bruce Rolstad Denby and Jakob Kristoffer Süld	**Classification** ● Free ○ Restricted
Client(s) Miljødirektoratet	**Client's reference**

Abstract

As part of the 'Nasjonalt Beregningsvektøy for Lokal Luftkvalitet' project (National modelling system for local air quality) the Norwegian Meteorological Institute (MET) calculates, archives and processes meteorological data for the years 2010, 2015 and 2016. The meteorological data provide the required 3D spatial meteorological fields needed for air quality model calculations that are carried out by the Norwegian institute for air research (NILU). These data are also freely available to the public and methods for distribution have been provided. The model used is the operative numerical weather prediction model AROME, coupled to the surface model SURFEX. For 2015 and 2016 data from the AROME-MetCoOp forecasts, at 2.5 km resolution, are archived to provide coverage for all of Norway. In addition the three regions used in the Bedre Byluft forecasts system that cover the largest cities, at 1 km resolution, are also archived. These data are processed, to match the required format for NILU's dispersion models, and are made available through METs THREDDS data distribution server. In this document the data and data availability are described. Further to this a statistical analysis for the year 2015 is carried out and the 2.5 and 1 km calculations compared. An analysis of the meteorological models ability to describe inversion strengths, important for air quality applications, is provided. The results show that both model resolutions provide very satisfactory predictions for wind, temperature and precipitation and that statistically there is no significant difference between 1 and 2.5 km resolution, when compared to measurement stations. Based on these and previous results it is recommended to streamline the Bedre Byluft and NBV production lines by using solely 2.5 km AROME-METCoOp data in the future.

Keywords

AROME-MetCoOp, air quality, numerical weather prediction, verification

Disiplinary signature

Responsible signature

Abstract

As part of the ‘Nasjonalt Beregningsvektøy for Lokal Luftkvalitet’ project (National modelling system for local air quality) the Norwegian Meteorological Institute (MET) calculates, archives and processes meteorological data for the years 2010, 2015 and 2016. The meteorological data provide the required 3D spatial meteorological fields needed for air quality model calculations that are carried out by the Norwegian institute for air research (NILU). These data are also freely available to the public and methods for distribution have been provided. The model used is the operative numerical weather prediction model AROME, coupled to the surface model SURFEX. For 2015 and 2016 data from the AROME-MetCoOp forecasts, at 2.5 km resolution, are archived to provide coverage for all of Norway. In addition the three regions used in the Bedre Byluft forecasts system that cover the largest cities, at 1 km resolution, are also archived. These data are processed, to match the required format for NILU’s dispersion models, and are made available through METs THREDDS data distribution server. In this document the data and data availability are described. Further to this a statistical analysis for the year 2015 is carried out and the 2.5 and 1 km calculations compared. An analysis of the meteorological models ability to describe inversion strengths, important for air quality applications, is provided. The results show that both model resolutions provide very satisfactory predictions for wind, temperature and precipitation and that statistically there is no significant difference between 1 and 2.5 km resolution, when compared to measurement stations. Based on these and previous results it is recommended to streamline the Bedre Byluft and NBV production lines by using solely 2.5 km AROME-METCoOp data in the future.

Meteorologisk institutt
Meteorological Institute
Org.no 971274042
post@met.no

Oslo
P.O. Box 43 Blindern
0313 Oslo, Norway
T. +47 22 96 30 00

Bergen
Allégaten 70
5007 Bergen, Norway
T. +47 55 23 66 00

Tromsø
P.O. Box 6314, Langnes
9293 Tromsø, Norway
T. +47 77 62 13 00

www.met.no

Table of contents

1 Introduction **5**

2 Climatological overview for 2015 **6**

3 Model description and data **9**

3.1 Data overview 9

3.2 Data status 12

3.3 Data distribution 12

3.4 Memory requirements for data storage 15

4 Verification results **16**

4.1 Statistical method 16

4.2 Monthly statistics 17

4.3 Frequency distribution 20

5 Modelled temperature inversions and boundary layer height **22**

5.1 Oslo 22

5.2 Bergen 25

6 Conclusions and recommendations **29**

6.1 Conclusions concerning the model error verification results 29

6.2 Modelled inversions and boundary layer height 29

6.3 Impact of resolution 30

6.4 Model resolution and applications 30

6.5 Recommendations 31

Acknowledgements **32**

References **33**

Appendix **34**

Archived variables in meteorological forecast fields 34

Vertical and horizontal coordinates of the meteorological data 35

1 Introduction

As part of the ‘Nasjonalt Beregningsvektøy for Lokal Luftkvalitet’ project (National modelling system for local air quality) the Norwegian Meteorological Institute (MET) has processed and archived meteorological model forecast data for 2015 and 2016, in addition to reanalysis data from 2010 previously reported in Süld and Denby (2015). These data are provided from two sources: 1) the Bedre Byluft forecast system at 1 km resolution (e.g. Denby et al., 2015), which covers three regions in southern Norway and 2) from the operative numerical weather prediction system (MetCoOp) used daily as the Norwegian and Swedish forecasting model at 2.5 km resolution. Both calculations are made using the AROME model.

This report builds on the previous one from Süld and Denby (2015) and provides a description and status of the datasets. We also carry out a statistical assessment of the meteorological data for 2015 and investigate the ability of the AROME model to prognose temperature inversions in two of the cities. Comparisons are made of 1 and 2.5 km meteorological calculations throughout and recommendations concerning further use of the AROME model in both Bedre Byluft and NBV are made.

2 Climatological overview for 2015

The year 2015 was characterised by higher temperatures and precipitation than normal, when compared to the reference period 1961-1990. An analysis of the climate for this year is provided in Ganstø et al. (2015). For 2015 the average temperature in Norway was 1.8 ºC above normal, being the third warmest year since 1900. The average temperature was only below normal in a small area of Westland. Precipitation was on average 125% above normal. Only in some areas of Troms and parts of Finmark was precipitation below the norm. The general distribution of temperature and precipitation deviation from the norm for the entire year is shown in Figure 1 and 2. No climatological analysis of wind has been carried out for this year.

2015 showed low or average levels of PM and NO_2 concentrations, compared to the past 10 years (http://www.luftkvalitet.info). There were almost no exceedances of the EU's NO_2 hourly limit value were recorded, apart from in Oslo where exceedances of the hourly and annual NO_2 limit value were recorded. However national target values for PM_{10} were exceeded in Drammen, Grenland, Lillehamar and Stavanger. Though there was some variation across Norway, 2015 should be considered a 'mild' air pollution year, compared to 2010 which saw meteorological conditions leading to 'high' air pollution.

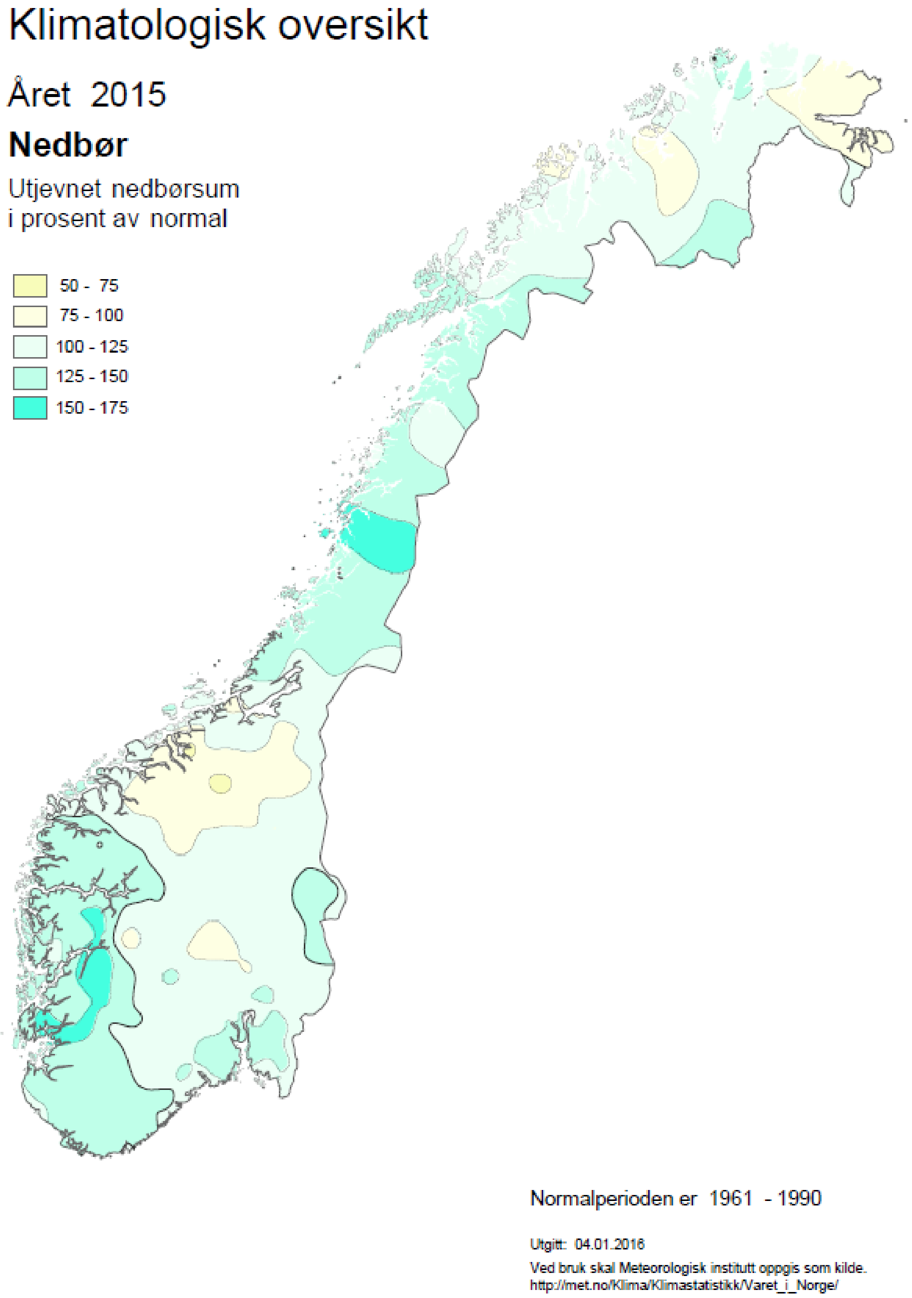


Figure 1. Climatological overview of precipitation in Norway taken from Ganstø et al. (2015).

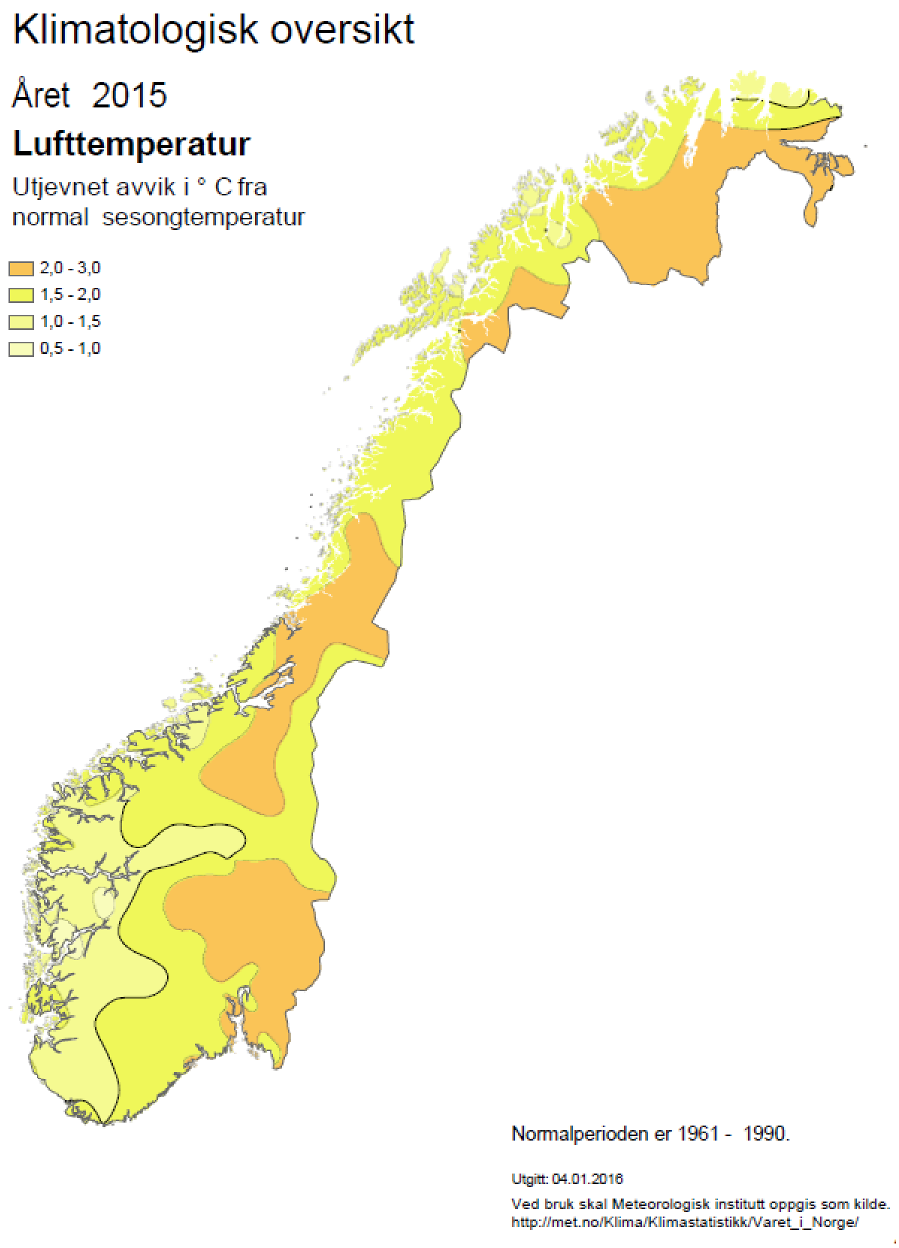


Figure 2. Climatological overview of 2 m temperature in Norway taken from Ganstø et al. (2015).

3 Meteorological data and availability

3.1 Model data for 2015 and 2016

A description of the meteorological model has been provided in the previous NBV report (Süld and Denby, 2015). What differs compared to that report is that the calendar year was not recalculated but use has been made of existing forecast data from Bedre Byluft and MetCoOp forecasts, which have been archived for the purposes of NBV. The Bedre Byluft forecasts provide 1 x 1 km^2 meteorological fields that cover three regions of Norway and includes the selected cities for NBV, Figure 3. Despite use of existing data significant effort was put into filling gaps that occurred in the datasets, since Bedre Byluft forecasts sometimes fail, as well as technical problems related to storage and processing. For MetCoOp data 12 hourly forecasts are aggregated in time, for Bedre Byluft data 24 hour forecasts are averaged in time. On occasions when Bedre Byluft data were missing then the second day of Bedre Byluft forecast (24-48) was used.

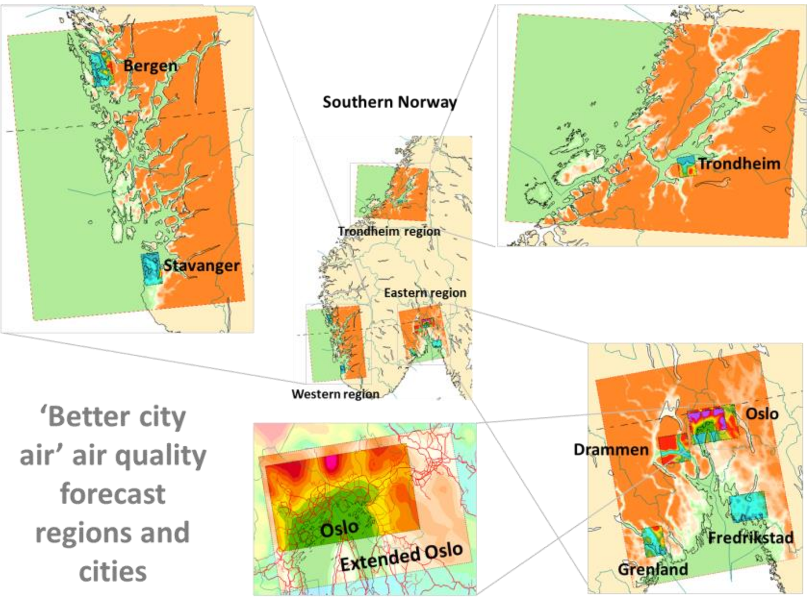


Figure 3. Bedre Byluft regions modelled at 1 x 1 km^2.

3.2 Data overview

Meteorological data has been produced, processed and archived for use in NBV for the years 2010, 2015 and 2016. The following basis datasets are archived

1. Recalculations of 2.5 km AROME-MetCoOp meteorology for all of Norway and Sweden for the calendar year 2010
2. Recalculations of 1 km AROME-MetCoOp meteorology for southern Norway for the calendar year 2010
3. Archived data from 2.5 km AROME-MetCoOp forecast meteorology for all of Norway and Sweden for the calendar year 2015 and 2016
4. Archived data from 1 km Bedre Byluft AROME-MetCoOp forecast meteorology for three regions in southern Norway (East, West and Trondheim) for the calendar year 2015 and 2016

From these basis datasets the following data is produced and made available to the public through the THREDDS data server (http://thredds.met.no)

1. Monthly 3D meteorological fields at 1 km resolution with hourly time steps at 8 selected cities. The format is netcdf and the fields are made suitable for the application of the EPISODE dispersion model.
2. Monthly 3D meteorological fields interpolated from 2.5 km to 1 km resolution with hourly time steps at 12 selected towns. The format is netcdf and the fields are made suitable for the application of the EPISODE dispersion model.
3. Daily 2D meteorological fields at 2.5 km resolution with hourly time steps for all of Norway. The format is netcdf. These files are intended for the extraction of near surface meteorological time series at any point in Norway.

The following variables are stored in the files processed for NBV. The archived variables from the original METCoOP and Bedre Byluft calculations are given in the Appendix. Both 2D and 3D variables are stored in the city files, whilst only the 2D variables are stored in daily 'all of Norway' files. A description of the vertical levels used is provided in the Appendix.

Table 1. List of meteorological variables available in netcdf output files from NBV

Variable name	**Units**	**Variable description**	**Type of field (2D or 3D spatial dimensions**	**Timing (I=instantaneous, A=accumulated or average over last hour)**
specific_humidity_epi	kg/kg	Model level specific humidity	3D	I
air_temperature_epi	K	Model level temperature	3D	I

x_wind_epi	m/s	Model level x wind speed	3D	I
y_wind_epi	m/s	Model level y wind speed	3D	I
turbulent_kinetic_energy_epi	m^2/s^2	Model level turbulent kinetic energy	3D	I
pressure_epi	Pa	Model level pressure	3D	I
elevation_epi	m	Model level elevation, does not change	3D	I
surface_air_pressure	Pa	Surface air pressure	2D	I
surface_elevation	m	Surface elevation, does not change	2D	I
air_temperature_0m	K	Surface temperature	2D	I
air_temperature_2m	K	2 m air temperature	2D	I
relative_humidity_2m	(0-1)	2 m relative humidity	2D	I
specific_humidity_2m	kg/kg	2 m specific humidity	2D	I
x_wind_10m	m/s	10 m x wind speed	2D	I
y_wind_10m	m/s	10 m y wind speed	2D	I
boundary_layer_height	m	Height of the boundary layer, based on TKE	2D	I
surface_roughness_momentum	m	Roughness length for momentum (z_0)	2D	I
surface_roughness_temperature	m	Roughness length for temperature (z_H)	2D	I
precipitation_amount	kg/m^2 (mm w.e.)	Total precipitation	2D	A
cloud_area_fraction	0-1	Total cloud area fraction	2D	I
liquid_water_content_of_surface_snow	kg/m^2 (mm w.e.)	Liquid water content of the surface snow	2D	I
downward_eastward_momentum_flux_in_air	$kg/m/s^2$	Surface momentum flux in x direction	2D	A
downward_northward_momentum_flux_in_air	$kg/m/s^2$	Surface momentum flux in y direction	2D	A
surface_upward_latent_heat_flux	W/m^2	Upward latent heat flux	2D	A
surface_upward_sensible_heat_flux	W/m^2	Upward sensible heat flux	2D	A
surface_downwelling_shortwave_flux	W/m^2	Downwards shortwave radiation (global radiation)	2D	A
surface_downwelling_longwave_flux	W/m^2	Downwards longwave radiation	2D	A

3.3 Data status

The following table provides the status of the publicly available data, at the time of writing of this report.

Table 2. Status of the meteorological data for NBV. Areas marked in grey are not applicable, areas marked in green are complete and areas marked in orange are in progress, awaiting data or are awaiting orders. The number of months processed (or days in the case of the 'all of Norway' data fields) are given.

	1 km monthly data 2010	1 km monthly data 2015	1 km monthly data 2016	2.5 km monthly data 2010	2.5 km monthly data 2015	2.5 km monthly data 2016	2.5 km daily surface data 2010	2.5 km daily surface data 2015	2.5 km daily surface data 2016
Bergen	12	12	8	12					
Drammen	12	12	8	12					
Grenland	12	12	8	12					
Nedreglomma	12	12	8	12					
Oslo	12	12	8	12					
StorOslo	12	12	8	12					
Stavanger	12	12	8	12					
Trondheim	12	12	8	12					
Norway							365	364	213
Aalesund				2					
Halden				1					
Harstad				12	11				
Kristiansand				1					
Kristiansund				1					
Lillehammer				12	11				
MoiRana				1					
Moss				12	11				
Narvik				1					
Sandefjord				1					
Tromsø				2					

3.4 Data distribution

All publicly available data listed in Table 1 and 2 are available through the THREDDS data server. Direct access to the NBV data is through the following link http://thredds.met.no/thredds/nbv.html

There are a number of possible methods for downloading these data. The two major ones are the direct downloading of netcdf files for a specified city and a given month and downloading of aggregated time series data at points from either the city files or the ‘all of Norway’ files.

3.4.1 Downloading individual data files

The following steps show how to manually download individual monthly city files.

- Go to http://thredds.met.no/thredds/nbv.html
- Choose ‘All available files’
- Choose a year (e.g. 2010)
- Choose a city (e.g. Stavanger)
- Choose a month (e.g. AROME_25KM_STAVANGER_20101201_EPI.nc)
- Choose Access through HTTPserver to download the file (i.e. HTTPServer**:** /thredds/fileServer/nilu_nbv_files/2010/STAVANGER/AROME_25KM_STAVANGER_20101201_EPI.nc)

This process produces a URL that allows direct access to the files. In this case the following URL is produced.

http://thredds.met.no/thredds/fileServer/nilu_nbv_files/2010/STAVANGER/AROME_25KM_STAVANGER_20101201_EPI.nc

The manual process is unnecessary if scripts are used to produce URLs of this type.

3.4.2 Downloading aggregated time series data

If time series data are required that covers times larger than an individual data file, e.g. a year, then it is possible to request aggregated data. This is particularly useful for point data. Use of the aggregated data for downloading field files is not recommended as this will require large data files and long downloading times. Even so, when a region is aggregated for the first time then the process can take several minutes. Once the aggregation has been done and cached then this process is much shorter. For the case of a time series data at a point the following steps can be taken.

- Go to http://thredds.met.no/thredds/nbv.html
- Choose one of the cities or Norway (e.g. Aggregated_BERGEN_1KM)
- Choose **NetcdfSubset:** /thredds/ncss/nilu_nbv_bergen1km_agg
- Select a latitude and longitude position, the variables required, start and end date and the format required in the NCSS interface.

This will produce a URL for these data, in this case we have chosen 2m temperature and boundary layer height for a year and downloading in csv format. A screen shot of this example page is given in Figure 3.

http://thredds.met.no/thredds/ncss/nilu_nbv_bergen1km_agg?var=air_temperature_2m&var=boundary_layer_height&latitude=60.4&longitude=5.2&time_start=2015-01-01T00%3A00%3A00Z&time_end=2015-12-31T00%3A00%3A00Z&accept=csv_file

As in the previous example the URL can be directly edited or scripted to allow efficient downloading.

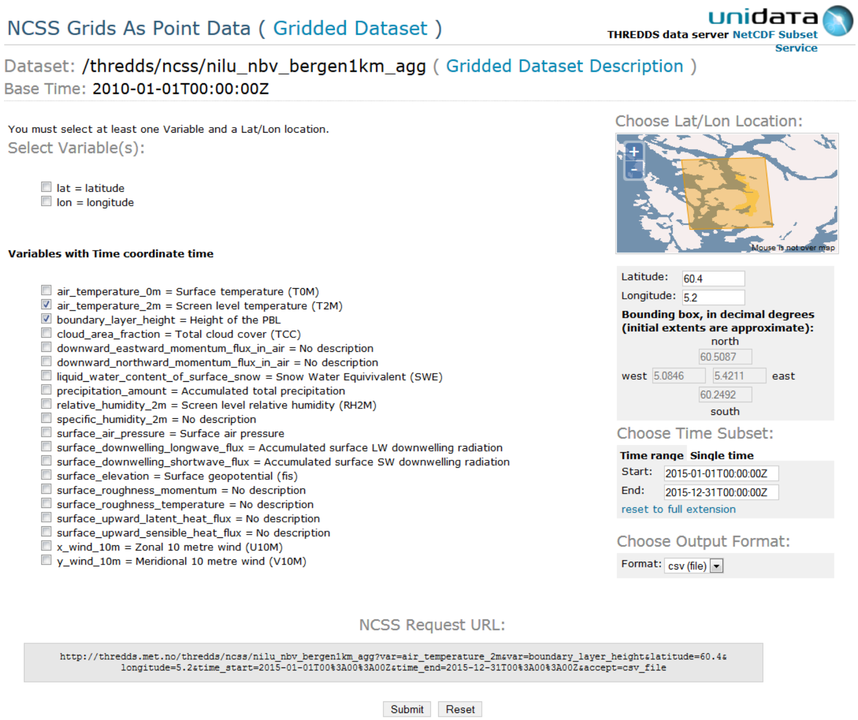


Figure 4. Screen shot of NCSS download page used for accesing time series data as described in the text.

3.4.3 Overview of downloading functionalities

The following functionalities are available on the THREDDS server. Other methods can thus be used to download these data depending on the needs of the user.

1. **OPENDAP:** Allows a selection of variables and region within the file
2. **HTTPServer:** Direct download of files
3. **WCS:** Web Coverage Service. Not available for these data
4. **WMS:** Web Map Service. Standard for web based mapping in xml format.
5. **NetcdfSubset:** Interface for selecting variables, regions and times from the data file. Can extract from points (Grid as Point Dataset) or as gridded data (Gridded Dataset)

3.5 Memory requirements for data storage

One year of 2.5 km data requires 6.8TB of storage, or roughly 570 GB per month. One month for the three 1 km model domains requires 100GB of storage. Extracted data for the cities requires less storage, at around 10 GB per month. The final storage requirements for three years of data, the planned datasets for NBV, requires approximately 25 TB of data.

4 Verification 2015

4.1 Statistical method

All model forecasts in this report are verified against observations by interpolating (bilinear) the grid based forecasts to the observational sites. Verification is carried out for wind speed, temperature and precipitation based on statistical parameters that are regularly applied in other MET verification reports that are produced every three months, for example Homleid and Tveter (2016). For the application here the short forecast period (less than 12 -24 hours) does not require an assessment of the errors as a function of forecast time, as the statistical parameters vary little over this short period. Statistics are thus not shown as a function of the forecast hour but are aggregated into monthly statistics.

The following assessments are shown

1. Monthly error statistics for 10 m wind speed, 2 m temperature and 12 hour accumulated precipitation.
2. Frequency distribution plots for 10 m wind speed, 2 m temperature and 12 hour accumulated precipitation.

All observations for the verification come from Klimadatavarehuset at MET and only synop stations are used. The number of available stations for comparison lies between 70 – 230 stations, dependent on the meteorological parameter. However, we have chosen to use only stations that are within the three Bedre Byluft regions, in order to facilitate comparison of 1 and 2.5 km calculations. This reduces the number of available stations to around 60 stations. Not all stations have valid data through the entire year so the number of stations used for each hour also varies slightly.

The verification statistics applied to continuous variables are standard in MET verification reports and defined in Table 3. For this report we present monthly values for the Mean Error (ME), which indicates the bias of the model, and the Standard Deviation of the Error (SDE), which indicates the distribution of the error around this mean (hourly uncertainty). The other statistical parameters of RMSE and MAE are only presented in the summary tables for the entire year.

Table 3. Mathematical definitions of the statistical parameters used in the verification

Statistic	Acronym	Formula	Range	Optimal score
Mean Error	ME	$\frac{1}{n} \sum_{i=1}^{n}(f_i - o_i)$	$-\infty$ to ∞	0
Mean Absolute Error	MAE	$\frac{1}{n} \sum_{i=1}^{n} \mid f_i - o_i \mid$	0 to ∞	0
Standard Deviation of Error	SDE	$\left(\frac{1}{n} \sum_{i=1}^{n}(f_i - o_i - ME)^2 \right)^{1/2}$	0 to ∞	0
Root Mean Square Error	RMSE	$\left(\frac{1}{n} \sum_{i=1}^{n}(f_i - o_i)^2 \right)^{1/2}$	0 to ∞	0

4.2 Monthly statistics

Here we compare the monthly statistics for both the 2.5 and 1 km resolution calculations. Comparison is carried out at sites within both the 2.5 and 1 km domains. This includes 51-55 stations for 10 m wind speed, 69-72 stations for 2 m temperature and 47-53 stations for 12 hourly precipitation.

In Figure 5 the monthly statistics of ME and SDE are presented for 10 m wind speed. Wind speed bias is positive in the winter (too high wind speeds) and only slightly negative in the summer. The standard deviation of the error is also highest during the winter. This follows the same seasonal trend as the average wind speed, not shown, that is highest in winter and lowest in summer. There is little to no difference between the 2.5 and 1 km calculations.

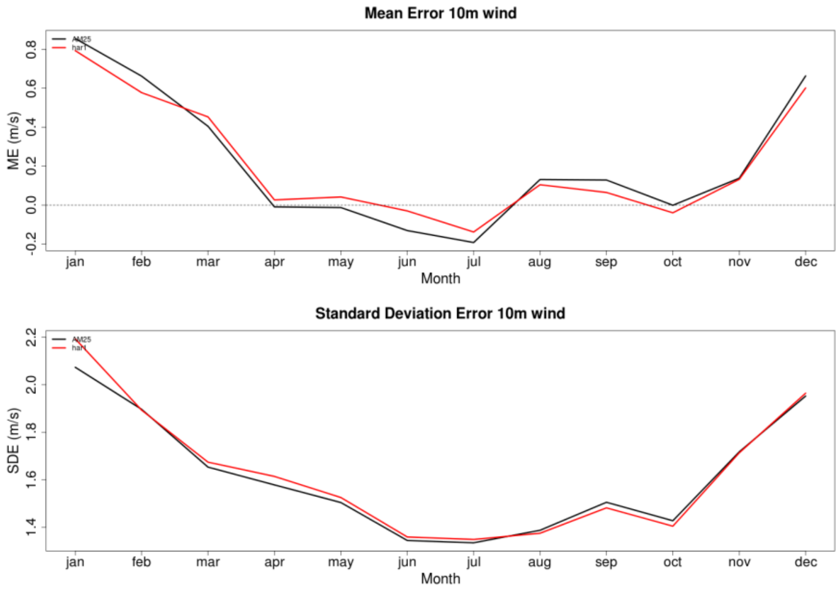


Figure 5. Monthly mean error (top) and monthly standard deviation error (bottom) for hourly 10 m wind speed. Black line (AM25) indicates the 2.5 km METCoOp calculation and the red line (har1) the Bedre Byluft 1 km calculation. Between 51-55 measurement sites are used in the analysis.

In Figure 6 the monthly statistics of ME and SDE are presented for 2 m temperature. Temperature bias is slightly negative throughout the year. Absolute bias for the 1 km model is slightly less as it better resolves the topography. The standard deviation of the error is highest during the winter. This reflects higher model temperature errors under cold stable conditions. Apart from the slight difference in bias there is little to no difference between the 2.5 and 1 km calculations.

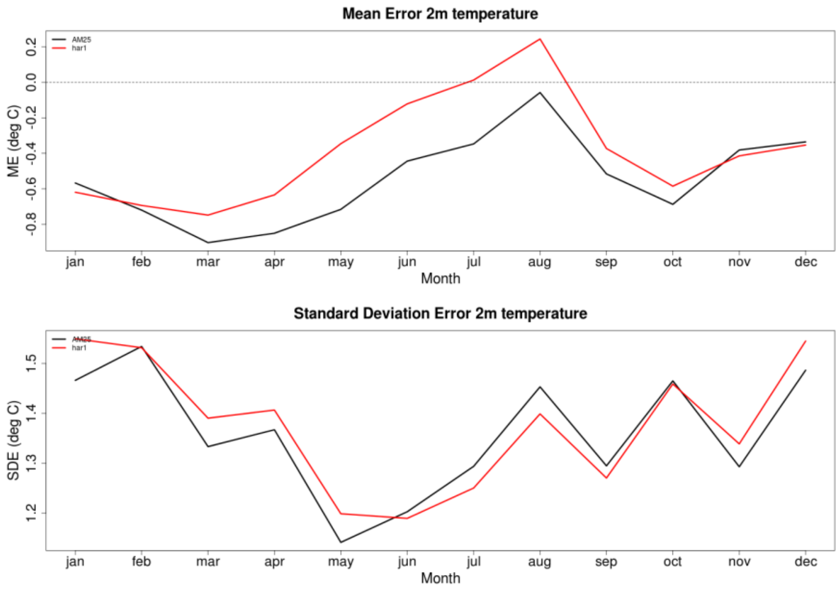


Figure 6. Monthly mean error (top) and monthly standard deviation error (bottom) for hourly 2 m temperature. Black line (AM25) indicates the 2.5 km METCoOp calculation and the red line (har1) the Bedre Byluft 1 km calculation. Between 69-72 measurement sites are used in the analysis.

In Figure 7 the monthly statistics of ME and SDE are presented for 12 h precipitation. Precipitation bias for 2.5 km calculations is very low throughout the year. For 1 km the bias is slightly negative during winter. The standard deviation of the error is highest during the summer-autumn period which also corresponds to the period with highest precipitation. For the case of precipitation the 2.5 km resolution model performs better.

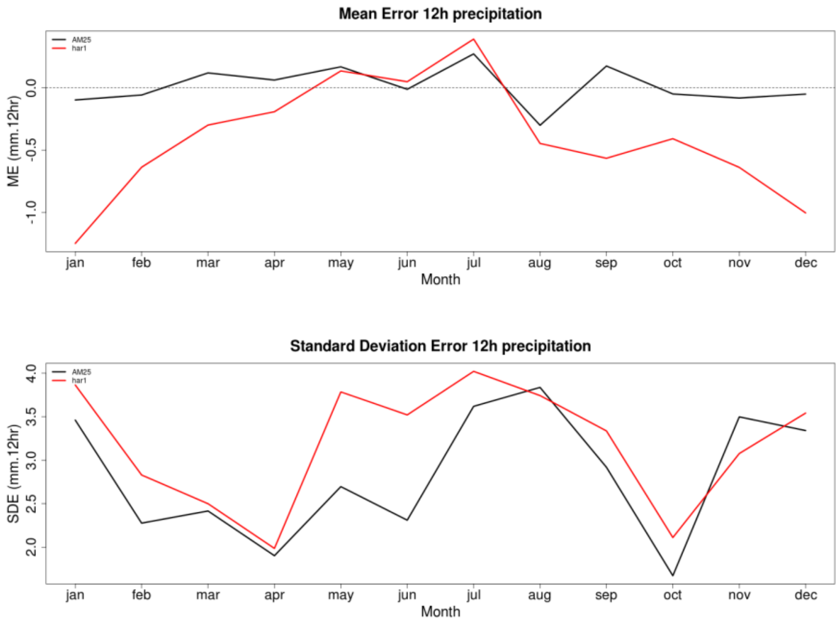


Figure 7. Monthly mean error (top) and monthly standard deviation error (bottom) for hourly 2 m temperature. Black line (AM25) indicates the 2.5 km METCoOp calculation and the red line (har1) the Bedre Byluft 1 km calculation. Between 47-53 measurement sites are used in the analysis.

In Table 4 the annual statistics are summarised. For all three meteorological parameters the mean error (ME) is quite low compared to the mean values. This indicates that there are no significant biases in the model over the short model forecast period. For wind speed the statistical error indicators of MAE, RMSE and SDE are all less than half of the mean wind speed, whilst for precipitation the errors tend to be as large as the mean value. The relatively large values for SDE and RMSE for precipitation are partly be due the "on/off" behaviour of precipitation and the timing and placement issues that follow from this. There is little to no difference in the statistical analysis for the 2.5 and 1 km calculations for wind speed and temperature. For 12 hour precipitation the 2.5 km model performs noticeably better.

Table 4. Total statistics for all sites and all hours

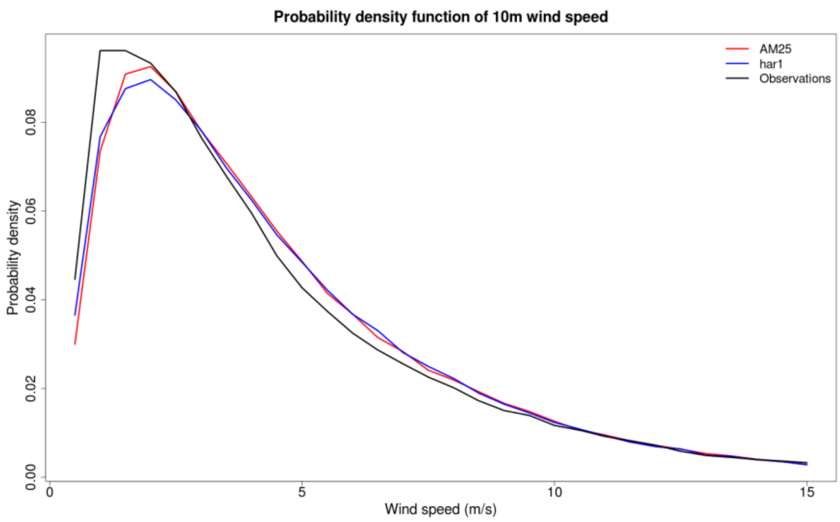
Parameter 2.5 km AROME	**ME**	**MAE**	**RMSE**	**SDE**	**MEAN (obs)**	**NUMBER**
10 wind speed (m/s)	0.22	1.41	1.83	1.61	4.12	51-55
2m temperature (ºC)	-0.54	1.24	1.56	1.36	7.17	69-72
12h precipitation (mm.12hr)	0.01	1.26	2.83	2.83	2.18	47-53

Parameter 1 km AROME	**ME**	**MAE**	**RMSE**	**SDE**	**MEAN (obs)**	**NUMBER**
10 wind speed (m/s)	0.215	1.44	1.85	1.63	4.12	51-55
2m temperature (ºC)	-0.39	1.26	1.59	1.38	7.17	69-72
12h precipitation (mm.12hr)	-0.40	1.48	3.25	3.19	2.18	47-53

4.3 Frequency distribution

To assess the statistical distribution of the wind speed, temperature and precipitation the probability density (normalised frequency distribution), which describes the frequency distribution of wind, temperature and precipitation for all hours at all stations is presented. From this it is possible to assess if the model over or under predicts over different ranges of these meteorological parameters. The distributions are shown in Figure 8 and we make the following comments:

- The model slightly under predicts the frequency of wind speeds < 1 m/s for both model resolutions but slightly over predicts for wind speeds from 3 – 10 m/s. Though synoptic weather stations are placed to be representative of larger areas they still tend to be influenced by local surface conditions and obstacles that are not included in the model calculations, so measured wind speeds can be strongly affected by local conditions, e.g. topography and obstacles. Despite this, the frequency distribution for wind speed from the model is considered to be quite good.
- The model slightly over predicts for temperatures below zero and slightly over predicts for temperatures above zero, reflecting the temperature bias in the model, but generally captures the temperature distribution very well. This good fit is partially attributable to the initialisation of the surface temperature with observations and the short forecast period over which the statistics are taken.
- The modelled and measured precipitation frequency distributions are well matched for both resolutions.
- There is no significant difference in the frequency distributions for the 2.5 and 1 km calculations.



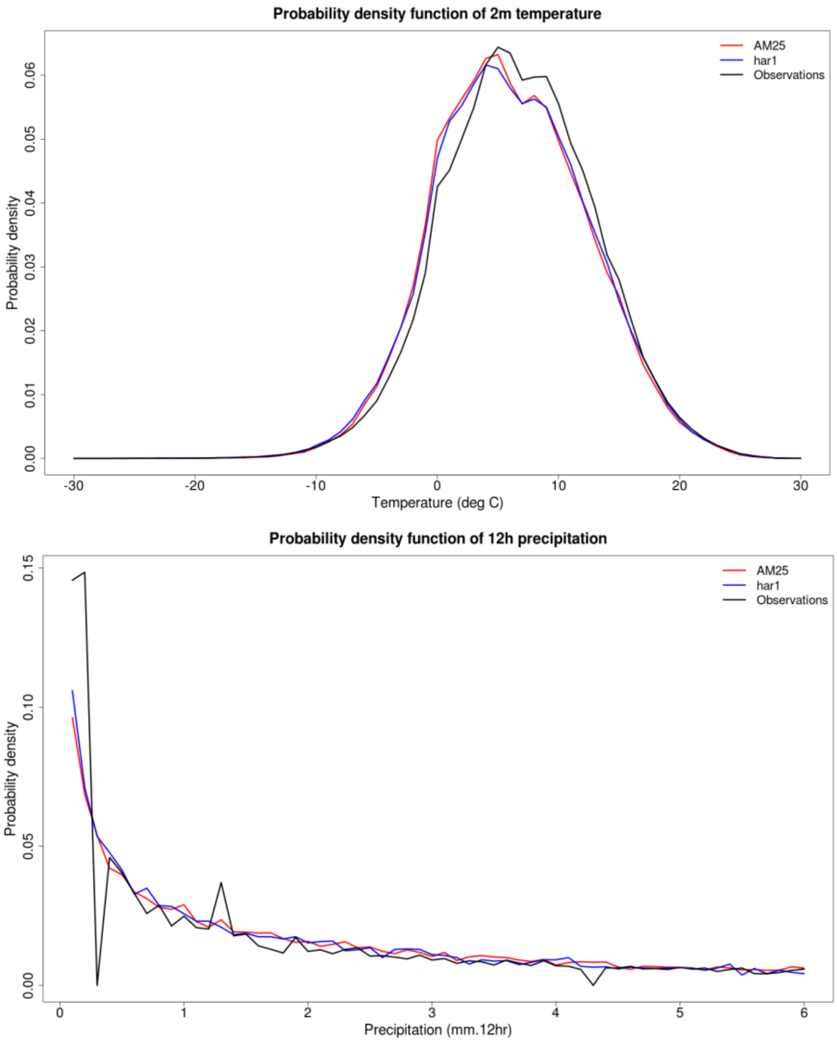


Figure 8. Probability density functions for modelled and observed wind speed (top), temperature (middle) and precipitation (bottom). For wind speed the bin size is 0.5 m/s, for temperature 1 ºC and for precipitation 0.1 mm.12hr.

5 Modelled temperature inversions and boundary layer height

In this section we compare modelled and measured inversion strengths during the winter periods of 2010 and 2015. This is done by comparison of 2 m temperature at different heights in Oslo and Bergen where such measurements are available. Modelled 2 m temperature is extracted at the same positions as the measurement sites. In complex terrain modelled heights are generally not the same as measurements and this must be taken into account. In addition to the temperature measurements we compare modelled and measured wind speed during inversion events and investigate the modelled boundary layer height.

Appropriate measurement data in Oslo is available in both 2010 and 2015 but only in 2015 in Bergen. Both 1 km and 2.5 km meteorological data are available in 2010 so a comparison will be made for this year as well. In table 5 we show the list of stations used for the comparison. For Oslo the model height is lower (70 m and 210 m for 1 and 2.5 km respectively) at the highest station Tryvann. For Bergen the model heights are higher (35 and 120 m for 1 and 2.5 km respectively) at the lowest station Florida. This will naturally lead to an underestimation of the inversion strengths calculated by the model in both cases.

Table 5. Information concerning the observational data used in the inversion analysis

Station	City	Measurement height (m.a.s.l.)	1 km model height (m.a.s.l.)	2.5 km model height (m.a.s.l.)	Years available
FV18-NATTLANDSFJELLET	Bergen	230	247	227	2015
BERGEN-FLORIDA	Bergen	12	47	135	2015, 2010
BLINDERN	Oslo	94	92	85	2015, 2010
BYGDØY	Oslo	15	15	16	2015
TRYVANNSHØGDA	Oslo	514	444	306	2015, 2010

5.1 Oslo

The most significant inversion event in the winters of 2010 and 2015 occurred in the first two weeks of January 2010. For this period we show, in Figures 9 and 10, the following:

1. observed and modelled 2 m temperature at Blindern
2. observed and modelled potential temperature difference between Tryvann and Blindern,
3. observed and modelled wind speed at Blindern
4. observed and modelled wind direction at Blindern
5. modelled boundary layer height and vertical profile of the potential temperature gradient (K/m) at Blindern

Figure 9 shows the results for the 1 km simulation and Figure 10 for the 2.5 km simulation. We note the following points concerning these figures.

- The temperatures, wind speeds and wind directions are well reproduced by both the model resolutions
- The inversion strength is very well reproduced, when taking into account the height differences between model and measurements, by both resolutions
- The boundary layer height predicted by the model during the inversion periods is very low, at its minimum possible value corresponding to the lowest grid level of 12 m. This indicates that the Turbulent kinetic energy prognosed by the model is very low and that there should be very little to no mixing in the lowest layers of the model.

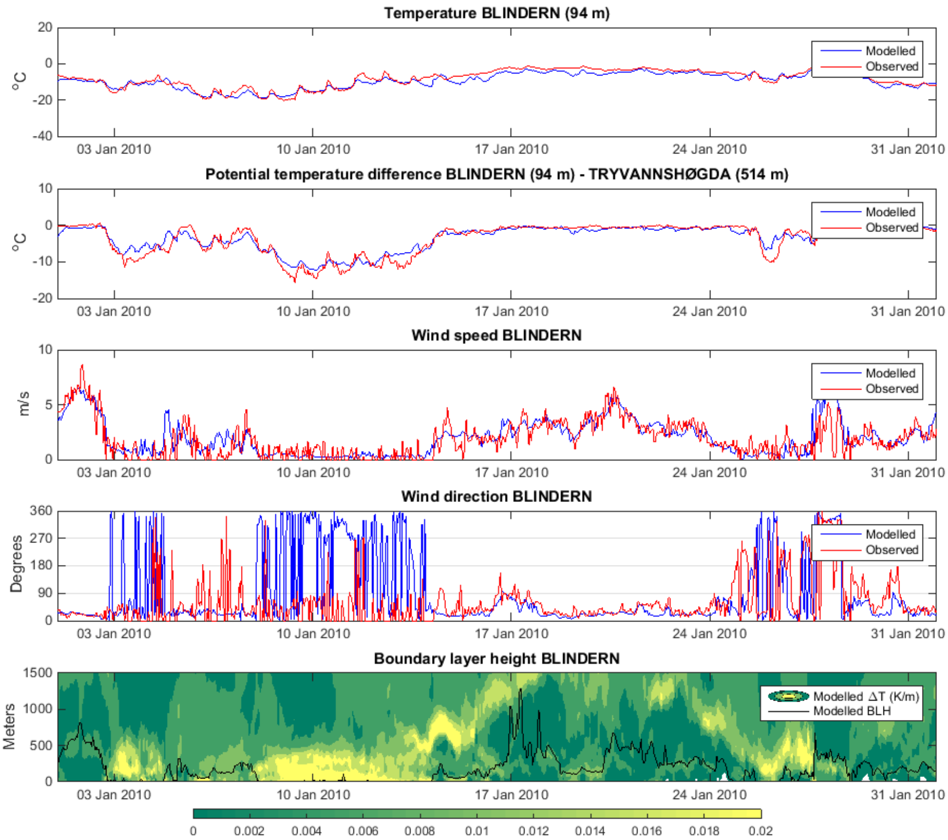


Figure 9. Comparison of modelled (1 km resolution) and observed meteorological parameters for the period January 2010 in Oslo. See text for details

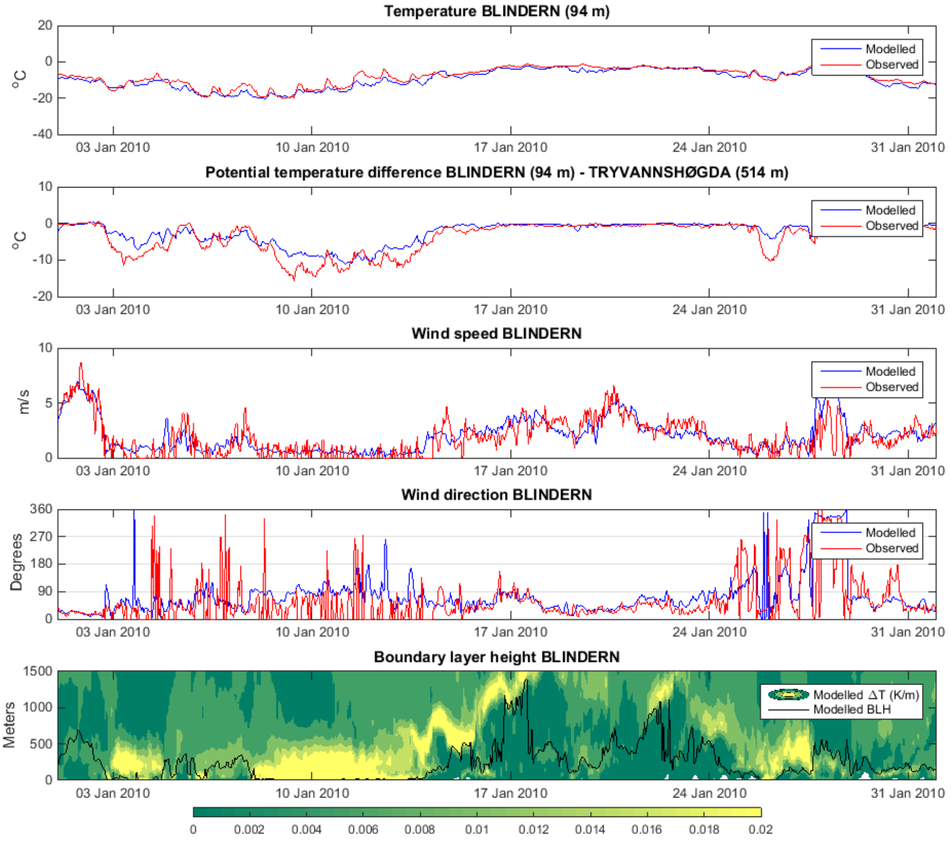


Figure 10. Comparison of modelled (2.5 km resolution) and observed meteorological parameters for the period January 2010 in Oslo. See text for details.

The most significant inversion event in 2015 occurred in the second week of February in Oslo. The same comparison, as for 2010, is shown for this period (Figure 11). The model successfully represents this inversion event and the other observed meteorological parameters.

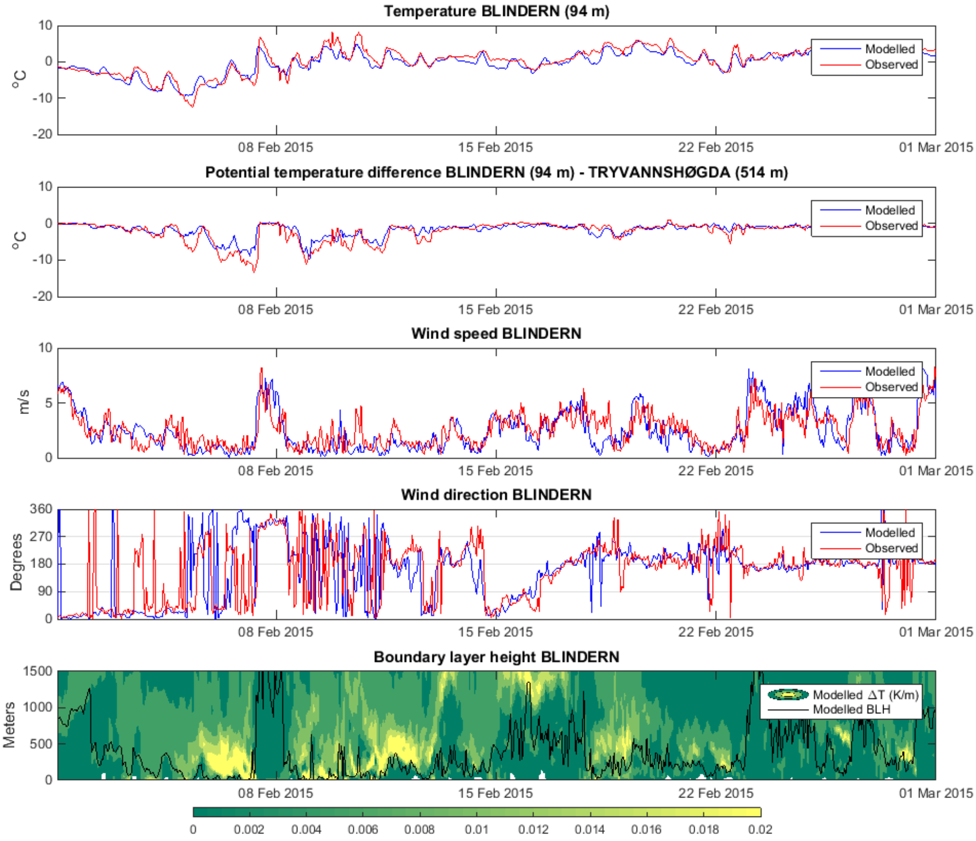


Figure 11. Comparison of modelled (1 km resolution) and observed meteorological parameters for the period February 2015 in Oslo. See text for details

5.2 Bergen

The road side meteorological station FV18-NATTLANDSFJELLET, with a height of 230 m, was unfortunately not available in 2010 when the strongest inversions occurred in Bergen so the comparison of observed and modelled inversion is limited to 2015. The strongest sustained inversion occurred for a 3 day period at the end of December 2015 (Figure 12). This was a fairly mild inversion event that was also well represented by the model. The model also well reproduced the temperature and winds at the Florida site.

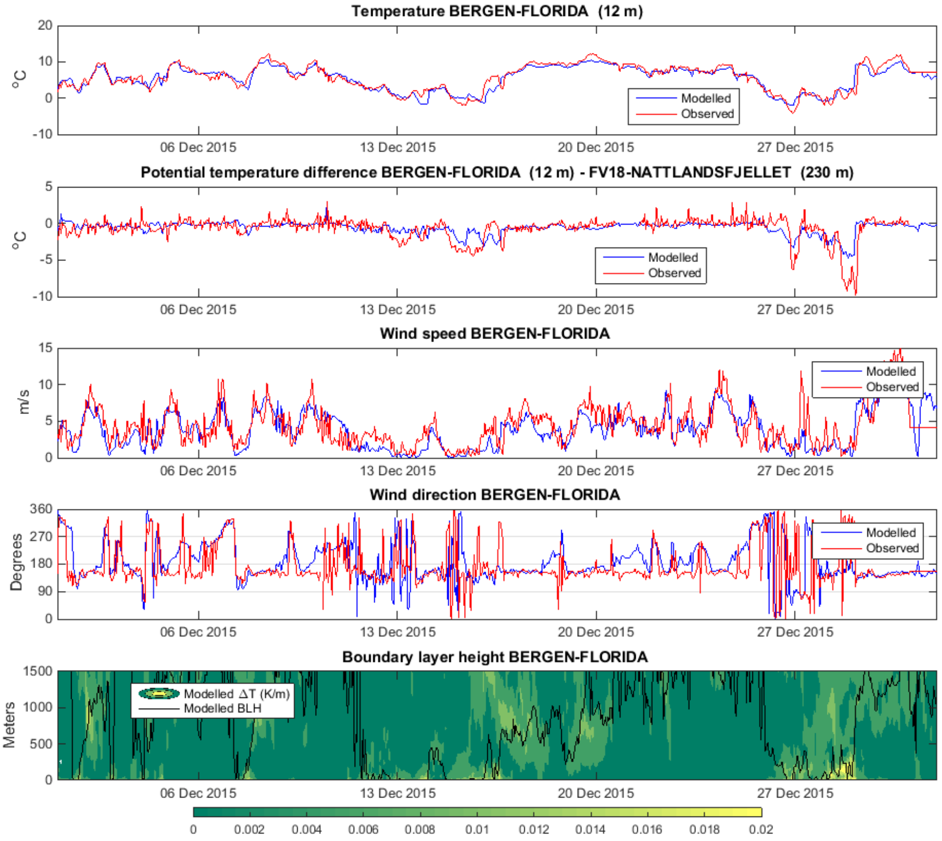


Figure 12. Comparison of modelled (1 km resolution) and observed meteorological parameters for the period December 2015 in Bergen. See text for details

In Figures 13 and 14 we show a comparison of modelled and measured meteorological parameters for the January 2010 period in Bergen. During this period, as in the Oslo case, a strong inversion occurred during the first 2 weeks of January. Since data from FV18-NATTLANDSFJELLET is not available we do not provide a comparison of inversion strengths. In this case there is a more significant difference between the two model resolutions. This difference is mainly visible in the wind direction where the 2.5 km resolution wind direction is rotated around 70^{o} during the inversion period. This is the result of topography that is not as well represented in the 2.5 km calculation. Despite this wind speeds, temperatures and boundary layer heights are very similar in both model calculations. Both model calculations overestimate the temperatures by around 5 ^{o} C, indicating that for this event neither model resolution successfully prognosed the intensity of the inversion.

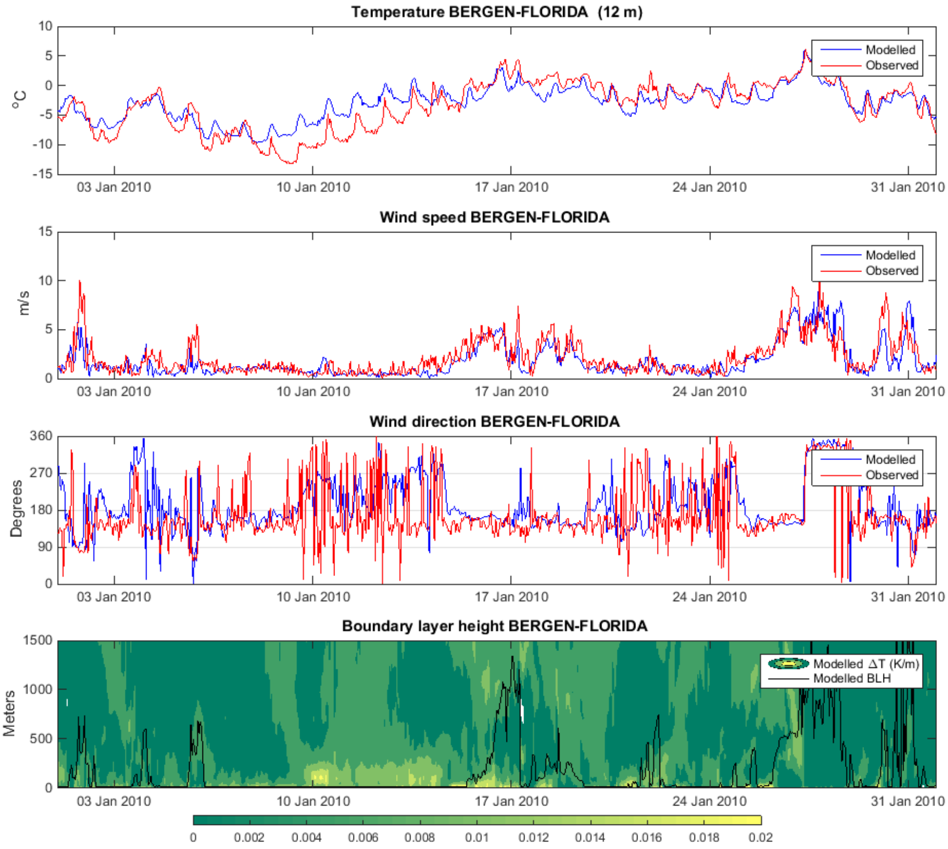


Figure 13. Comparison of modelled (1 km resolution) and observed meteorological parameters for the period January 2010 in Bergen. See text for details.

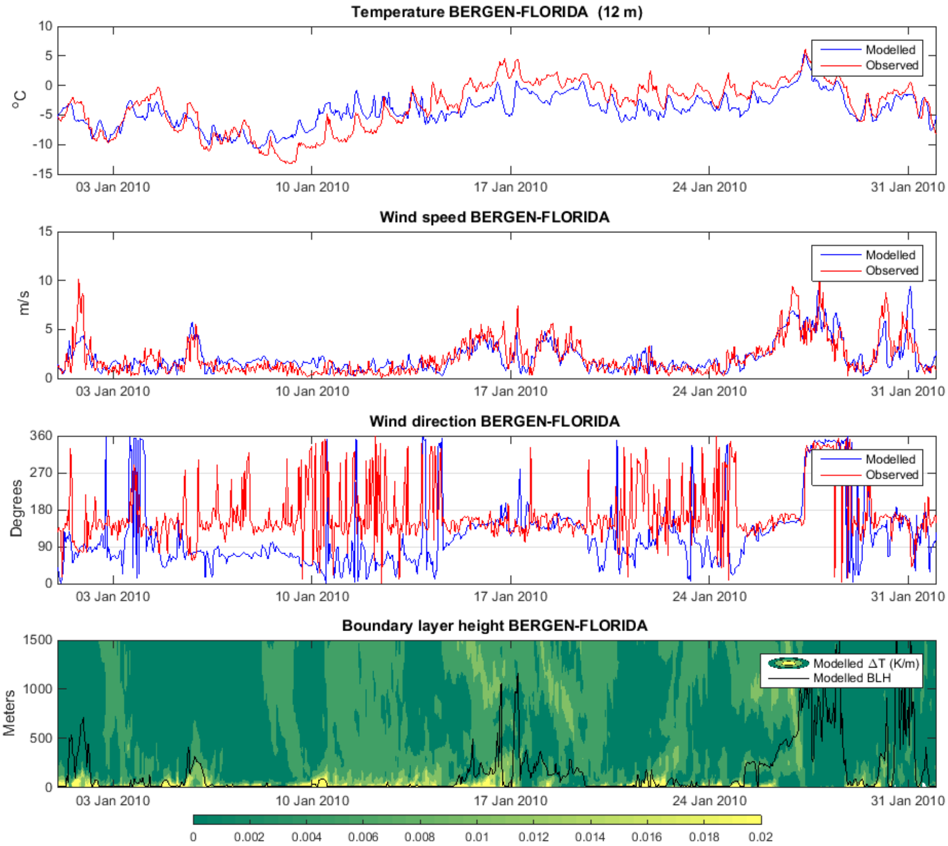


Figure 14. Comparison of modelled (2.5 km resolution) and observed meteorological parameters for the period January 2010 in Bergen. See text for details

6 Conclusions and recommendations

6.1 Conclusions concerning the model error verification results

Verification of the standard synoptic meteorological parameters of 10 m wind speed, 2 m temperature and precipitation (12 hour accumulated) has been carried out. Between 50 to 70 synoptic stations have been used to determine a number of error statistics on a monthly basis. In particular the mean error (ME), that represents the bias in the model, and the standard deviation of the error (SDE), that represents model uncertainty on an hourly basis, has been assessed.

Error statistics indicate satisfactorily low biases in all three meteorological parameters addressed but also show seasonal differences. Wind speeds are positively biased in winter and slightly negatively biased in summer, temperatures are slightly negatively biased throughout the year and precipitation has a slight negative bias in spring and autumn.

Seasonally there is higher model uncertainty during the winter for wind speed and temperature but a higher uncertainty in precipitation during the summer/autumn. Higher uncertainty in wind and temperature during the colder winter months likely reflects the models decreased ability to reproduce the colder more stable conditions found then, though more attention to both the radiation and turbulence processes in the model are required to determine why this occurs.

A comparison of modelled and observed frequency distributions for wind speed, temperature and precipitation show a very good statistical representation of these. The model slightly under predicts the frequency of low wind speeds.

6.2 Modelled inversions and boundary layer height

A number of inversion events in Oslo and Bergen were assessed. The comparison of modelled and measured inversion strength showed that the model successfully models the inversions in Oslo but did not produce strong enough inversions in Bergen during a long inversion event in 2010. Despite this the model successfully reproduced wind speeds during these periods and predicted low turbulence intensity and minimum boundary layer heights.

The question of how well the meteorological model predicts inversions is to a large extent academic as this information does not go further into the dispersion model EPISODE. The same is true for temperature and temperature profiles as these are also not used by the dispersion model. In information concerning the turbulent kinetic energy (TKE) is also not used by EPISODE, since it applies its own parameterisation for the boundary layer mixing, based on the boundary layer height and surface fluxes provided by the meteorological model. In that parameterisation the minimum mixing height is 50 m, larger than that predicted by the meteorological model during these inversions, and minimum levels of dispersion are also enforced by the EPISODE model. In addition the line source model (HIWAY2), used to predict traffic contributions, does not include any reflection from the boundary layer height (inversion height). Until the EPISODE model starts to make use of this information then the question of inversion strengths is to a large extent irrelevant. It is surface stability and wind which are the defining meteorological parameters necessary for the dispersion calculations.

6.3 Impact of resolution

For both the validation statistics and the inversion study a comparison of 2.5 km and 1 km resolutions has been carried out. Statistically there is very little difference between the two resolutions and boundary layer heights and inversion strengths are very similar for both resolutions. The only significant difference seen is in the wind direction in cases, such as Bergen, where the topography is not sufficiently resolved at the 2.5 km resolution. For Oslo, and all other sites with less complex terrain, there is no improvement in the 1 km calculations. A similar conclusion was arrived at in the previous report (Süld and Denby, 2015).

Recirculation of polluted air within a city bounded by significant topography has not been addressed in this report. In an earlier report for Bedre Byluft (Ødegård, 2011) recirculation and the impact of resolution was studied for Bergen using the UM model. It was found that 1 km calculations with that model could generate recirculation patterns during strong inversion events. However, the AROME model uses spectrally based dynamics. The minimum wavelength for circulations it can reproduce is around 5 grid sizes. For Bergen, with a basin width of just 2-3 km this means that even 1 km resolution is not sufficient to reproduce such recirculation. To address this higher resolutions are required, but the AROME model has not been developed and has never been applied at resolutions less than 1 km.

The final impact of enhanced resolution will need to be assessed by the air quality model itself. Air quality measurements provide information on the transport and dispersion of pollutants within the cities and correctly modelling these will provide verification of both the meteorological and air quality models.

6.4 Model resolution and air quality applications

It is important to note that calculations for NBV are not intended to provide hourly time series of data, but to provide statistical results based on means and percentiles. It is by no means given that erroneous wind directions for certain periods have any significant impact on these statistics. The same can be said for Bedre Byluft forecasts. Their aim is to generally predict air quality within a city, rather than give exact time series at measurement stations. 2.5 km AROME calculations are carried out every 6 hours as part of the meteorological forecasting system at MET and are well verified, robust, used in a wide range of applications and are guaranteed with backup solutions. 1 km calculations are carried out solely for Bedre Byluft and provided further for the NBV application. There are significant costs in establishing and maintaining the 1 km calculations, as well as storage requirements. For the most cost effective production of meteorological data the questions should be asked. Are the NBV statistics significantly better to warrant the use of these extra resources? Would a Bedre Byluft forecast be any different with the use of 2.5 km meteorological data? Based on the meteorological assessment carried out here, and the previous NBV report, then the objective answer to these two questions is no. However, the final word must rest with the results of the dispersion calculations.

6.5 Recommendations

The AROME model is under continuous development in a host of countries and there has been significant improvements over the past years. The model is considered to be very good under many conditions and the results presented here confirm this. There are still some areas where the model can be improved, one of these being its ability to predict inversions. Currently MET applies a post processing routine to weather forecasts to adjust for this. Unfortunately this post-processing is only applied to the surface layer for temperature so it will not affect the dynamics of the model itself and cannot be used in air quality applications. The following recommendations are given:

- Continuous involvement in the Harmonie community and implementation of improvements when they occur.
- Unless proven otherwise by dispersion calculations it is recommended to use only the AROME 2.5 km model for both Bedre Byluft forecasts and NBV data.

Acknowledgements

References

Denby B.R., Jacob Suld, Arne Kristensen, Ingrid Sundvor, Islen Vallejo Henao, Sam Erik Walker (2015). Bedre byluft: Endringer i 2014 og forskningsresultater av prognoser for meteorologi og luftkvalitet i norske byer vinteren 2013-2014. MET report 08/2015.
http://met.no/Forskning/Publikasjoner/MET_report/?module=Files;action=File.getFile;ID=6391

Gangstø,R., Heiberg, H., Kristiansen, S., Mamen, J., Szewczyk-Bartnicka, H., Tilley Tajet, H.T. (015) Været i Norge: Klimatologisk oversikt Året 2015 MET inf. (13/2015)
http://met.no/Forskning/Publikasjoner/MET_info/2015/?module=Files;action=File.getFile;ID=6675

Homleid, M. and F.T.Tveter (2016). Verification of Operational, Weather Prediction Models, September to November 2015. MET report 16/2016
http://met.no/Forskning/Publikasjoner/MET_info/?module=Files;action=File.getFile;ID=6728

Süld J.K and Denby, B.R. Verification of AROME-MetCoOp reanalysis for 2010: Application for the NBV project. METreport (unpublished).

Ødegaard, V., Gjerstad, K.I., Abildsnes, H., Olsen, T. (2011). Bedre byluft: Prognoser for meteorologi og luftkvalitet i norske byer vinteren 2010-2011. Oslo, met.no (met.no report, 8/2011). http://met.no/Forskning/Publikasjoner/filestore/report8_2011.pdf

Appendix

Archived variables in meteorological forecast fields

The following table lists the archived model parameters from AROME and SURFEX. Not all these data are available in the processed fields (Table 1)

Parameter	Units	Dimensions
AROME		
Surface temperature (T0M)	K	(time, 0, y, x)
Snow Water Equivivalent (SWE)	kg/m^2	(time, 0, y, x)
Surface geopotential (fis)	m^2/s^2	(time, 0, y, x)
Momentum flux (u,v)	N/m^2	(time, 0, y, x)
Accumulated TOA net downward SW radiation	W s/m^2	(time, top, y, x)
Accumulated net downward surface SW radiation	W s/m^2	(time, 0, y, x)
Accumulated TOA outgoing LW radiation flux	W s/m^2	(time, top, y, x)
Accumulated net downward surface LW radiation	W s/m^2	(time, 0, y, x)
Accumulated latent heat evaporation flux	W s/m^2	(time, 0, y, x)
Accumulated latent heat sublimation flux	W s/m^2	(time, 0, y, x)
Water evaporation amount	kg/m^2	(time, 0, y, x)
Accumulated Snow Sublimation	W s/m^2	(time, 0, y, x)
Accumulated downwelling surface sensible heat flux	W s/m^2	(time, 0, y, x)
Accumulated surface SW downwelling radiation	W s/m^2	(time, 0, y, x)
Accumulated surface LW downwelling radiation	W s/m^2	(time, 0, y, x)
Instantanous rainfall at surface	kg/m^2	(time, 0, y, x)
Instantaneous snowfall amount at surface	kg/m^2	(time, 0, y, x)
Instantaneous graupel	kg/m^2	(time, 0, y, x)
Screen level temperature (T2M)	K	(time, 2, y, x)
Screen level relative humidity (RH2M)		(time, 2, y, x)
10 metre wind (U10M) (u,v)	m/s	(time, 10, y, x)
Total cloud cover (TCC)		(time, 0, y, x)
Convective cloud cover		(time, 0, y, x)
Cloud cover of high clouds (HCC)		(time, 0, y, x)
Cloud cover of medium height clouds (MCC)		(time, 0, y, x)
Cloud cover of low clouds (LCC)		(time, 0, y, x)
Wind gusts in 10m height (u,v)	m/s	(time, 10, y, x)
Max screen level temperature last hour	K	(time, 0, y, x)
Min screen level temperature last hour	K	(time, 0, y, x)
Height of the PBL	m	(time, 0, y, x)
Hail diagnostic	%	(time, 0, y, x)
Instantaneous snow in pressure levels	kg/m^2	(time, pressure, y, x)
Instantanous rain in pressure levels	kg/m^2	(time, pressure, y, x)
Instantaneous graupel in pressure levels	kg/m^2	(time, pressure, y, x)
Vertical vind pressure levels	m/s	(time, pressure, y, x)
Potential vorticity	Km^2 kg^-1 s^-1	(time, pressure, y, x)
Mean Sea Level Pressure (MSLP)	Pa	(time, msl, y, x)

Precipitable water	m	(time, top, y, x)
Surface air pressure	Pa	(time, 0, y, x)
Convective Available Potential Energy (CAPE)"	J/kg	(time, 0, y, x)
Wind model levels	m/s	(time, hybrid, y, x)
Air temperature model levels	K	(time, hybrid, y, x)
Specific humidity model levels	Kg/kg	(time, hybrid, y, x)
Atmospheric cloud condensed water content in model levels	kg m-2	(time, hybrid, y, x)
Cloud ice in model levels	kg m-2	(time, hybrid, y, x)
Cloud cover in model levels	%	(time, hybrid, y, x)
Turbulent kinetic energy (TKE)	m^2/s^2	(time, hybrid, y, x)
Geopotential model levels	m^2/s^2	(time, hybrid, y, x)
Accumulated total precipitation	kg/m^2	(time, 0, y, x)
Total accumulated solid precipitation	kg/m^2	(time, 0, y, x)
Wind gust	m/s	(time, 10, y, x)
SURFEX		
Vegetation index (VEG)		(time, 0, y, x)
Sea surface temperature (SST)		(time, 0, y, x)
2 m temperature (T2M)	K	(time, 2, y, x)
2 m specific humidity (Q2M)	kg/kg	(time, 2, y, x)
2 m relative humidity (HU2M)		(time, 2, y, x)
TG1	K	(time, -, y, x)
TG2	K	(time, --, y, x)
WG1	m^3/m^3	(time, -, y, x)
WG2	m^3/m^3	(time, --, y, x)
WGI1	m^3/m^3	(time, -, y, x)
WGI2	m^3/m^3	(time, --, y, x)
WSNOW_VEG1	kg/m^2	(time, 0, y, x)
RSNOW_VEG1	kg/m^2	(time, 0, y, x)
ASNOW_VEG		(time, 0, y, x)
LAI		(time, 0, y, x)
Roughness length momentum (Z0)	m	(time, 0, y, x)
Roughness length temperature (Z0H)	m	(time, 0, y, x)
RI		(time, 0, y, x)
CD	W/s^2	(time, 0, y, x)
CE	W/s/K	(time, 0, y, x)
LE	W/m^2	(time, 0, y, x)
H	W/m^2	(time, 0, y, x)
Momentum flux (FM) (u,v)	kg/ms^2	(time, 0, y, x)
Net radiation (RN)	W/m^2	(time, 0, y, x)
Surface energy flux (GFLUX)	W/m^2	(time, 0, y, x)

Vertical and horizontal coordinates of the meteorological data

The monthly data is provided in a specific coordinates system based on the EPISODE models grid.

The horizontal positioning of the EPISODE model grid is defined in the UTM 1984 Zone 32 projection (Unit: meter). The model origin (lower left corner) and the grid dimensions in east and west for the defined EPISODE domains are listed in Table ?.

	X0	Y0	XDIM	YDIM
Bergen	285000	6685500	16	27
Drammen	552500	6613000	23	22
Grenland	528040	6542350	16	23
Oslo	579500	6633000	29	18
Oslo extended	578500	6625000	39	28
Stavanger	301500	6523000	14	25
Trondheim	564000	7022000	14	16
Aalesund	348500	6921500	21	17
Halden	618800	6548000	25	19
Harstad	788000	7641000	20	15
Kristiansand	432000	6435800	36	28
Kristiansund	430000	6993000	15	9
Lillehammer	570900	6730500	47	61
MoiRana	722700	7358600	18	13
Moss	587500	6575200	40	32
Narvik	836100	7607000	19	14
Sandefjord	545200	6537500	43	38
Tromsø	871900	7749600	25	22

For all cities the horizontal grid spacing is: DX = DY = 1000 m

This means that the positions of the midpoints of the grid cells are:

$X(i,j) = X0 + (i - 0.5) * DX \quad ; i = 1, NX$

$Y(i,j) = Y0 + (j - 0.5) * DY \quad ; j = 1, NY$

For the vertical coordinate the grid layer thickness is defined and are adjusted according to surface elevation. At grid cells with zero topography (sea level) the ZDIM = 35 layer thicknesses are defined as:

24, 24, 24, 26, 27, 28, 31, 34, 36, 40, 44, 48, 50, 57, 59, 69, 71, 79, 87, 92, 100, 107, 118, 126, 137, 148, 158, 172, 179, 192, 204, 214, 227, 238, 248.

This gives a maximum grid depth of 3518 m. The above list of layer depths gives the following heights above sea level of the midpoints of each layer:

12, 36, 60, 85, 111.5, 139, 168.5, 201, 236, 274, 316, 362, 411, 464.5, 522.5, 586.5, 656.5, 731.5, 814.5, 904, 1000, 1103.5, 1216, 1338, 1469.5, 1612, 1765, 1930, 2105.5, 2291, 2489, 2698, 2918.5, 3151, 3394.

The vertical extent of the model is defined from the ground, $z = h(x,y)$, up to a constant height, $z = H_0$, (here 3518 m) above sea level. This means that the model applies a stretched vertical coordinate, or a terrain following sigma-coordinate system, given by the following transformation:

$$\sigma_k = H_0 \frac{z_k - h(x,y)}{H_0 - h(x,y)}$$

The denominator of the above equation is identical to the total vertical depth of the model, i.e. D(x,y), and k = 35 for the first layer above ground.

The physical extent of the model domain when applying this transform is depicted in Figure 1.

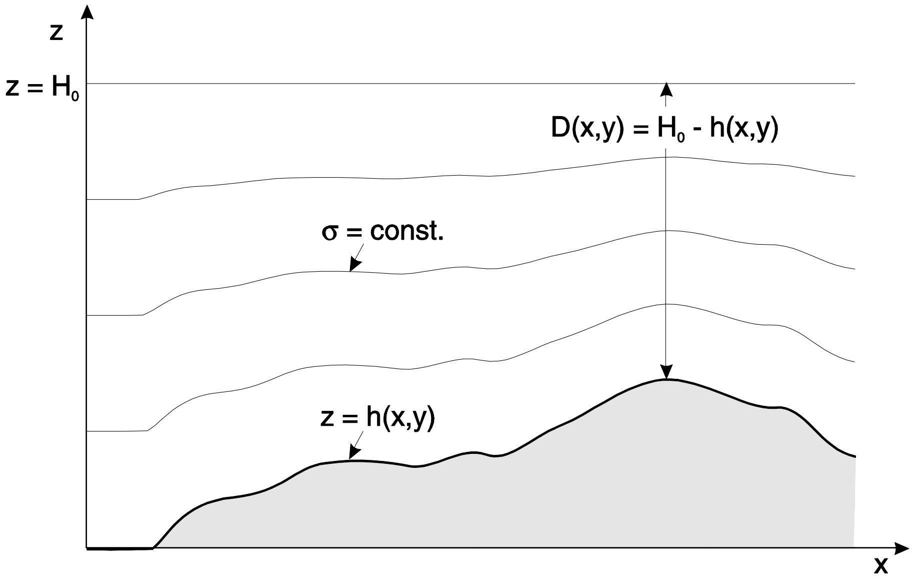


Figure 4: A schematic representation of the vertical extent of the model domain and the position of the model layers, when the terrain following coordinate transform is applied.

The topography, *h(x,y)* is taken from the AROME model output, i.e. the topography values for the grid midpoints positions X(i,j) and Y(i,j). The 3D vertical height of the midpoint of each model layer is then computed by the following formula:

$$z_k(x,y) = \sigma_k \frac{H_0 - h(x,y)}{H_0} + h(x,y)$$

for k = 35 to 1 starting from the ground layer. The σ_k values are taken from the above list of heights above sea level of the midpoints of the model layers.