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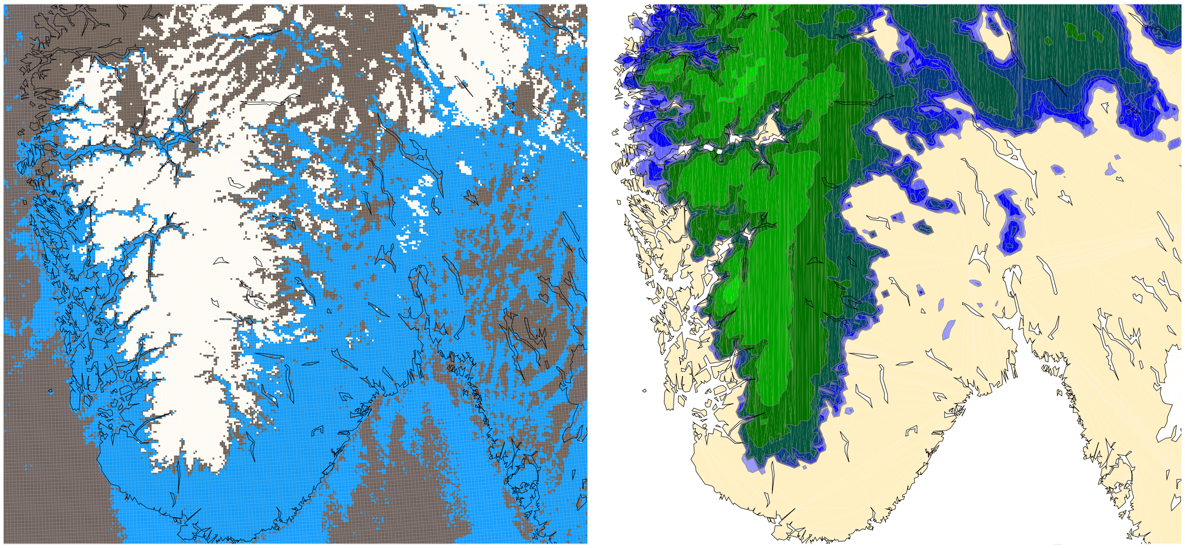
Mariken Homleid and Mari Anne Killie



CryoRisk Probability of snow and Harmonie 4 km experimental Snow Water Equivalent, South Norway 31 march 2012

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Authors

Mariken Homleid and Mari Anne Killie

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Abstract

Snow analysis experiments with HARMONIE have been performed for the spring 2012 on a domain covering Norway and Sweden. The snow cover is currently modelled by the one-layer snow scheme of SURFEX. Snow analysis is performed by Optimal Interpolation using snow depth observations from synoptic stations to update the snow water equivalent. A reference run has been performed to demonstrate the performance of the current setup, which is good in regions with representative observations. The network of synoptic stations is however sparse. Potential improvements by inclusion of additional snow depths from a precipitation gauge network are examined and shown to be significant. The first experiments with CryoRisk satellite data have also been performed and demonstrate the ability of the data to discriminate between snow free and snow covered ground. Snow aspects in HARMONIE are presented initially.

Keywords

Snow modelling and snow analysis in NWP, optimal interpolation, conventional snow depth observations, probability of snow derived from satellite data

Disiplinary signature	Responsible signature
	Øystein H
Jørn Kristiansen, Head NWP	Øystein Hov, Head R&D

1 Introduction

The presence of snow cover influences the near surface weather and particularly the temperature. Snow has high albedo and reflects 40-95 % of incoming solar radiation, while snow free ground normally reflects less than 30 %. In winter the insulating properties of the snow cover reduces the energy exchange between the soil and the atmosphere. In spring available energy is used to melt snow as long as there is snow on the ground. In Numerical Weather Prediction (NWP) models the main motivation for a realistic modelling of snow is to improve the quality of near surface temperatures. Total amount of snow is, however, also of interest, e.g to calculate potential runoff.

A non-hydrostatic convection permitting NWP model HARMONIE (HIRLAM ALADIN Regional/Mesoscale Operational NWP In Europe) is under developement in cooperation between the HIRLAM (High Resolution Limited Area Model) and ALADIN (Aire Limitée Adaptation Dynamique Développement International) consortia. HARMONIE has been run daily in experimental mode at the Norwegian Meteorological Institute since 2008, will be operationalized in 2013 and is planned to replace the HIRLAM models in a few years.

Increased resolution in the NWP models necessitates more detailed and realistic description of the surface and of physical processes related to the interactions between surface and atmosphere. The surface scheme SURFEX (surface externalisée) (Moigne, 2012) has been introduced in HARMONIE for surface modelling, see Section 2.1.

Ground based snow depth observations are assimilated regularly into the NWP models in the snow analysis to account for deficiencies and uncertainties in the modelling of snow related processes, e.g. melting rate, preciptiation rate, surface temperature, surface type. The quality of the observations and how they are used in the snow analysis is decisive for the result.

Surface analysis in HARMONIE is performed with CANARI (Code d'Analyse Nécessaire à ARPEGE pour ses Rejets et son Initialisation) (Taillefer, 2002). Snow analysis was introduced in CANARI and tested in ALADIN and ARPEGE in 2000/2001 (Gaytandjieva,2000a,b/2001). The current version of the snow analysis in HIRLAM was implemented by Cansado (2004) with references to (Brasnett, 1999). The main features of the snow analysis as introduced in CANARI and HIRLAM are similar

- analysis method is Optimum Interpolation (OI)
- background error correlation includes a horizontal and a vertical term
- use only synoptic observations

Some changes were introduced in the original CANARI setup, based on experience with HIRLAM's snow analysis and experiments (Homleid, 2009). The current CANARI setup is presented in Section 2.2. The performance of the current setup with a 1-layer snow scheme is good with respect to modelling of snow amounts in regions with representative observations, but the network is sparse. Another problem is that snow depth observations are not always reported when the snow has disappeared in spring. The lack of '0' snow depth observations in the snow analysis will often lead to too late melting in the model in spring.

The Norwegian Meterorological Institute has over the last years made an effort to make snow depth observations from a precipitation gauge network, hereafter called climate stations, available on the Global Telecommunication System (GTS) in real time for assimilation in NWP models. Another activity has been to improve the routines for reporting '0' snow. Some more details are given in Section 3.1.

In this study, snow analysis experiments have been performed with HARMONIE to evaluate potential improvements with additional snow depth observations. Experiments with additional snow depths from climate stations show that more observations will improve the performance both with respect to snow cover and temperatures, see Section 4.

Promising results are also obtained in the first experiments with CryoRisk satellite data products which are presented in Section 3.2. The satellite data is used similar to the way ECMWF uses NOAA-NESDIS data in the snow analysis (de Rosnay, 2014). The ability of the data to discriminate between snow free and snow covered ground is demonstrated in Section 4 and also the potential of the data to improve the temperature forecasts in the melting season.

The results of the experiments are summarized and discussed in Section 5.

2 Snow aspects in HARMONIE

The HARMONIE system developed in cooperation between HIRLAM and ALADIN includes several configuration options. For physical parameterizations there are two main options; AROME and ALARO. AROME (Applications of Research to Operations at MEsoscale) is targeted for horizontal resolution 2.5 km or finer. It uses physical parameterizations based on the French academia model Meso-NH and the external surface model SURFEX (Surface externalisée). AROME has been operational at Météo-France since 18 December 2008, with a horizontal resolution of 2.5 km (Seity et al, 2011). ALARO has physical parameterizations targeted for grey scale resolutions (4-10 km). It is a spin-off of the Météo-France physical parameterizations used in the globale ARPEGE, but with a separate radiation scheme, 3MT micro-physical frame work, and the Toucans turbulence scheme. SURFEX is also used as surface model with ALARO in HARMONIE.

2.1 SURFEX

SURFEX was developed in coperation between Météo-France and academia for offline experiments and introduced in NWP models to ensure consistent treatment of processes related to surface. SURFEX includes routines to simulate the exchange of energy and water between the atmosphere and 4 surface types (tiles); land, sea (ocean), lake (inland water) and town. The land or nature tile can be divided further into 12 vegetation types (patches). The Interactions between Soil, Biosphere, and Atmosphere (ISBA) parameterization (Noilhan and Planton, 1989, Boone et al, 1999) is by default used at nature points udating temperature, water and ice in 3 layers (surface, soil and deep soil) and the properties of the snow.

2.1.1 SURFEX snow schemes

SURFEX has 3 optional snow schemes:
1. 'D95' : Single-layer snow scheme (Douville et al.,1995)
2. '3-L' : Multi-layer snow scheme (Boone and Etchevers, 2001)

3. 'CRO' : CROCUS for snow avalanche warnings (Brun et al., 1989, 1992)

The current HARMONIE version uses the 1-layer 'D95' which has three prognostic fields; snow water equivalent (SWE), snow density and albedo.

The 3-layers scheme provides a more realistic modelling of e.g. the insulation properties of snow and includes heat content as a prognostic variable and snow temperature and liquid water as diagnostic variables.

2.1.2 ECOCLIMAP and permanent snow

SURFEX includes a global database of land surface parameters at 1 km resolution, ECOCLIMAP (Masson, 2003). Glaciers are represented as 'permanent snow'. The 'permanent snow' domains with ECOCLIMAP1 are too large, e.g. at Iceland, Svalbard and in Norway, see Fig. 1. The surface will in these domains have some of the properties of snow covered ground e.g. albedo and roughness, also when there is no snow on ground. A more realistic snow cover map is available with ECOCLIMAP2 (Donier, 2012).

2.2 CANARI snow analysis

Surface analysis with CANARI was introduced in cycle 33h0 of HARMONIE and became default option from cycle 33h1. CANARI is a part of the IFS/ARPEGE source code and was developed for both surface and upper air analysis in ARPEGE/ALADIN and is based on OI. The current version of CANARI in HARMONIE analyses univariately one layer of snow represented as Snow Water Equivalent (SWE). Here follows some details.

2.2.1 Optimum Interpolation

The performance of OI depends on the specification of the statistics of observation and background errors. The influence of the observations is limited both horizontally and vertically and is modelled by structure functions for the background error correlation. The horizontal and vertical background error structure functions have been modified to be closer to the operationally used settings in HIRLAM, see Fig. 2 and 3. The ratio between the specified standard deviations of the observation and background errors determines how close the analysis will be to the observations. The current values of 5 kg/m^2 for both observation and background errors give analysed values midway between the observation and the background at the observations points.

2.2.2 Conversion between observed snow depths and analyzed snow water equivalent

Observed snow depths are converted to SWE by climatological monthly mean values for snow density identical to the ones applied in HIRLAM which are increasing from 143 kg/m^3 in the autumn to 312 kg/m^3 in the spring.

2.2.3 Quality control

Quality control is an essential part of the snow analysis. A first guess check, but no spatial quality control, is performed for snow in CANARI. The observations are compared to first guess values and flagged as correct, probably correct or incorrect depending on the magnitude of the normalized deviation between observation and first guess. The deviations are normalized by the square root of the sum of observation and background error covariances, and compared to a threshold given in a namelist. As the initial snow might be quite unrealistic is it appropriate to have wide limits at cold starts, to avoid rejection of observations which are far from the initial snow field. Operational runs will probably benefit from more narrow limits, to avoid the assimilation of e.g. erronous snow observations in summer. Currently RCSNSY in namelist NAMCOK is set to 20 which correspond to a snow depth of about 30 cm.

2.3 CANARI and SURFEX

With SURFEX as surface scheme the surface analysis is performed in two steps. CANARI is used for horizontal interpolation and followed by a consistent update of related surface fields based on analysis increments interpolated to all nature grid point.

Only the 1-layer snow scheme is properly updated so far. The 1-layer snow scheme includes 3 snow fields; SWE, snow density and albedo. To avoid that the snow analysis introduces snow where there is no snow, SWE is set to 0 if the first guess is snow free and the surface temperature is above zero. Snow density and snow albedo are undefined where SWE=0. Snow density and albedo are initialized in points which get initial snow in the snow analysis, by 200 kg/m^3 and 0.675 respectively .

2.4 Initial snow field at cold starts

The initial snow cover is taken from the boundary model at cold starts.

The ECMWF model has glaciers represented with 10 meters of water, which means that the initial snow fields in the current setup with ECMWF as boundary model will have huge piles of snow/ice in some domains. This is problematic as the glaciers cover too large domains e.g. at Iceland and Svalbard. The amounts are too large to be melted in SURFEX. So if there are no representative observations, the snow will remain for very long.

The problem of excessive snow amounts in the initial fields has been solved by initially setting an upper limit of 500 kg/m^2 SWE.

2.5 Snow analysis frequency

Most Norwegian synoptic stations report snow only once a day, at 06 UTC. It is thus recommended to perform snow analysis only at 06 UTC as the few observations available at 00, 12 and 18 UTC will otherwise be given too strong influence.

3 Experiments with additional snow observations

The snow analysis in the current versions of HIRLAM and HARMONIE uses synoptic observations only. The performance is good in regions with representative observations, but the network of synoptic stations is rather sparse. The effect of additional snow depth observations from climate stations has been evaluated. Satelitte data also gives additional information. The challenge is to exploit the information within the snow analysis.

3.1 Snow depth observations from climate stations

Snow depth observations from synoptic stations are available for operational use in NWP models via Global Telecommunication System (GTS). Snow depths are also recorded daily at 06 UTC in a Norwegian network of climate stations. These observations have been available on GTS since 12 March 2013. Similar observations from Sweden were available on GTS already from December 2010.

The routines for reporting no snow have until now been inadequate at Norwegian synoptic stations. The routines will be improved by including an additional observation of 'surface conditions' to be able to report the useful 0 kg/m^2 on GTS in real time.

3.2 CryoRisk satellite data

A framework for probabilistic classification of sea ice using optical satellite data has been developed at the Norwegian Meteorological Institute. In the CryoRisk project the method was adapted to work over land, leading to a snow cover product for mainland Norway and Sweden. The resolution is 1.5 km.

The CryoRisk snow cover product relies on satellite data from the Advanced Very High Resolution Radiometer (AVHRR/3) instrument as well as on model surface temperature data. The AVHRR instrument has 6 channels in the optical, near-infrared and infrared, and flyes onboard a group of polar orbiting, operational satellites which at time of writing includes the EUMETSAT satellite MetOp-A and the National Oceanic and Atmospheric Administration (NOAA) family of satellites NOAA-15, NOAA-16, NOAA-18 and NOAA-19. The method is sunlight dependent, and thus there are no products available during winter when the sun is less than 5 degrees above the horizon.

The method consists of two steps. In the first step a Bayesian approach is used to calculate the probabilities for the three independent classes "snow", "no snow" and "cloud". The cloud masking and the identification of snow cover are thus done in the same operation. Bayes approach is based on pre-knowledge of the statistical behaviour of the possible surface classes. Extensive, manual collection of training data has been done to meet this need. Each satellite pass is processed individually.

In the second step all processed swaths for a certain time interval are collected and "averaged". If a pixel is cloud covered (here defined by having a probability for cloud larger than 40%) for all satellite passes of the aggregation period, the pixel remains cloud covered in the final product. If during the aggregation period there are one or more satellite passes during the aggregation period for which the probability of cloud is smaller than 40%, the probabilities for “snow” and “no snow” are averaged. This gives two probability values for the pixel in the final product: the averaged probability for “snow” “given cloud free” (according to the definition written above), and the averaged probability for “no snow” “given cloud free” (again according to the definition of cloud cover written above). The product files contain both of these probabilities as well as a classified field. The classified product is derived from the two probabilities by setting a threshold at 50%. If the averaged probability for snow is above 50% the pixel is classified as “snow”. If not, the pixel is classified as “no snow”.

A “cloud free” snow cover product is the ultimate goal. When aggregating over a time window, the clouds will move with time, and the aggregated product can have less cloud covered pixels than the individual, processed swaths. At time being all available processed swaths in the time window have the same weight and can influcene the aggregated product equally. In CryoRisk, the aggregated product is based on satellite observations from the previous 7*24 hours. A new aggregated product is generated every hour should there be new satellite data available.

A thorough validation of the CryoRisk product has not yet been done. There are, however, indications that the algorithm has a tendency of underestimating the snow cover towards the end of the melting season.

For the purpose of testing the CryoRisk product in HARMONIE, a daily snow cover product is made (i.e.: the aggregation “window” is reduced from 7*24 hours to 24 hours, and there is no “running window”).

For more details on the method, see (Killie, 2011).

3.3 Experiments

Snow analysis experiments have been performed with HARMONIE cycle 37h1.beta.2 with ALARO physics and 4 km resolution on a domain covering Norway and Sweden for the period March-May 2012. The experiments got initial fields and boundaries from ECMWF, and had a 14 days warm-up period from 15 February 2012. The following experiments have been performed:

REF: 37h1.beta.2 with minor changes (bug-fixes)
EXP2: REF + snow depths from climate stations
EXP3: REF + snow depths from climate stations,
reduced influence radius of background error
EXP4: REF + CryoRisk satellite data with 15 km resolution, error statistis as EXP3,
use of satellite data only when first guess <25 kg/m^2
EXP5: REF + CryoRisk satellite data with 15 km resolution, error statistis as EXP3,
use of satellite data when first guess <100 kg/m ^{2} (and wider limits in quality control)

Snow depths from climate stations were treated as snow depths from synoptic stations in the snow analysis. They were incerted into the Observational DataBase (ODB) through an additional ascii file. The influence radius in the reference setup, which was also used in EXP2, is very wide and adapted to the sparse network of synoptic stations. The influence radius of the background error in EXP3 was reduced substantially, see Fig. 2. The standard deviations of the background errors and snow depth observations are both 5 kg/m^2.

CryoRisk satellite data were in EXP4 and EXP5 experiments thinned to 15 km resolution while full resolution is 1.5 km. The satellite data was used as follows:
- "no snow" observations were used as 0 kg/m^2
- "snow" observations were used only where the first guess had less than 25 kg/m^2, which with snow density typical of e.g. March corresponds to 10 cm snow. The satellite observations were set to 10 cm snow depth. The satelitte data was supposed to have uncorrelated errors. The standard deviation of the observation errors was set to 8 kg/m^2, which is higher than the corresponding values for the snow depth observations and implies that the satelitte data was given less weight.

EXP5 was analog to EXP4, but used more "snow" observations from the satellite; everywhere the first guess had less than 100 kg/m^2. The satellite observations were also here set to 10 cm snow depth.

4 Results

The snow analysis experiments were performed in spring and include the melting season when the sensitivity of surface temperatures to the presence of snow is large. Both the modelling of the snow cover and the effect on near surface weather forecasts, particularly 2 meter temperature, were studied.

4.1 Evaluation of snow on ground

The snow fields were evaluated qualitatively by comparisons to CryoRisk maps and to snow depth observations from synoptic and climate stations. It is not meaningful to compare summary statistical scores calculated at observing stations as different selections of the observations already are used in the experiments.

31 March 2012 had clear sky over the southern part of Norway and excellent conditions for the satellites to 'see' the snow cover. A CryoRisk map with the classes "snow", "no snow" and "cloud" is shown in full resolution (1.5 km) in Fig. 4. The figure includes also the SWE (given in tonn/m^2) of the different experiments 31 March 2012 06 UTC. The resemblance of the experiments with the CryoRisk map varies. REF has good agreement in snow covered regions, but has snow left in some regions that seem to be snow free. That is also the case with EXP2 and EXP3 which used additional observations from climate stations. EXP3 shows better agreement with the CryoRisk map than EXP2 which also has some snow free regions along and east of Sognefjorden which obviously is snow covered. The resemblance of EXP4 with the CryoRisk map is striking although there are regions where the snow on ground has disappeared too rapid. EXP5 which used more satellite "snow" observations has excessive snow amounts in many regions. The satellite data when used in a proper way helps to discriminate between snow free and snow covered gound.

Time series of experimental snow depths (converted from SWE) and observed snow depths were studied. The main findings are summarized below and refer to figures with typical results.

Stations referred to are shown in Fig. 5 where the results from Fig. 4 are repeated for reference, but for a domain in the Eastern part of Norway.

Both the reference and all experiments showed relatively good performance at synoptic stations as long as the snow depths were reported, see e.g. time series from Skåbu, Rena, Vest-Torpa and Hakadal, respectively, Figs. 6, 7, 8 and 9.

A shortcomming of the reporting routines has untill now been that snow free ground or '0' snow not has been reported. Close inspection of Figs. 8 and 9 from Vest-Torpa and Hakadal reveals that all experiments except EXP4 had some snow on ground also after the snow disappeared in the end of March.

The snow depth observations from the climate stations used in EXP2 and EXP3 were taken from the observational data base at the Norwegian Meteorological Institute and included also '0' observations at some stations. Improved performance was the result at most climate stations, see Figs. 10 and 11 from Ukkestad and Lunner, respectively. The influence from the climate stations might however degrade the performance at nearby synoptic stations, see Fig. 9 with results from Hakadal which is situated 10 km south east of Ukkestad. EXP3 with reduced influence radius of bacground error showed generally better performance than EXP2, see results from Vest-Torpa in Fig. 8.

Snow depth observations from the synoptic station Bjørnholt were not used in the snow analysis experiments. That makes Bjørnholt a good candidate for fair comparisons of the different experiments. Time series from Bjørnholt, Fig. 12, demonstrate the potential of the CryoRisk satellite data to discriminate between snow free/snow covered ground. All experiments except EXP4 had snow at Bjørnholt one month longer than in reality, an indication of too slow snow melting with the current 1-layer snow scheme.

4.2 Near-surface forecast skill

Mean Sea Level Pressure (MSLP), 2 meter temperature and 10 meter wind speed forecasts have been evaluated against synoptic observations to examine the effect of improved snow depth analysis. Figs. 14 and 15 give monhly mean and standard deviation of the forecast errors summarized over all Norwegian synoptic stations as a function of lead time for March, April and May 2012.

EXP3 with reduced influence radius gave better results than EXP2, and only EXP3 has been included in the figures. The use of additional snow depth observations from climate stations gave significant improvements of 2 meter temperature forecasts in April and May, minor improvements also in March. Small improvements are also seen for MSLP and 10 meter wind speed in April and May.

Also the CryoRisk satellite data gave some improvements, particularly of 2 meter temperature in May. Fig. 15 with summary results for May demonstrates the sensitivity of the forecasts to how the satellite data was used. EXP5 used CryoRisk "no snow" observations and "snow" observations where first guess <100 kg/m^2. Summary results indicate degraded quality of the near surface forecasts, see upper panel of Fig. 15. EXP4 which used CryoRisk "no snow" observations and "snow" observations only when first guess <25 kg/m^2 gave improved forecasts. The May results of EXP4 were comparable with EXP3, see lower panel of Fig. 15.

5 Discussion

Snow analysis performed by OI using snow depths from synoptic stations gives good results in regions with representative observations. The network is however sparse. Snow analysis experiments with two additional sources of observations, from climate stations and CryoRisk satellite data, have been performed. Two setups have been tested for each data source, in addition to a reference run.

Snow depths from climate stations were used in the same way as snow depths from synoptic stations. EXP2 had identical specification of the error statistics as the reference. In EXP3 the horizontal influence of the observations was reduced. Both experiments, and particularly EXP3, show clear positive impact of additional snow depth observations from climate stations. EXP2 and EXP3 benefit not only from having additional observations from the climate stations inlcluded, but also from the fact that '0' snow observations from the climate stations also are found in the climate data base and used in the experiments. The observations from the climate stations, hopefully including the '0's, will soon be available on GTS in real time and enter operational snow analyses.

These first experiments with CryoRisk satellite data utilize the data on 15 km resolution. Both experiments used all "no snow" observations, but EXP4 used less of the "snow" observations than EXP5. The difference in performance illustrates the sensitivity to the way the observations are used. It has been shown that the use of CryoRisk satellite data, as done in EXP4, gave more realistic distribution of the snow cover in spring and also signicant improvements with respect to 2 meter temperature in May. More experiments should however be performed, with finer resolution, refined specification of error statistics and better quality control. To use the 'probability of snow' values as 0 / 10 cm snow depths is clearly not optimal, and one can expect further improvements by utilizing more advanced methods as e.g. Extended Kalman Filter.

It would also be interesting to run an experiment including snow depths from synoptic and climate stations and CryoRisk satellite data. As long as only few '0' observations from synoptic or climate stations are available in operational snow analysis via GTS, the benefit of including satellite data in the melting season will probably be worth the effort.

Acknowledgements

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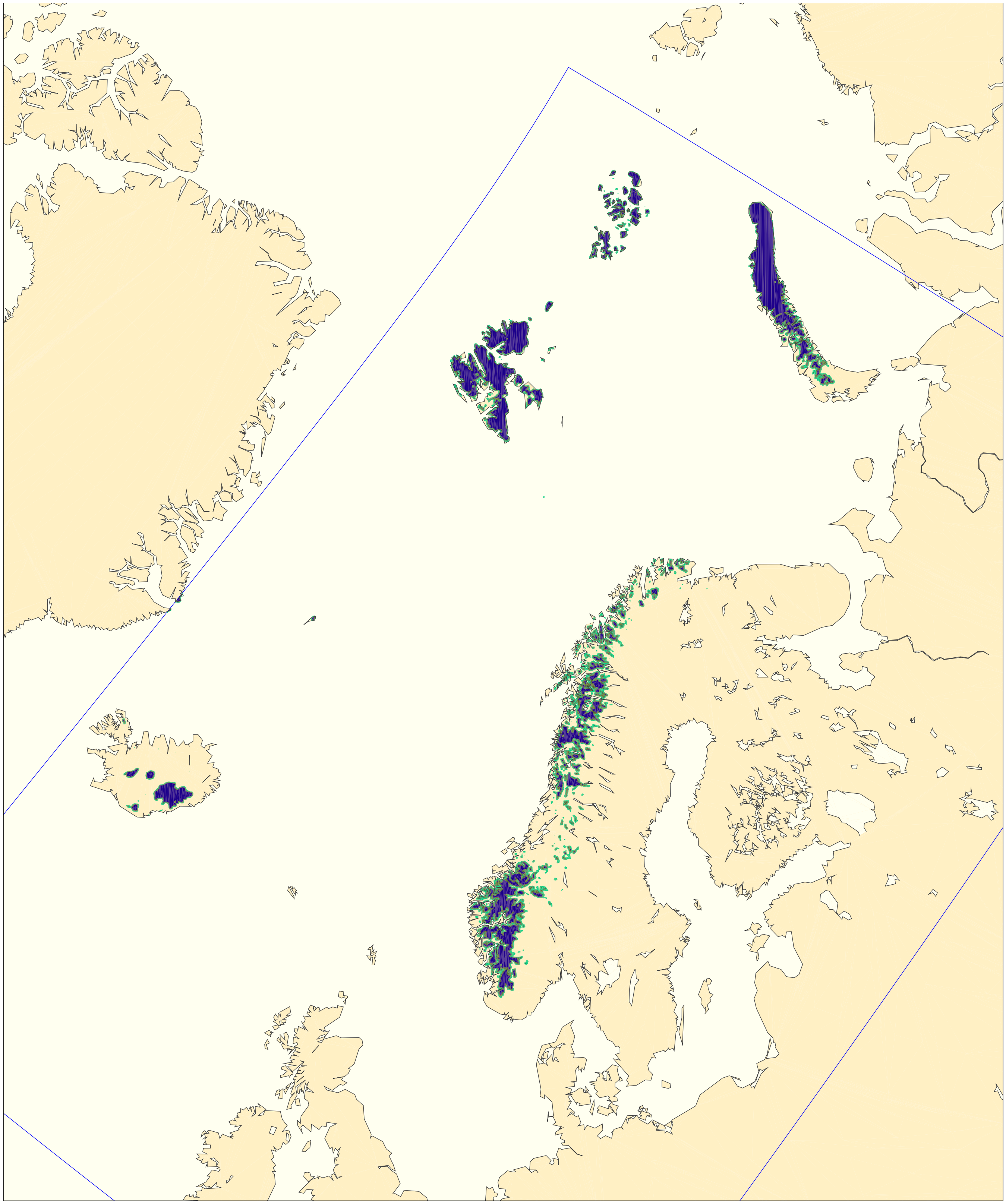

Figure 1: Permanent snow from ECOCLIMAP1.

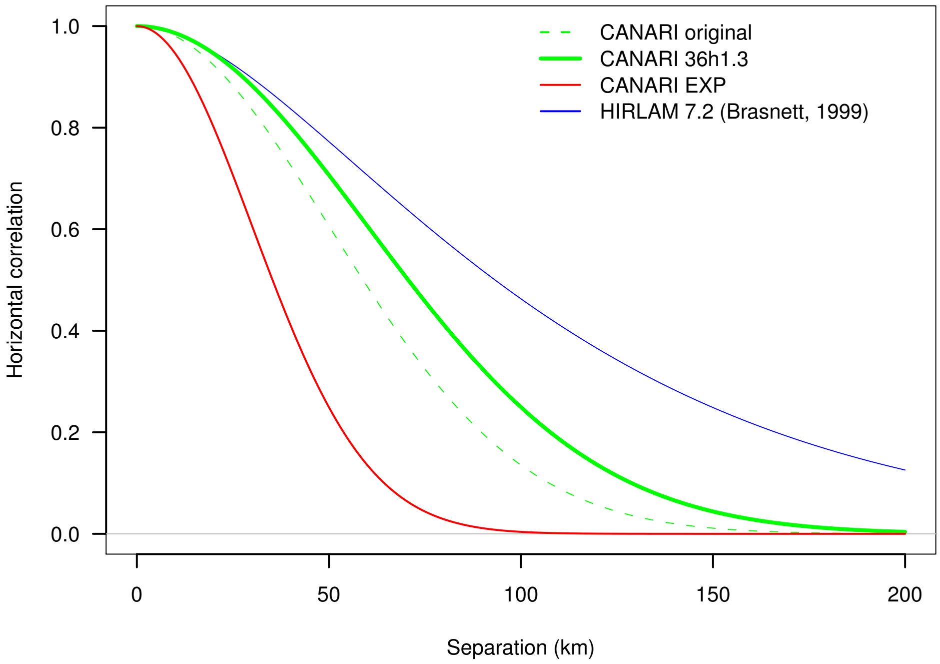

Figure 2: Horizontal correlation of background errors.

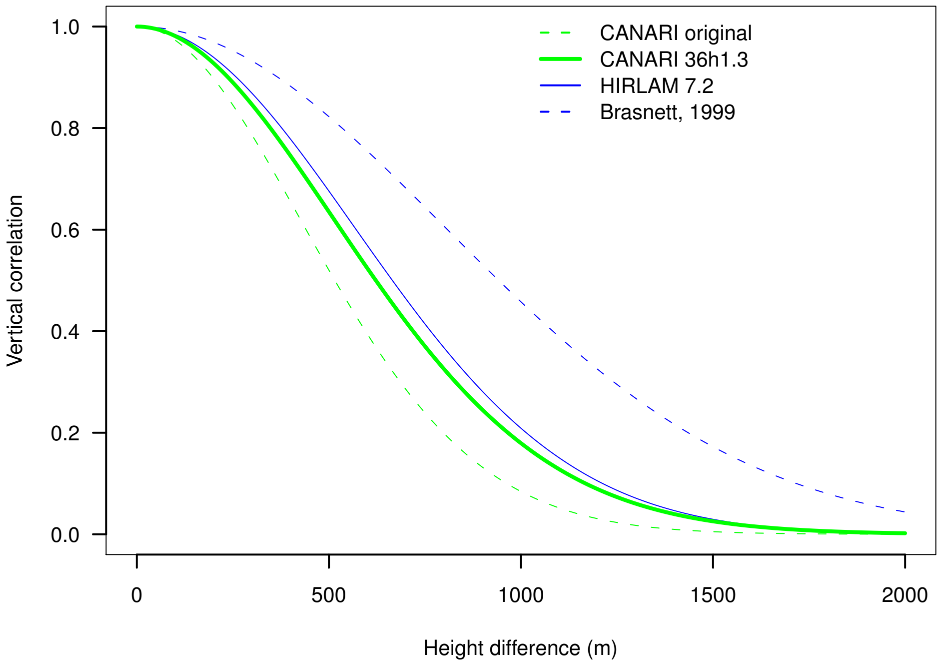

Figure 3: Vertical correlation of background errors.

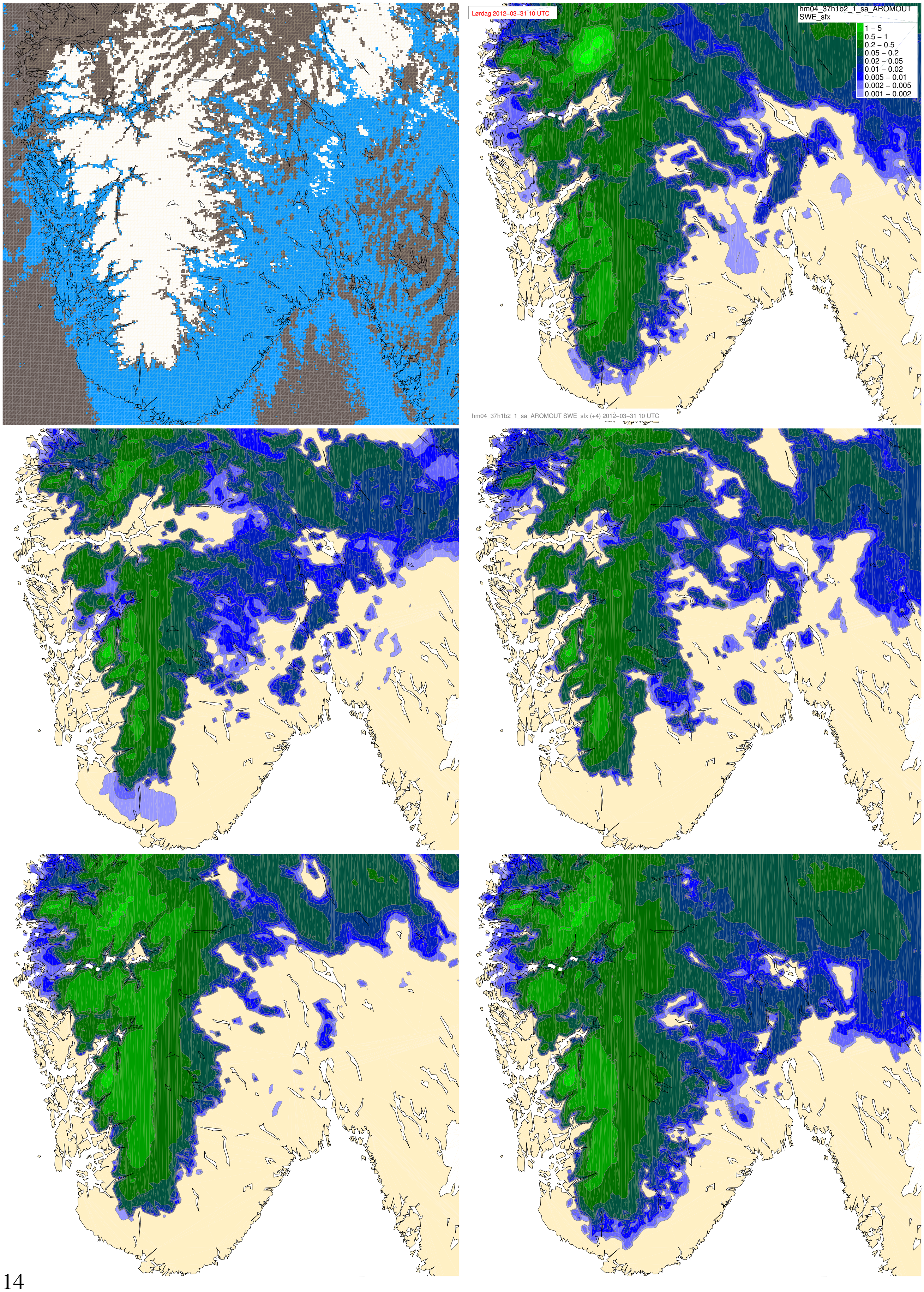

Figure 4: CryoRisk and analysed SWE from Harmonie 4 km experiments, REF/EXP2/EXP3/EXP4/EXP5 (from top left to bottom right), South Norway 31 March 2012, 06 UTC.

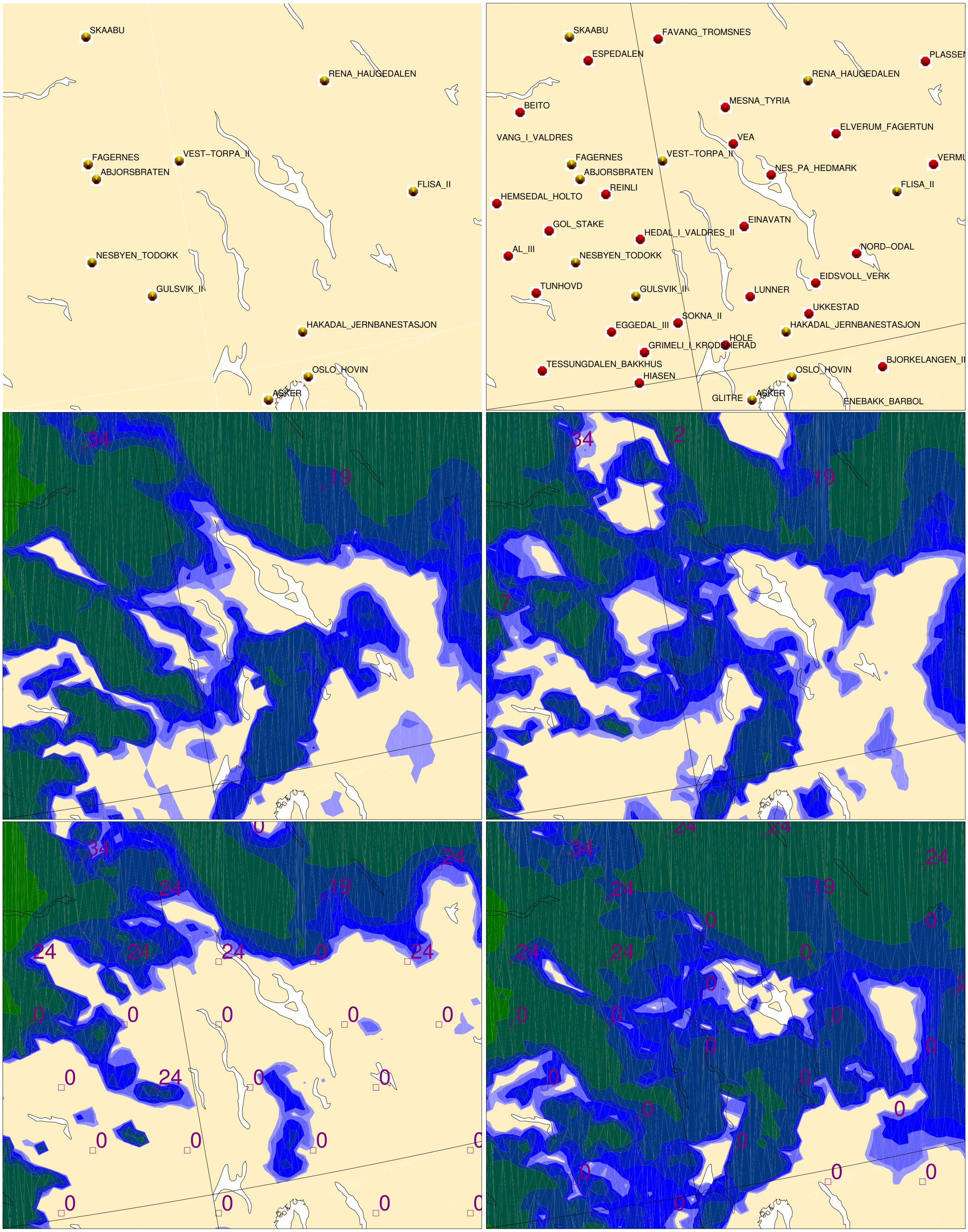

Figure 5: Synoptic stations, climate stations and analysed SWE from Harmonie 4 km experiments, REF/EXP3/EXP4/EXP5 (from top left to bottom right), south eastern part of Norway 31 March 2012, 06 UTC. Observations, converted to SWE in kg/m^2, used in the snow analysis in pink.

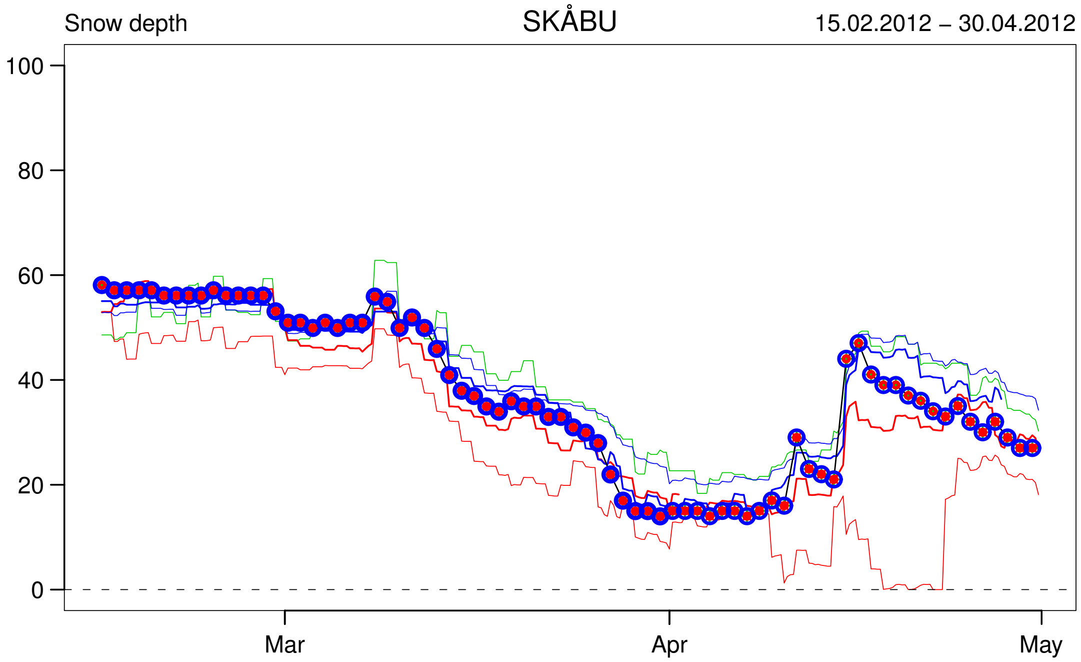

Figure 6: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Skåbu 15 February to 30 April 2012.

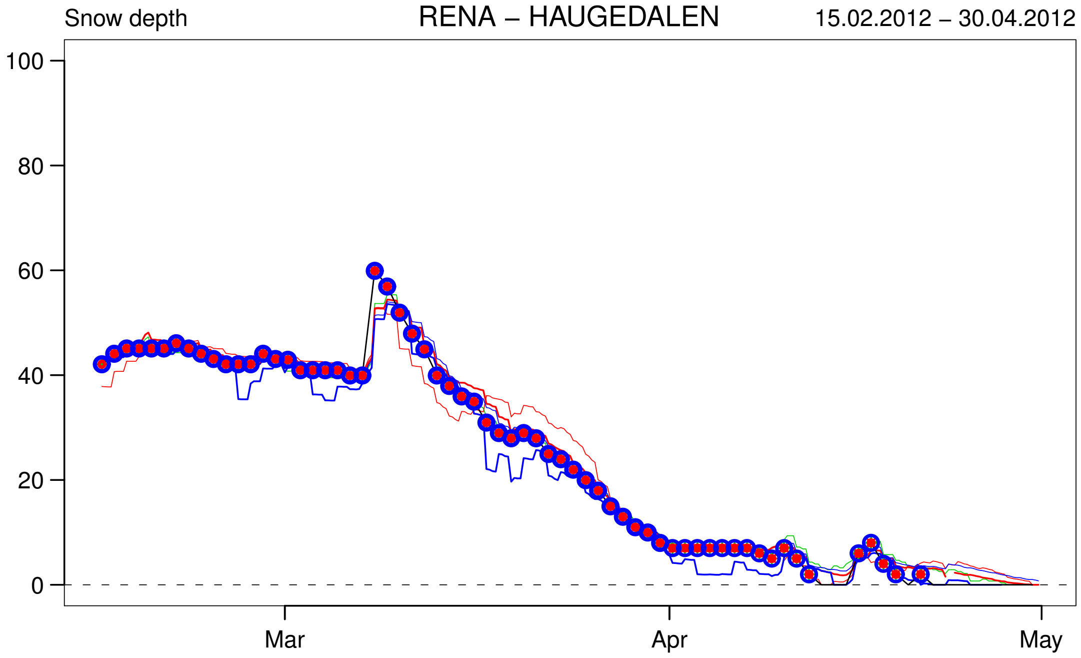

Figure 7: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Rena 15 February to 30 April 2012.

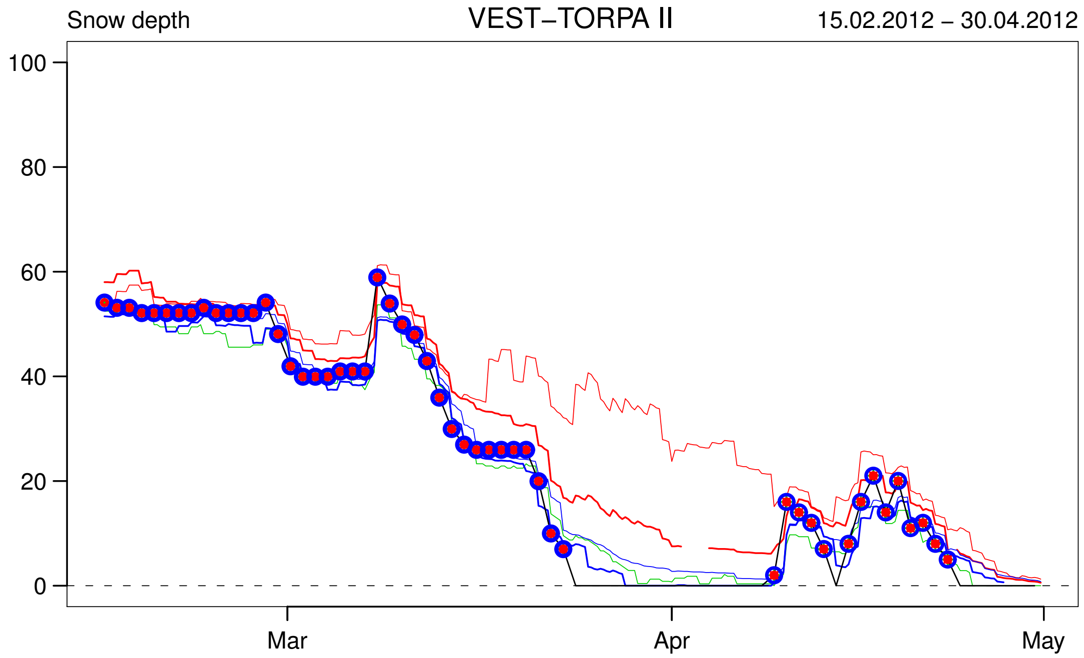

Figure 8: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Vest-Torpa 15 February to 30 April 2012.

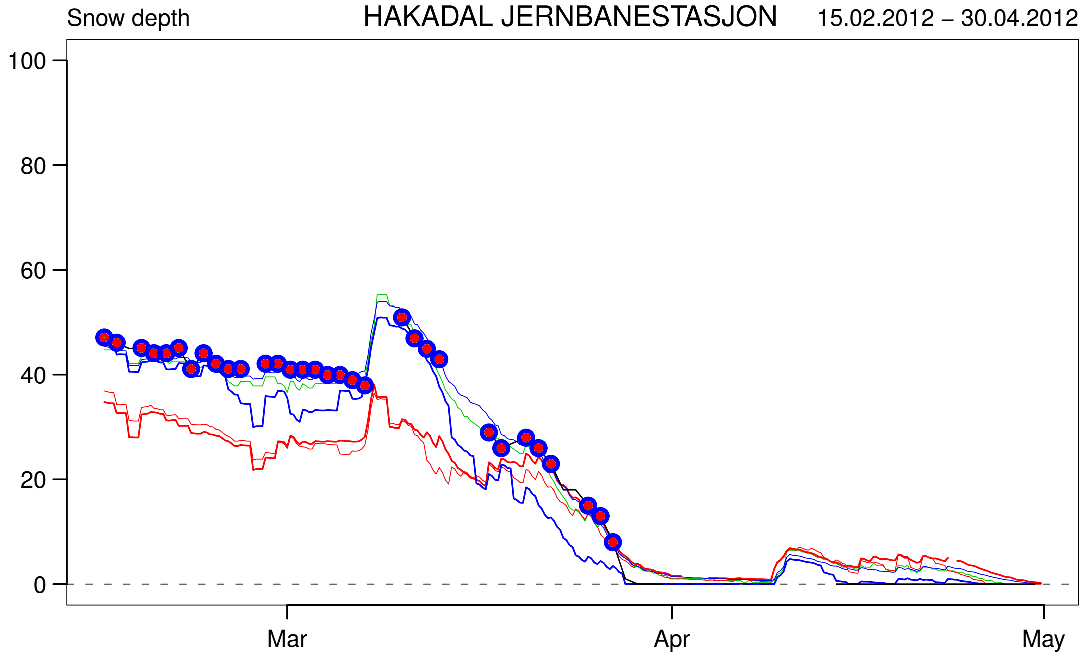

Figure 9: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Hakadal 15 February to 30 April 2012.

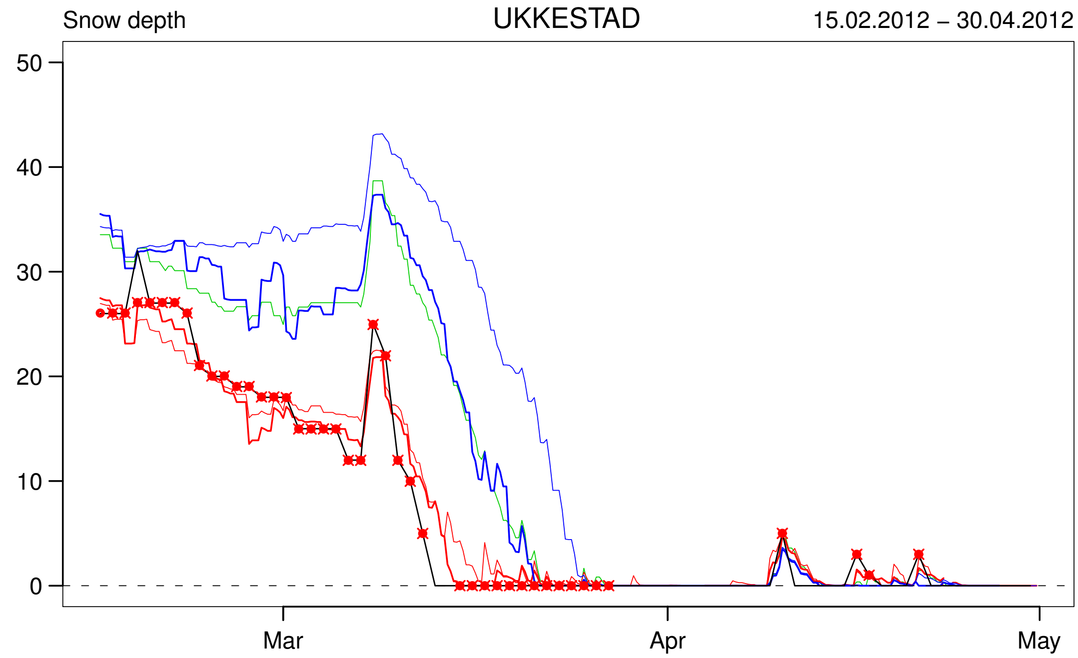

Figure 10: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Ukkestad 15 February to 30 April 2012.

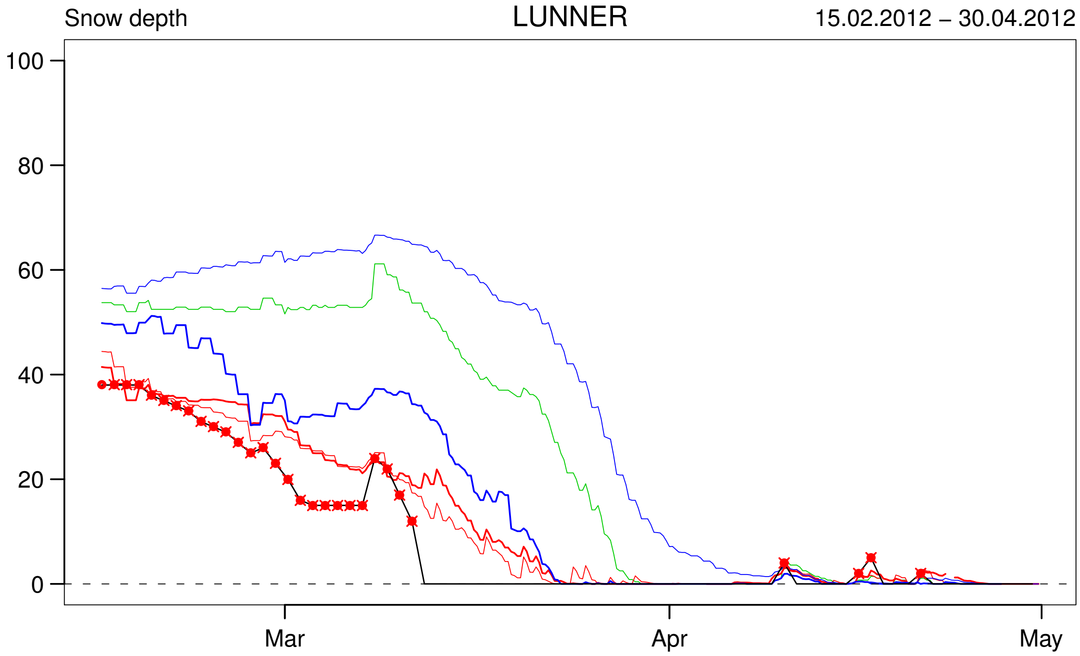

Figure 11: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Lunner 15 February to 30 April 2012.

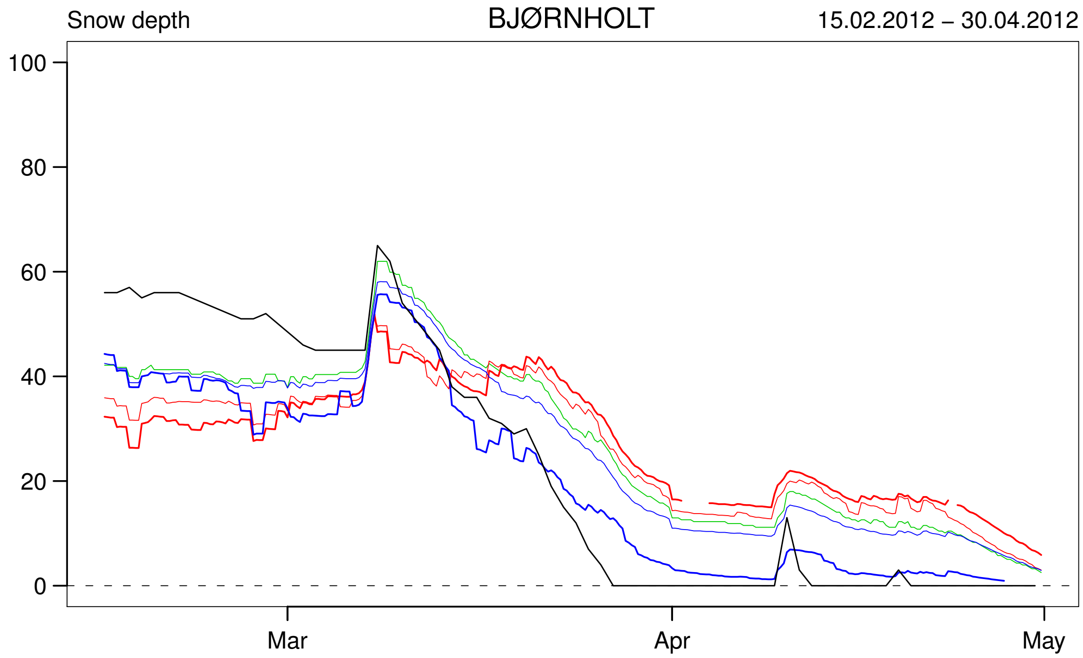

Figure 12: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Bjørnholt 15 February to 30 April 2012.

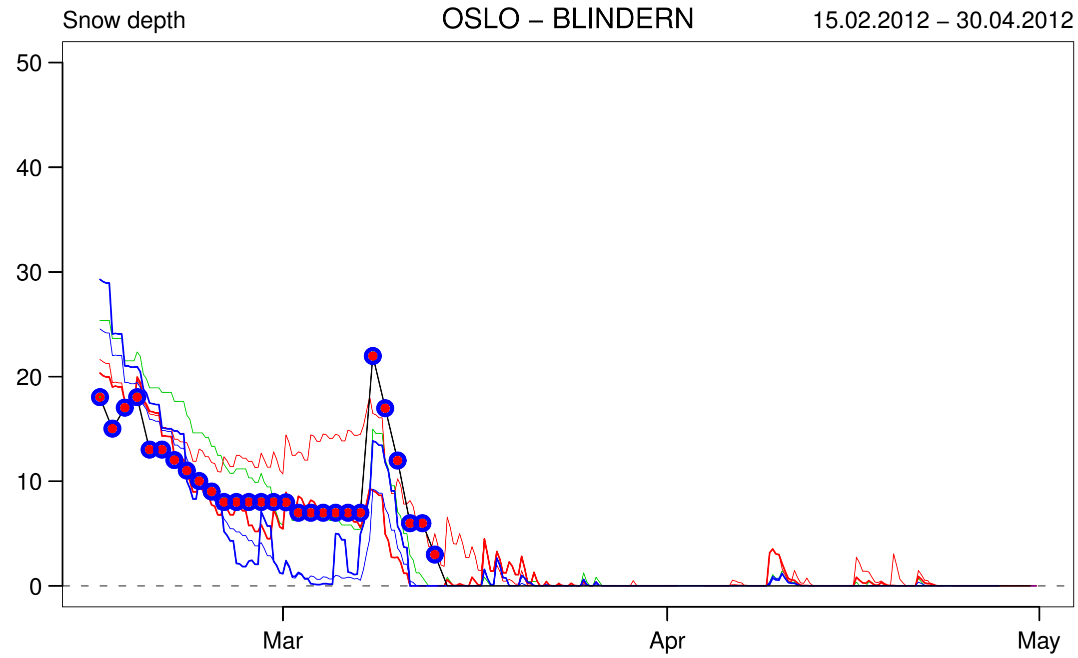

Figure 13: Analysed SWE converted to snow depths by climatological snow density values; REF (green), EXP2 (red), EXP3 (**red**), EXP4 (**blue**), EXP5 (blue). Snow depth observations in black, covered by red/blue circles if used in EXP2-3/EXP4-5 respectively. Oslo 15 February to 30 April 2012.

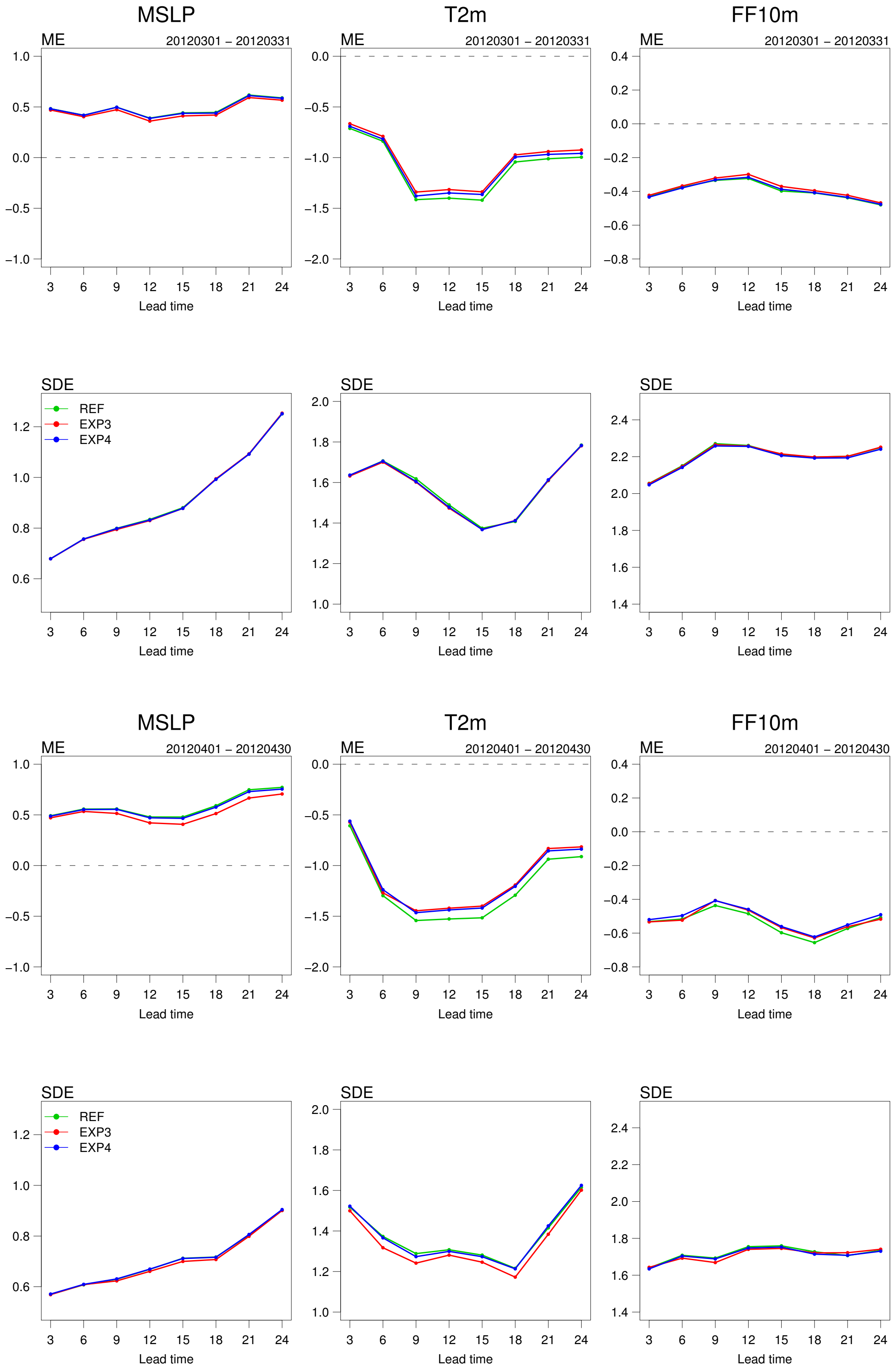

Figure 14: Mean Sea Level Pressure, 2 meter temperature and 10m wind speed monthly mean (ME) and standard deviation of forecast errors (SDE) for **March** (upper panel) and **April** (lower panel) 2012; REF (green), EXP3 (red) and EXP4 (blue).

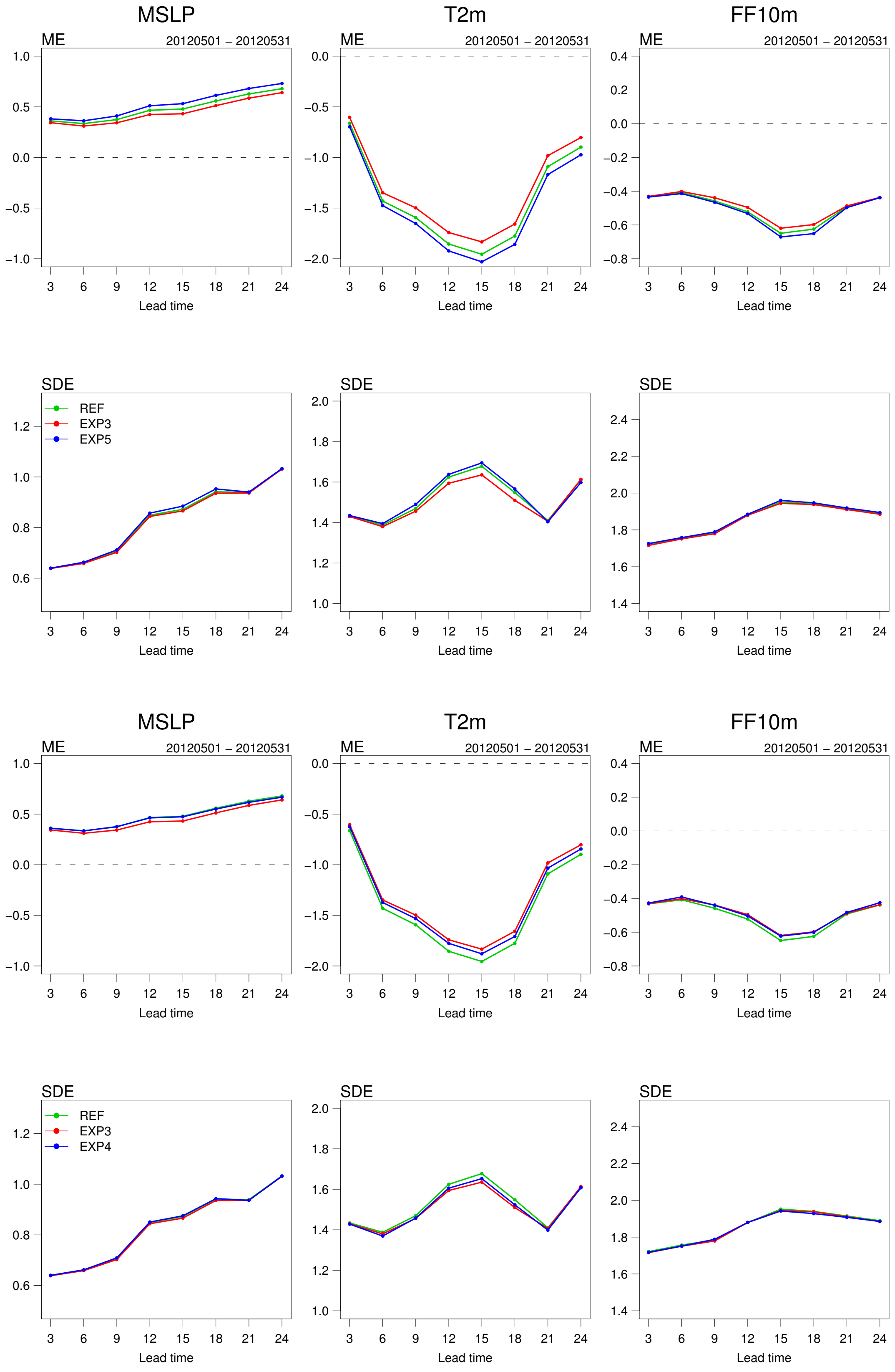

Figure 15: Mean Sea Level Pressure, 2 meter temperature and 10m wind speed monthly mean (ME) and standard deviation of forecast errors (SDE) for May 2012; **upper** panel includes REF (green), EXP3 (red) and **EXP5** (blue), **lower** panel REF (green), EXP3 (red) and **EXP4** (blue).