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Snow data assimilation at ECMWF

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Over the last few years, significant changes to snow analysis have been implemented in the operational ECMWF land data assimilation system. The Optimal Interpolation interface to observations was revised, allowing the implementation of land surface observation monitoring capabilities for snow and screen-level observations in Cycle 40r1 of ECMWF's Integrated Forecasting System (IFS). Developments also include improvements in the combined use of snow depth and snow cover data. Cycle 40r1 has been operational since November 2013.

An evaluation against independent observations shows that the revised snow data assimilation performs better than the earlier version on a range of scores. The revision has brought clear improvements both in snow depth and near-surface weather parameter forecasts. Continuous observation monitoring provides evidence of the high quality of short-range ECMWF snow depth forecasts, but it also shows a slight continuing overestimation of snow depth in the background field and the analysis compared with independent observations.

History of ECMWF snow data assimilation

The first ECMWF snow data assimilation system was implemented more than 25 years ago, based on the Cressman interpolation technique. It was limited to the use of in situ snow depth observations (SYNOP observations). ECMWF's snow analysis was revised in 2004 to introduce 24-km Interactive Multi-Sensor Snow and Ice Mapping System (IMS) snow cover information, in addition to the SYNOP snow depth measurements. This led to a more realistic representation of the extent of snow cover in the operational analysis (*Drusch et al.*, 2004). However, the persistent large amounts of snow in the northern hemisphere during the cold winter of 2009/2010 highlighted several problems in the operational snow analysis and motivated further work to improve the snow data assimilation method and the processing of snow observations.

In November 2010 (IFS Cycle 36r4), the snow analysis code was revised to use a two-dimensional (2D) Optimal Interpolation (OI) method instead of the Cressman interpolation. The difference between the Cressman and the OI analyses mainly results from differences in the structure functions that determine how an observation influences the analysis in the surrounding region. Compared to the Cressman interpolation, the 2D OI produces smoother and more realistic snow analysis patterns that are in better agreement with in situ observations (*de Rosnay et al.*, 2014). In the same IFS cycle, the use of IMS was revised in several ways to improve the data and model colocation. The snow cover IMS product itself, which is provided by the US National Environment Satellite Data and Information Service (NESDIS), was upgraded to a higher resolution (4 km), providing useful spatial detail particularly in coastal areas.

These revisions in the use of IMS snow cover data had a positive impact on atmospheric forecast quality, both for screen-level parameters and for the northern hemisphere geopotential height at 500 hPa, which significantly improved up to the 4-day forecast range. Further improvements in IMS data acquisition and assimilation in 2012 led to a reduction in IMS snow cover data latency by 12 hours. The latest improvements, implemented in November 2013 (IFS Cycle 40r1), include the revision of the surface analysis interface to observations to enable the monitoring of conventional land surface and IMS snow cover observations. This has been achieved by using the Observation Data Base (ODB) format for both types of observations. Along with these modifications, the snow data assimilation algorithm was revised to assimilate IMS non-zero snow cover observations together with in situ snow depth observations in the OI analysis.

Snow observations

In situ snow depth observations constitute a very important and very reliable source of information for the snow data assimilation system. They are provided by the SYNOP station network and are made available in near real-time on the Global Telecommunication System (GTS) for numerical weather prediction (NWP) applications. In addition to SYNOP observations, National Meteorological Services (NMSs) maintain national snow depth measurement networks. For example the US SNOTEL (SNOwpack TELemetry) network provides snow depth measurements that are used for snow data assimilation at the National Oceanic and Atmospheric Administration (NOAA). The Cooperative Observer Program (COOP) also constitutes a very dense in situ snow depth measurement network in the US. However, these additional in situ snow depth observations are currently not available on the GTS for operational NWP applications.

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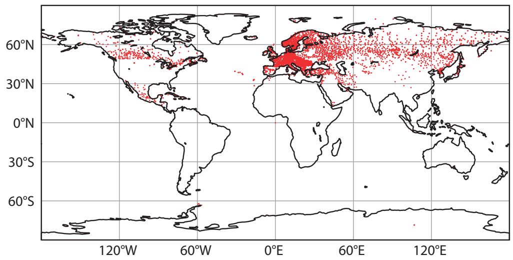
Snow observations used at ECMWF

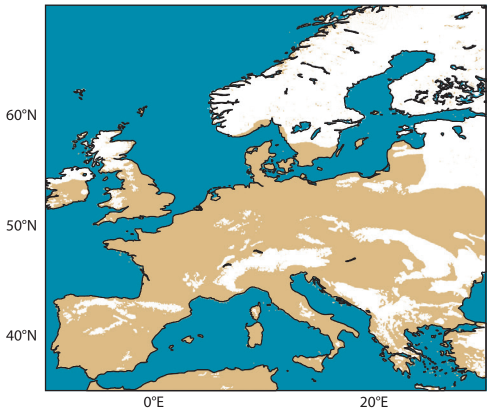
A

The snow analysis relies on SYNOP and national networks of snow depth ground observations available on the GTS as well as on the IMS snow cover information available for the northern hemisphere.



The map shows the spatial distribution of in situ station reports available on the GTS on 20 January 2015. On this day, 16,112 snow depth observations were reported from 3,810 stations. A total of 2,844 stations reported snow depth using the Traditional Alphanumeric Code (TAC), 663 stations reported additional snow data using the dedicated snow BUFR template, 303 new SYNOP stations reported in BUFR, and 1,573 stations reported both in BUFR and TAC. In IFS Cycle 40r1, the first two types of snow depth reports are used.

The IMS product provides cover maps for the northern hemisphere. It combines microwave and visible sensors to provide binary snow cover information in all weather conditions. An IMS observation of snow indicates that at least 50% of the grid cell is snow-covered.



IMS snow cover data over Europe on 20 January 2015

In Europe, an initiative launched in 2011 by ECMWF and NMSs in ECMWF's Member States has begun to improve the availability of in situ snow depth observations. NMSs were encouraged to use a dedicated BUFR format developed by ECMWF to report their additional national snow depth observations on the GTS. This has led to a significant increase in the availability of in situ observations for operational NWP. To date, seven ECMWF Member States (Sweden, the Netherlands, Denmark, Romania, Hungary, Norway and Switzerland) report snow depth daily from more than 600 additional stations in their networks. These additional in situ observations are used alongside previously available SYNOP reports in the operational snow depth analysis (Box A). In 2013, this European initiative was extended to the World Meteorological Organization (WMO) in the context of the Snow Watch project of the Global Cryosphere Watch programme in order to make data from synoptic and climate networks more widely available over the GTS (*Brun et al.*, 2013). Improving access to snow observations is also a key objective of the current European Cooperation Science and Technology (COST) Action on snow (ES1404).

Although these developments have improved the availability of in situ snow depth observations, snow depth observations are still unavailable to NWP for many regions of the world. Satellite observations provide useful information, especially in remote locations with sparse in situ station coverage. The IMS snow cover product is widely used by the NWP community to analyse snow depth. It is a multi-sensor product that combines satellite data primarily from visible sensors with microwave data and weather station reports to provide snow cover information with good accuracy in all weather conditions. Several validation and comparative studies have demonstrated the accuracy of the IMS product against in situ and other products, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover product (*Brubaker et al.*, 2009, *Helfrich et al.*, 2007). At ECMWF, the IMS northern hemisphere daily product has been used operationally since 2004, initially at a resolution of 24 km and since 2010 at a resolution of 4 km. The 4-km IMS product includes sea ice extent as well as the snow cover information over land currently used by the land data assimilation system.

Snow data assimilation method

ECMWF snow analysis uses a 2D OI method that is performed every 6 hours. A short-range IFS forecast provides the snow depth background field, computed from the prognostic snow water equivalent and snow density variables. The observations used are in situ snow depth measurements and the IMS northern hemisphere snow cover product. The IMS product only provides information on the presence of snow for each 4-km grid cell. A snow cover IMS observation indicates that at least 50% of the grid cell is covered by snow, but it does not indicate the snow depth. To enable the snow cover product to be used quantitatively in the snow analysis, the IMS information is converted into quantitative snow depth information using the relation between snow cover and snow depth as detailed in Box B. In the snow data assimilation, the quality control includes a redundancy check and a first guess departure check. More details can be found in the IFS Cycle 40r1 documentation available on ECMWF's website. The revised snow OI algorithm implemented in IFS Cycle 40r1 enables observations to be assimilated jointly from in situ reports and IMS snow cover in the OI. It replaces the two-step algorithm that was used from 2004 to 2013, in which, prior to the analysis, the snow depth background field was replaced with 0.1 m of snow at locations where the background field had no snow while the IMS indicated the presence of snow (Box B).

Data assimilation experiments and results

To evaluate the impact of the revised snow analysis on snow depth and forecasts of near-surface weather parameters, global data assimilation experiments were performed. They were conducted at T511 (40-km grid) with IFS Cycle 40r1 from 1 October 2012 to 30 April 2013. The two experiments differ only in their snow analysis, with one experiment set up to use the IFS Cycle 38r2 snow analysis ('old') and the other experiment using the revised IFS Cycle 40r1 snow analysis ('revised').

Evaluation using independent snow depth observations

To evaluate the impact of the revised snow analysis, it is important to use independent observations. For the purpose of this study, a fixed subset of 251 in situ stations (around 10% of available stations) reporting near-real-time snow depth observations were randomly selected to provide validation data. Their snow depth reports were excluded from the assimilation (for both experiments) during the entire period. Figure 1 shows the location of the independent validation snow depth stations reporting on 10 December 2012. They are mostly located in Europe and Siberia. A few validation stations are also located in Mongolia, Iran, Canada and Central America.

The presence of snow on the ground in the data assimilation experiments was evaluated for every day from 1 October 2012 to 30 April 2013. The evaluation presented here is based on a 2x2 snow/no-snow contingency table:

	Snow observed	**No snow observed**
Snow in analysis	a Hits	b False alarm
No snow in analysis	c Misses	d Correct no snow

The following scores are used for the evaluation:

- Accuracy = a+d / (a+b+c+d)
- Hit rate (probability of detection) = a / (a+c)
- False alarm ratio = b / (a+b)
- Threat score = a / (a+b+c)
- Frequency bias index = (a+b) / (a+c)

Table 1 summarises the scores obtained for the two data assimilation experiments conducted with the old and revised snow analyses. It shows that the revised scheme better captures the snow/no-snow occurrences with all the scores consistently improved against independent observations. The overall accuracy is increased from 0.92 to 0.94. The impact of the snow analysis revision on the snow occurrence accuracy is also shown in Figure 2a. Most of the points are above the diagonal, which is indicative of improvements in snow and no-snow detection.

This score is strongly influenced by the two most common categories (correct no snow in October and April and correct snow in December and January). The hit rate score is higher for the revised analysis (0.98) than for the old analysis (0.96), which shows that the revised analysis captures the occurrence of snow on the ground better than the old analysis. The false alarm ratio has been reduced from 0.12 to 0.09 and the threat score increased from 0.86 to 0.9. These two scores are also shown in the form of scatter plots in

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Figures 2b–c. Here again we see an overall improvement in the threat score and the false alarm ratio at the daily time scale. The frequency bias index is reduced from 1.10 to 1.07 in the revised snow analysis, which suggests that the new system reduces the overestimation of snow on the ground (compared to independent in situ observations).

Figure 3 shows the temporal evolution of the revised snow analysis scores against the independent in situ observations of snow depth. The four elements of the contingency table are represented as a percentage of the total number of events. Since almost all the in situ stations are located in the northern hemisphere, annual cycles of correct snow and correct no-snow events follow the northern hemisphere winter season. In October, most stations report snow-free conditions, which are well captured by the analysis. From October to December, the proportion of snow events correctly detected increases to about 80%. The proportion of the sum of hits and correct no-snow events represents the accuracy, which remains above 90% throughout the season, with a mean value of 0.94, as indicated in Table 1. Figure 3 shows that misses are very infrequent compared to false alarms. This is consistent with the slight overestimation of snow occurrence in the IFS shown in Table 1, with frequency bias index values larger than one.

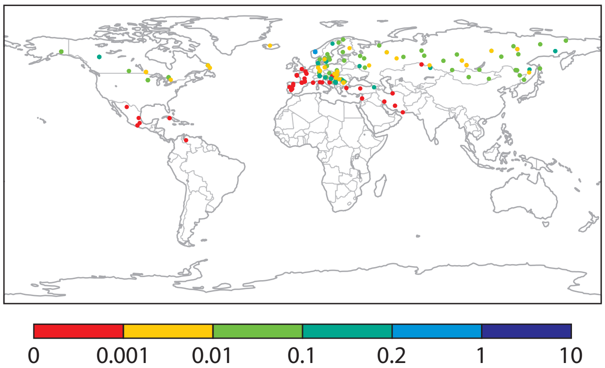

Figure 1 In situ stations used for research experiment evaluation. The colour scale illustrates snow depth in metres on 10 December 2012. These stations are the subset of 251 stations used in the evaluation, which were randomly selected from the SYNOP network and national networks. They are not used in the data assimilation experiments and therefore they constitute an independent validation dataset.

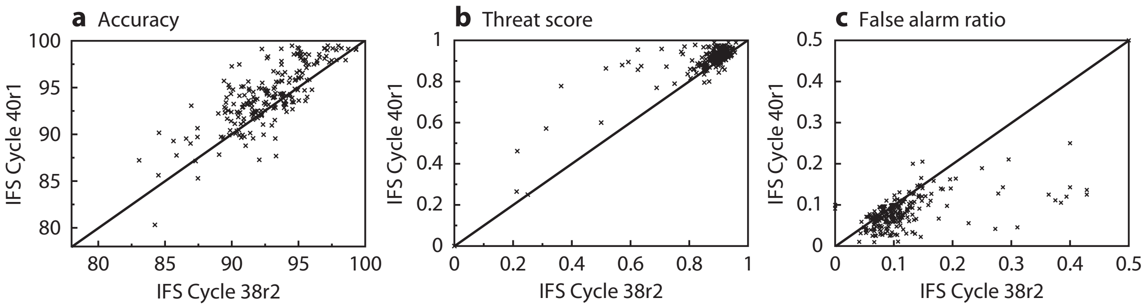

Figure 2 Snow analysis scores for the revised IFS 40r1 snow analysis versus the IFS 38r2 analysis for (a) accuracy, (b) threat score, and (c) false alarm ratio in the period October 2012 to April 2013. Each cross represents the scores computed against 251 independent in situ snow depth observations for a given date. The scatter plots show the results for each of the 212 days from 1 October 2012 to 30 April 2013. The black line represents the one-to-one line.

	Accuracy	Hit rate	False alarm ratio	Threat score	Frequency bias index
IFS 38r2 snow depth analysis	0.92	0.96	0.12	0.86	1.10
IFS 40r1 snow depth analysis	0.94	0.98	0.09	0.90	1.07

Table 1 Global evaluation of snow depth analyses using IFS Cycles 38r2 and 40r1 for the period from 1 October 2012 to 30 April 2013.

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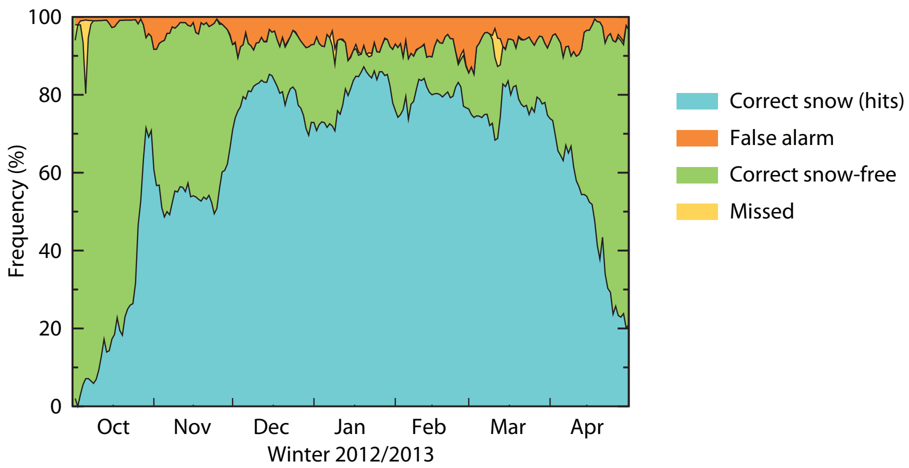
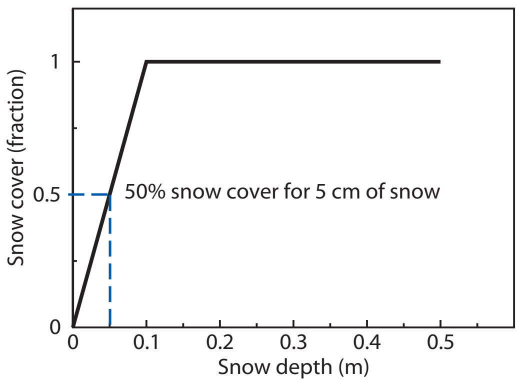


Figure 3 Time evolution of the revised 40r1 snow analysis global scores (in percent) against independent in situ stations for October 2012 to April 2013.

IMS snow cover data assimilation in the IFS

B

IMS provides binary information on the presence of snow for each grid cell but it does not give any quantitative information on snow depth. In IFS Cycle 40r1, the model relation between snow cover and snow depth (*Dutra et al.,* 2010), as shown in the figure on the right, is used to convert snow cover IMS information into a snow depth estimate relevant for data assimilation. The assumption is that 0.05 m of snow corresponds to 50% snow coverage, which is the IMS binary threshold. For cells with binary snow-free conditions, IMS is converted into 0 cm of snow depth. So, snow-free IMS observations enter the analysis with an assumed snow depth of 0 cm whatever the model background. Snow cover observations enter the analysis with an assumed snow depth of 5 cm if the model background indicates snow-free conditions. Snow cover IMS observations do not enter the analysis if the model background already indicates snow cover (see table). In this way, the model background, in situ and IMS observations are optimally combined in the OI analysis. Standard deviation values of background, in situ and IMS snow depth error are set at 0.03 m, 0.04 m and 0.08 m, respectively. This single-step algorithm replaces the previous two-step algorithm used until IFS Cycle 38r2: In a first step, a Direct Insertion (DI) approach was used to update the model background with 0.1 m in the case of snow-covered conditions in IMS and snow-free conditions in the model. In a second step, IMS snow-free observations were used in the analysis using the same observation error as with in situ data.



Model relation between snow cover and snow depth used to convert IMS binary information of snow cover into quantitative snow depth information in the event of a snow- free background.

IMS \ **Model**	**Snow**	**Snow-free**
Snow	not used	Data assimiliation 0.05 m
Snow-free	Data assimilation 0 m	Data assimilation 0 m

IMS equivalent snow depth observation that enters the snow analysis depending on the IMS and background snow status.

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Forecasts scores

Figure 4 shows the mean impact for October 2012 to April 2013 of the revised snow analysis on temperature and humidity forecasts at 1000 hPa and at 850 hPa. It shows that the revised analysis improves both temperature and humidity forecasts. At 1000 hPa, the root mean square error is significantly reduced at all forecast ranges for humidity and until day 5 for temperature. At 850 hPa, the error is reduced until forecast day 4 for both humidity and temperature. Figure 5 shows a map of the root mean square error difference between the revised and old snow analyses for the 72-hour temperature and humidity forecasts. It shows a clear error reduction in continental areas of the northern hemisphere, particularly in parts of North America and Northeast Asia.

Observation monitoring

IFS Cycle 40r1 has been used for operational forecasts since 19 November 2013. As part of the implementation of the revised snow analysis, the interface to observations was also revised to allow the monitoring of observations of conventional screen-level parameters, snow depth and IMS snow cover. Operational monitoring is an important part of the ECMWF data assimilation system. It ensures the continuous evaluation of observation counts and departures of background fields and analyses from observations both spatially and in time. It helps to identify and subsequently blacklist suspect observations. When relevant, feedback is communicated to data providers. Observation monitoring is also important for the evaluation of IFS model and data assimilation system experiments.

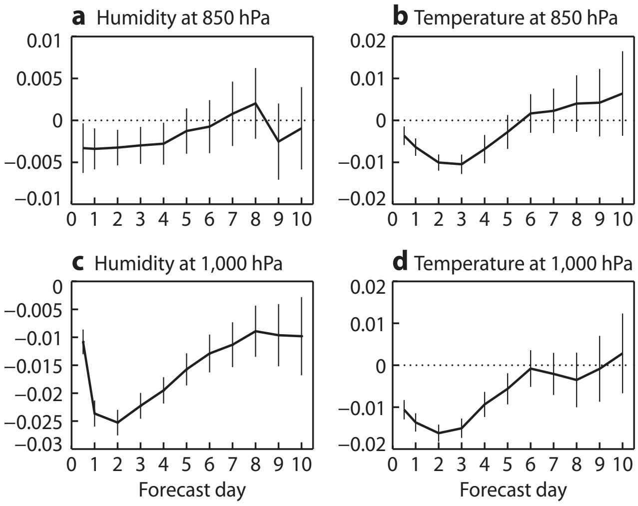

Figure 4 Impact of the revised snow analysis on the normalised root mean square error difference between IFS Cycles 40r1 and 38r2 (40r1 minus 38r2) for (a) humidity forecasts at 850 hPa; (b) temperature forecasts at 850 hPa; (c) humidity forecasts at 1,000 hPa and (d) temperature forecasts at 1,000 hPa in the extratropical northern hemisphere (20° to 90° latitude). Scores are computed against own analysis from 01 October 2012 to 30 April 2013. Error bars indicate 95% confidence range.

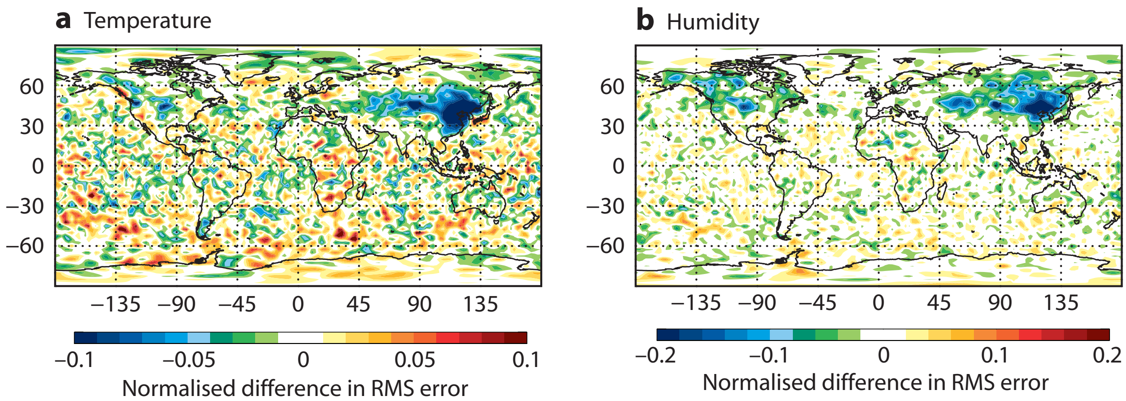

Figure 5 Normalised impact of the revised snow analysis compared to the old snow analysis on the root mean square error of 72-hour forecasts of (a) temperature and (b) humidity at 1,000 hPa. Scores are computed against own analysis for October 2012 to April 2013. Blue shades indicate a smaller root mean square error in the revised snow analysis, yellow and red shades indicate a larger root mean square error in the revised snow analysis.

Figure 6a shows a monitoring map of the mean number of observations used in the surface analysis for December 2014 to February 2015. It illustrates the uneven distribution of snow depth reports, with very dense snow depth observations available over Europe and sparse observation reporting over the USA and China and in the southern hemisphere. ECMWF's operational monitoring of the number of snow depth observations provides a clear and continuous record of current near-real-time availability of in situ snow depth reports on the GTS. It feeds into WMO snow watch initiatives aiming to improve snow depth report availability.

Figure 6b shows the standard deviation of the ECMWF innovations (observation minus background) for December 2014 to February 2015. It shows a mean standard deviation of around 0.029 m, which is indicative of the high quality of short-range ECMWF snow depth forecasts evaluated against snow depth reports. The time evolution of these statistics is also monitored operationally, as shown in Figure 7 for December 2014 to February 2015. Figure 7a shows the evolution of the mean departure of the background and of the analysis from observations. The negative values shown are consistent with a slight overestimation of snow depth, as discussed in the previous section, when compared against independent observations. In the operational snow analysis, the mean background and analysis departures over the whole period are -0.003 m and -0.001 m, respectively. The standard deviation, shown in Figure 7b, has mean values of 0.029 m and 0.025 m for background and analysis departures, respectively. Both statistics show good stability and consistent performance of the analysis through the winter season.

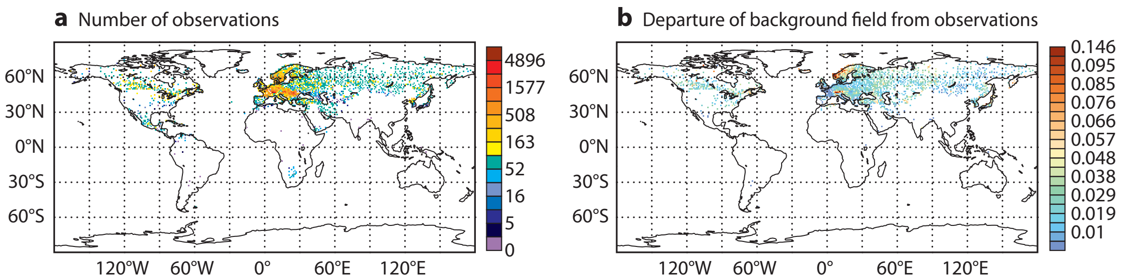

Figure 6 Snow monitoring statistics for December 2014 to February 2015 showing (a) the number of observations per 1-degree grid cell and (b) the standard deviation of the departure of background field values from observations, in metres.

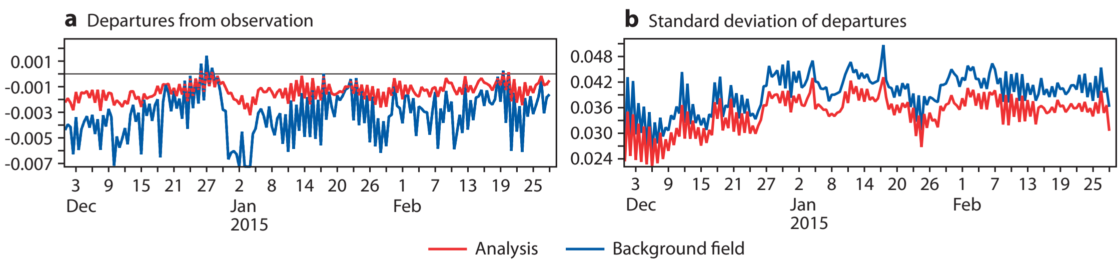

Figure 7 Monitoring time series from December 2014 to February 2015 of the ECMWF operational IFS Cycle 40r1 suite for conventional snow depth showing (a) mean departures of background field and analysis from observations, in metres (b) standard deviation of background field and analysis departures from observations, in metres.

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Summary

ECMWF's snow analysis has been revised substantially over the last few years. For the last two winters, IFS Cycle 40r1 has been used in operations. It has benefited from improvements in IMS snow cover data assimilation and new operational monitoring capabilities. Research experiments show a clear improvement of both snow depth and near-surface weather parameter forecasts directly related to the snow analysis revisions. An evaluation of snow depth analysis against independent snow depth reports shows that ECMWF's analysis performs very well in estimating snow depth and snow cover. The operational monitoring of snow depth observations helps to assess the quality of both observations and ECMWF's snow depth analysis and background field. This highlights the need for further improvements in the availability of near-real-time snow depth reports on the GTS for NWP applications.

Further reading

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