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Implementation of a Northern Hemisphere snow analysis in the global model

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Implementing a Northern Hemisphere snow analysis in the global model

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Abstract

Snow cover and amount are important components in the interaction between the land surface and atmosphere, but until recently there has been no observational snow information incorporated into the global model. This report presents a Northern Hemisphere snow analysis, based on satellite-derived observations of snow cover, which has recently been implemented in the operational global Unified Model (UM). The analysis uses daily snow maps from the National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service (NOAA/NESDIS) Interactive Multisensor Snow and Ice Mapping System (IMS) to modify the UM background snow amount. Assimilation trials carried out during the NH snow accumulation and ablation periods show improvements in analysed snow cover, both qualitatively and quantitatively, compared with unmodified control runs. Although the effect on the NWP Index of introducing the snow analysis is largely neutral, as expected, there is some evidence of small improvements in screen-level temperature and humidity forecasts. Several methods of validation and verification are presented and their results and implications discussed. The NH snow analysis delivers a basic snow assimilation system, which can be expanded and developed further in future iterations to improve the representation of snow cover and amount in the global and regional models.

Contents

1. Introduction

Snow is an extremely important component of the land surface system, substantially affecting the radiative and hydrological properties of the surface, and consequently the way it interacts with the atmosphere. Most importantly, snow cover dramatically increases the land surface albedo from between 0.05 and 0.4 (typical for bare soil and vegetation) to up to 0.9 for pure snow (Nolin and Liang, 2000), which has a huge effect on diabatic heating. In hydrological terms, water is accumulated in the snow pack during the winter season, and then released during snowmelt, with important effects on variables such as soil moisture and surface run-off. There are also effects on the near-surface air temperatures due to the insulating properties of snow, and the latent heat needed for snow melt. About 98% of global seasonal snow cover can be found in the Northern Hemisphere, where it affects between 7% and 40% of the land surface during the annual cycle (Armstrong and Brodzig, 2001, Hall, 1988), so it is clear that accurate representation of snow cover in numerical weather prediction (NWP) models is essential for calculations of surface exchange fluxes, and subsequent forecasts of atmospheric variables. An accurate knowledge of surface emissivities, which are affected by snow cover, is also important to enable the assimilation of satellite sounding data from surface-affected channels. Increases in the number of usable sounding channels could potentially yield considerable improvements to forecast accuracy, and so efforts to improve the surface representation are also important from the satellite data assimilation point of view.

Up until 2008 no observational snow information was used in the Met Office global NWP model. The surface snow variable in the Unified Model (UM) is snow depth (STASH code 0023) in units of kgm^{-2}. This is a prognostic variable in the model, but is internal to the UM, generated by snow precipitation. In this report, a snow analysis has been developed to assimilate satellite-derived observations of NH snow cover into the global UM. The primary aim is to improve the global model snow analysis, with no significant impacts on forecast skill anticipated, though improvements to screen level temperature and humidity forecasts are a possible benefit.

Section 2 describes the observational data that have been used, and their validation and use by other centres. Section 3 discusses the options for incorporating these data into the model and presents the development and implementation of the analysis scheme chosen. The assimilation trials carried out, and their validation and verification are discussed in Section 4. Finally, a summary and some plans for future work are presented in sections 5 and 6.

2. Data

Observations of snow cover can be retrieved from satellite, with global coverage and high temporal and spatial resolution. Currently the most widely used satellite-derived snow cover product for large-scale NWP is the Interactive Multisensor Snow and Ice Mapping System (IMS) from the National Oceanic and Atmospheric Administration’s National Environmental Satellite Data and Information Service (NOAA/NESDIS) (Ramsay, 1998). Although only currently available for the Northern Hemisphere (NH), it is freely available as an operational product, within a timeframe appropriate for use in NWP.

The IMS data consists of a daily map of NH snow cover and sea ice extent, which is drawn up by analysts on workstations that display data products and satellite imagery from a variety of sources, using the map from the previous day as the initial state. The primary data sources are visible imagery from polar orbiting and geostationary satellites. These NOAA polar orbiting (POES) and geostationary (GOES) satellites, European geostationary (METEOSAT) and polar orbiting (METOP) satellites, the Moderate resolution Imaging Spectroradiometer (MODIS), and the Japanese Multifunctional Transport Satellite (MTSAT) series. In addition, ground weather observations and microwave products from the Advanced Microwave Sounding Unit (AMSU) and Special Sensor Microwave Imager (SSM/I) are also incorporated, allowing detection in cloudy or low solar illumination conditions. The analyst also has access to a weekly sea ice analysis from the National Ice Center, the United States Air Force Snow and Ice Analysis Product, and snow products from the National Operational Hydrologic Remote Sensing Center, as well as several automated snow detection layers developed by NESDIS and National Centers for Environmental Prediction (NCEP)(Helfrich *et al.*, 2007).

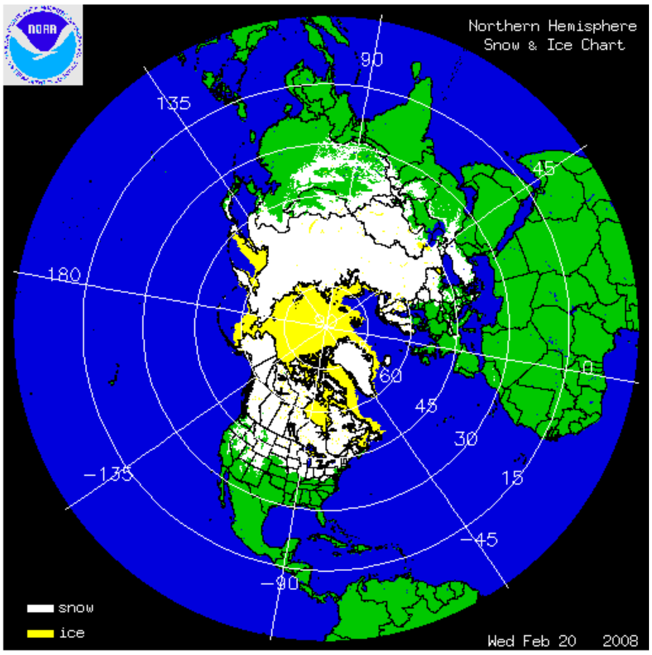

Figure 1. IMS NH Snow and Ice Chart for 20-02-08 (NOAA/NESDIS)

The IMS data are produced on a 6144 x 6144 grid, at approximately 4 km resolution. They are in polar stereographic projection, with the central meridian at 80^{o}W and the standard parallel at 60^{o}N. Figure 1 shows the IMS snow and ice map for 20th February 2008.

A number of intercomparisons and validation studies have been carried out using IMS snow cover data. Romanov (2000) made a quantitative comparison of snow cover products from IMS, SSM/I and a blended GOES and SSM/I automated product. He found an average difference in derived snow fraction between IMS and the blended product of only 3%, however, the SSM/I-only product showed significant deficiencies over forested areas and melting snow. Brubaker *et al.* (2005) compared IMS with both ground station and MODIS snow cover data. He found that IMS performed well against both ground measurements and MODIS data. Although snow detection rates are low (less than 40%) at the start of the winter, they increase as the snow accumulates, to 95% in December, against MODIS data. Detection rates are lower during the snowmelt but better than those during snow accumulation. 'No snow' detection rates are very high during snow accumulation and ablation (near 100%) but slightly lower at the peak of the winter.

IMS was originally created for use in NCEP forecasting models as an initial state of the surface cryosphere, and has been used as such for a number of years (Romanov *et al.*, 2003). It has also been adopted by ECMWF as an additional constraint in their snow analysis system (Drusch *et al.*, 2004) and serves an important function as a long-term climate record, with 40 years of continuous snow cover data. At the Met Office, IMS has been considered for use as input data to a snow analysis for some time. Preliminary investigations into the suitability of the data were performed by Cameron (2003). Cameron compared 20 months of IMS (24 km resolution) snow cover maps with UM snow cover. He found that snow cover formed slightly too quickly in the UM at the onset of winter, and melted far too rapidly in spring, when compared to the IMS data. His comparisons also revealed a tendency for the UM to overestimate the temporal variability in the snow cover. Over the two winter seasons analysed, the UM tended to underestimate snow cover in the USA, Europe, and north of the Caspian Sea, but overestimate snow cover in parts of the Far East, particularly in the 2002/2003 winter.

In comparisons of IMS snow cover with ECMWF operational snow water equivalent (SWE) analyses, prior to their assimilation of IMS, Drusch *et al.* (2004) note that the ECMWF model snow is also melted too rapidly in the spring. They found that the operational ECMWF analysis overestimated snow cover systematically, with the most pronounced differences at the snow edge. They also found systematic overestimation of snow extent over the Tibetan Plateau.

3. Development of a snow analysis

3.1 Snow analysis options

While the IMS data provides a simple binary diagnosis of snow cover (fully covered or no snow), the UM snow variable is snow amount, in kgm^{-2}, or areal density. The presence of snow cover indicates that some snow amount exists but gives no information about how much, and so there is no continuous relationship between the model states and the observations. The methods of assimilation available are therefore limited and unsophisticated, as explained by Rodell and Houser (2004) and simple update methods are commonly adopted. The presence of snow can be compared in model and observations and, where discrepancies arise, a set of rules can be followed to determine how to modify the model snow field.

While it is easy to remove model snow to agree with zero snow cover conditions in the IMS data, addition of snow to the model field is harder as the IMS data contain no information on non-zero snow amounts. Ideally, amounts added should minimally impact the local hydrology but be large enough to give snow residence times that are sufficiently long to impact the albedo. From reports by others on using snow cover observations to update model snow depths or snow amounts, it would appear that a snow water equivalent (SWE) of 10 mm, which is equivalent to an areal density of 10 kgm^{-2}, is accepted as a sensible quantity to add[1]. At ECMWF, 100 mm snow depth is added to snow-free model points for which 100% snow cover is obtained from IMS data (Drusch *et al.*, 2004). Rodell and Houser (2004) tested a snow analysis using MODIS snow cover data to update the Mosaic

[1] 10 kgm^{-2} areal density ≡ 100 mm snow depth ≡ 10 mm SWE based on snow density of 100 kgm^{-2} (Brasnett, 1999)

model, for use in the Global Land Data Assimilation System (GLDAS). Where the model SWE was zero but the MODIS data indicated greater than 40% snow cover, they added 5 mm SWE. However, they found that this thin layer was often melted immediately by the model.

Experiments were undertaken here to determine the effects of adding different quantities of snow to the UM. IMS snow cover data were used to update the UM snow amount field, and the UM then run for 2 days, for a summer and winter case, during which screen temperature error statistics were calculated, using SYNOP observations as ground truth. Snow was removed from the UM where the IMS data denoted no snow and, initially (Exp1), between 10 and 50 kgm^{-2} were added where the IMS data denoted snow but model snow amount was zero, depending on the mean snow amounts in the latitude band in question. Mean statistics were calculated separately for four regions of significant snow cover modification. Canada and Siberia were chosen for the summer case (June 2003) and USA and Eurasia were chosen for the winter case (February 2004). In each area examined, the RMS error and bias in screen temperature were increased for cases in which snow had been added, compared to an unmodified control run, but reduced in cases where snow had been removed. In a second experiment (Exp2) a constant snow amount of 10 kgm^{-2} was added where IMS denoted snow cover while the model was snow-free. The effect on the temperature statistics of this method of snow addition was less detrimental, indicating that additions of smaller quantities of snow during assimilation may be less damaging to forecasts of related screen level variables such as temperature. Results of these experiments are shown in Table 1 in terms of the change in RMS error and change in the modulus of the bias on modifying snow amounts. Positive changes denote an increase in error, or degradation, and negative changes denote a decrease in error, or improvement.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">All</th><th colspan="3">Added</th><th colspan="3">Removed</th></tr>
<tr><th>Δ RMSE</th><th>Δ |bias|</th><th>N</th><th>Δ RMSE</th><th>Δ |bias|</th><th>N</th><th>Δ RMSE</th><th>Δ |bias|</th><th>N</th></tr>
<tr><td rowspan="2">Canada Jun 2003</td><td>Exp1</td><td>0.5</td><td>1.0</td><td rowspan="2">33</td><td>1.1</td><td>1.7</td><td rowspan="2">28</td><td>-2.8</td><td>-2.5</td><td rowspan="2">5</td></tr>
<tr><td>Exp2</td><td>0.0</td><td>0.4</td><td>0.5</td><td>1.0</td><td>-2.7</td><td>-2.6</td></tr>
<tr><td rowspan="2">Siberia Jun 2003</td><td>Exp1</td><td>1.8</td><td>2.8</td><td rowspan="2">18</td><td>1.8</td><td>2.8</td><td rowspan="2">18</td><td rowspan="2" colspan="2"></td><td rowspan="2">0</td></tr>
<tr><td>Exp2</td><td>1.1</td><td>1.7</td><td>1.1</td><td>1.7</td></tr>
<tr><td rowspan="2">USA Feb 2004</td><td>Exp1</td><td>1.1</td><td>2.9</td><td rowspan="2">14</td><td>1.3</td><td>3.2</td><td rowspan="2">13</td><td>-2.6</td><td>-2.5</td><td rowspan="2">1</td></tr>
<tr><td>Exp2</td><td>0.1</td><td>0.9</td><td>0.2</td><td>1.1</td><td>-2.9</td><td>-2.8</td></tr>
<tr><td rowspan="2">Eurasia Feb 2004</td><td>Exp1</td><td>1.4</td><td>2.0</td><td rowspan="2">240</td><td>1.8</td><td>2.7</td><td rowspan="2">197</td><td>-0.7</td><td>-0.9</td><td rowspan="2">43</td></tr>
<tr><td>Exp2</td><td>0.6</td><td>1.0</td><td>0.9</td><td>1.4</td><td>-0.7</td><td>-0.9</td></tr>
</table>

Table 1. Mean statistics showing the impact on UM screen-level temperatures of modifying the UM snow amount field using IMS data, verified against SYNOP observations. Shown are the changes in RMS error and in the modulus of the bias in screen temperature (in K) when snow is modified compared to an unmodified run, where positive changes are increases in error, and negative changes are decreases in error. The bias did not change sign in any of the cases. In Exp1 snow was added in variable amounts (10-50 kgm^{-2}) whereas in Exp2 added snow was of a constant amount (10 kgm^{-2}). Results are shown for all cases, and separately for cases in which snow was added and removed. The number of cases contributing to the statistics is denoted by N.

Romanov *et al.* (2003), while monitoring snow cover fraction over North America, showed that there is a close correlation between snow fraction and snow depth in non-forested areas. This can be simply explained by considering that the deeper the snow pack becomes, the more vegetation it will completely cover, and therefore the higher the fraction of cover “seen” by satellite. As the vegetation canopy increases in height, the less likely complete snow cover is to be “seen” from space, and the correlation becomes less noticeable. However, they did show that the snow fraction remains sensitive to changes in the snow depth in lightly forested areas, and the correlation is still statistically significant even in the most densely forested regions.

These results suggest that there may be a way of extracting information about snow amounts from the IMS snow cover data, if they can be converted to fractional cover data. Several NWP models derive fractional snow cover from a gridbox value of snow-water equivalent (e.g. Drusch *et al*., 2004), and a relationship such as this is already used in the UM for specifying albedo as an interpolation between the snow-free and snowy albedos (Essery *et al.*, 1999):

$$a = a_0 + (a_s - a_0)(1 - e^{-DS})$$ **Equation 1**

Where a = actual albedo, a_0 = snow-free albedo, a_s = snowy albedo, S = snow-water equivalent, D = masking depth of vegetation

In reverse, this relation can be used to relate fractional cover to SWE in the following way:

$$S = \frac{(-\ln(1 - f_c))}{D}$$ **Equation 2**

Where f_c = fractional snow cover and D is set to 0.2 m

Figure 2 illustrates the relationship in Equation 2 between SWE and fractional cover, for a masking depth of 0.2 m.

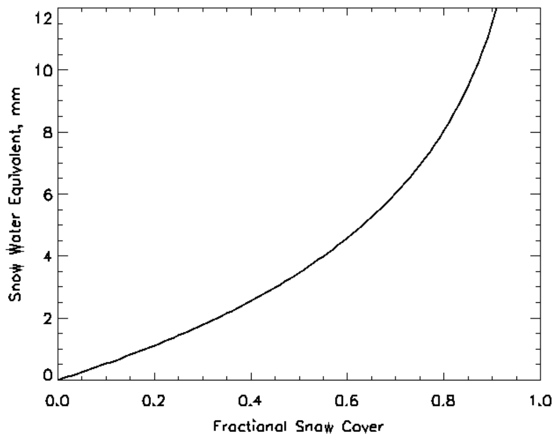

Figure 2. Relationship between snow water equivalent and fractional cover for a masking depth of 0.2 m

In light of reported difficulties in retaining added snow in models, (e.g. Rodell and Houser, 2004, Drusch *et al.,* 2004) experiments were conducted here with the single-column UM to determine whether snow addition could be more successfully retained if simultaneous changes were also made to model soil temperature. Single-column model trials were performed for a June and a February case, in which soil temperature in the top 2 soil layers was incrementally reduced to freezing. Figure 3 shows the snow residence time resulting from variations in initial snow depth and 1st layer soil temperature, for a summer and winter case. It is clear that the main residence time sensitivity is to snow depth, and that lowering the soil temperature has little effect in most situations. The section of closely packed contours in the winter case represents the rapid increase in residence time achieved when snow is still present at the onset of night, allowing it to be retained until morning. Rodell and Houser (2004) report that reducing the surface temperature to freezing when adding snow was similarly ineffective in extending the residence time. Considering these results, and that soil temperature nudging and screen temperature assimilation are both now implemented operationally, it was decided not to proceed further with simultaneous soil temperature increments.

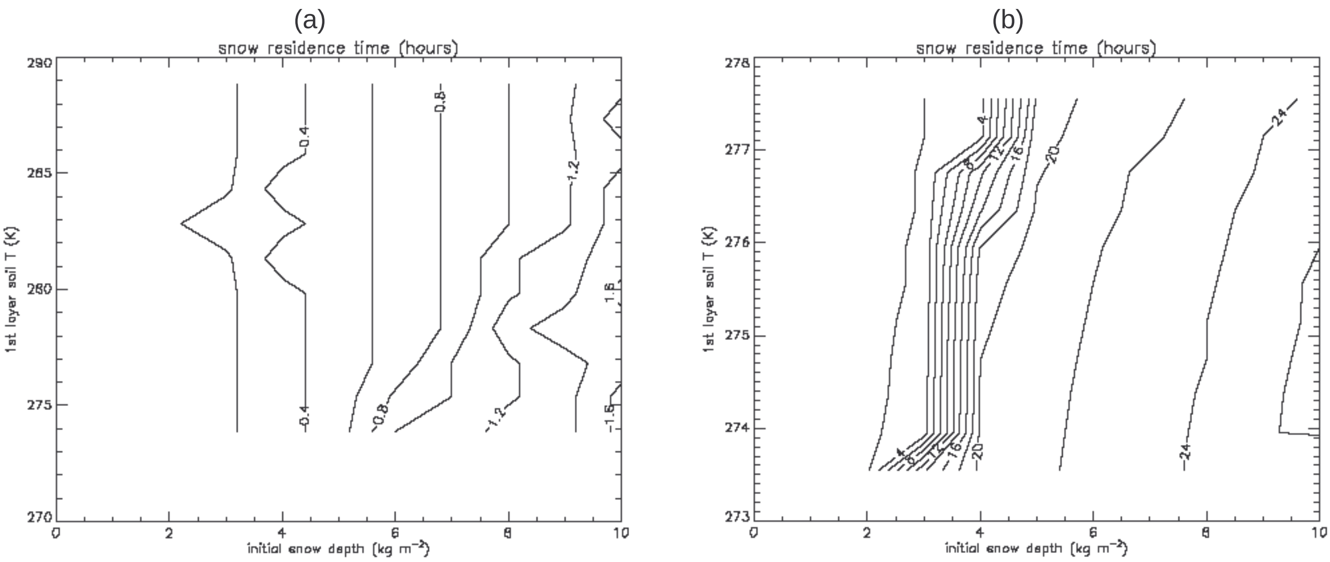

Figure 3. Snow residence time as a function of snow depth and temperature in the top soil layer for single-column UM simulations at Cardington for (a) 13th June 2005, and (b) 21st February 2006

3.2 Data processing

IMS data are converted to GRIB2 format by NCEP and placed on an operational server daily at about 23:00 UTC, from which they are retrieved by the Met Office. Each GRIB file is 9.3 MB in size and contains 2 records in their original projection:

1. Sea ice concentration, units fraction (0 or 1)
2. Snow cover, units % (0 or 100)

The snow cover record is extracted, monitored for the number of non-missing data, and number of data classified as 100% snow cover, then transferred to the MetDB.

Processing of the data and the snow analysis itself are carried out within the SURF system, during the QU06 run. On retrieval from the MetDB the snow cover data undergo a first iteration of quality control. Since the observations are at much higher resolution than the global NWP model grid, there are discrepancies in coastal regions between land and sea classification. Some snow cover data points lay within UM gridboxes which are classified as sea and these need to be excluded from further processing. The land-sea mask is read from the UM background file. The UM gridbox into which each snow cover observation falls is found and checked against the land-sea mask. Snow cover observations which either fall within a "sea" UM gridbox, or indicate missing data (value 128.0) are given a quality control flag value of 2, to allow their selective exclusion from further processing.

The full resolution snow cover observations are then reprojected to lat-lon projection and converted to a fractional cover product on the UM grid: the number of IMS snow cover points falling within each UM grid box is calculated and a fractional cover value computed from those points. Quality control is carried out on these fractional cover data to identify, and allow exclusion of, unrealistic IMS reports of snow covered land. A minimum fractional cover threshold of 0.03 is applied, below which a check is performed against a maximum UM surface temperature threshold of 283.15 K (Romanov *et al.* (2003) reports that snow often exists in satellite imagery pixels for which the brightness temperature exceeds freezing level by 10 K)). Fractional cover data failing these checks are given a quality control flag value of 1. These tests aim to identify incorrectly specified IMS data points. These are likely to be isolated occurrences since the snow cover map is drawn up by hand. By imposing the surface temperature threshold, exclusion of legitimate isolated snow cover points representing the edge of a snow field should be avoided. This method does not account for erroneous snow-free IMS points, but isolated errors of this type would not significantly affect the fractional cover for the grid-box (a slight reduction in snow cover will not affect the model nearly as much as a transition from no snow to snow).

3.3 The snow analysis scheme

The snow analysis combines information from both the fractional cover observational product, described above, and the UM snow amount (STASH 023) short-range forecast (the model background) from the previous model cycle to produce an analysis of snow amount. The analysed snow field is initialised to the model background snow amount field, and the analysis performed for all points with quality control flag value of 0 (these points have passed the quality control in the processing).

For this scheme, the analysed snow field is calculated in the following way:

1. Where fractional cover is zero, analysed snow amount is set to zero.
2. Where fractional cover is non-zero but UM background snow amount is zero, analysed snow amount is calculated according to the relation in Equation 2, up to a maximum value of 10.0 kgm^{-2}
3. Where both fractional cover and UM background snow amounts are non-zero no change is made
4. Where UM background land ice is non-zero no change is made

The main elements of the scheme are illustrated in Figure 4.

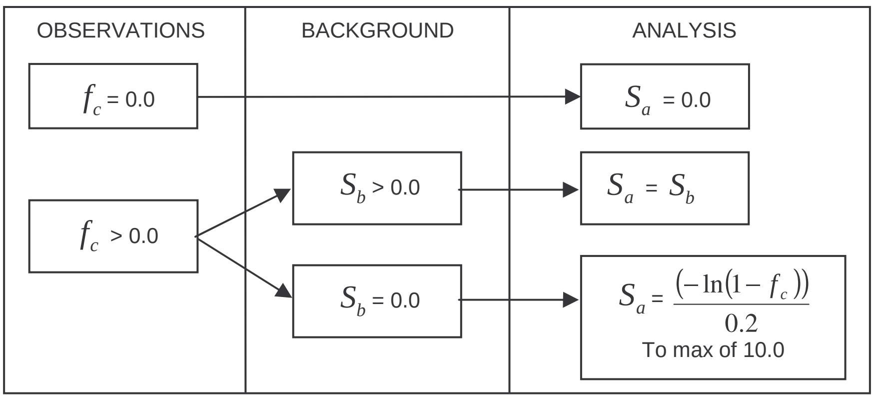

Figure 4. Schematic diagram showing how the snow analysis works, where f_c = fractional cover, S_b = background snow amount and S_a = analysed snow amount.

The analysed snow field is written to an ancillary file and used to update model, daily at 06Z. In the event that no IMS data are available in the MetDB, the model background snow amount field is written unchanged to the ancillary file.

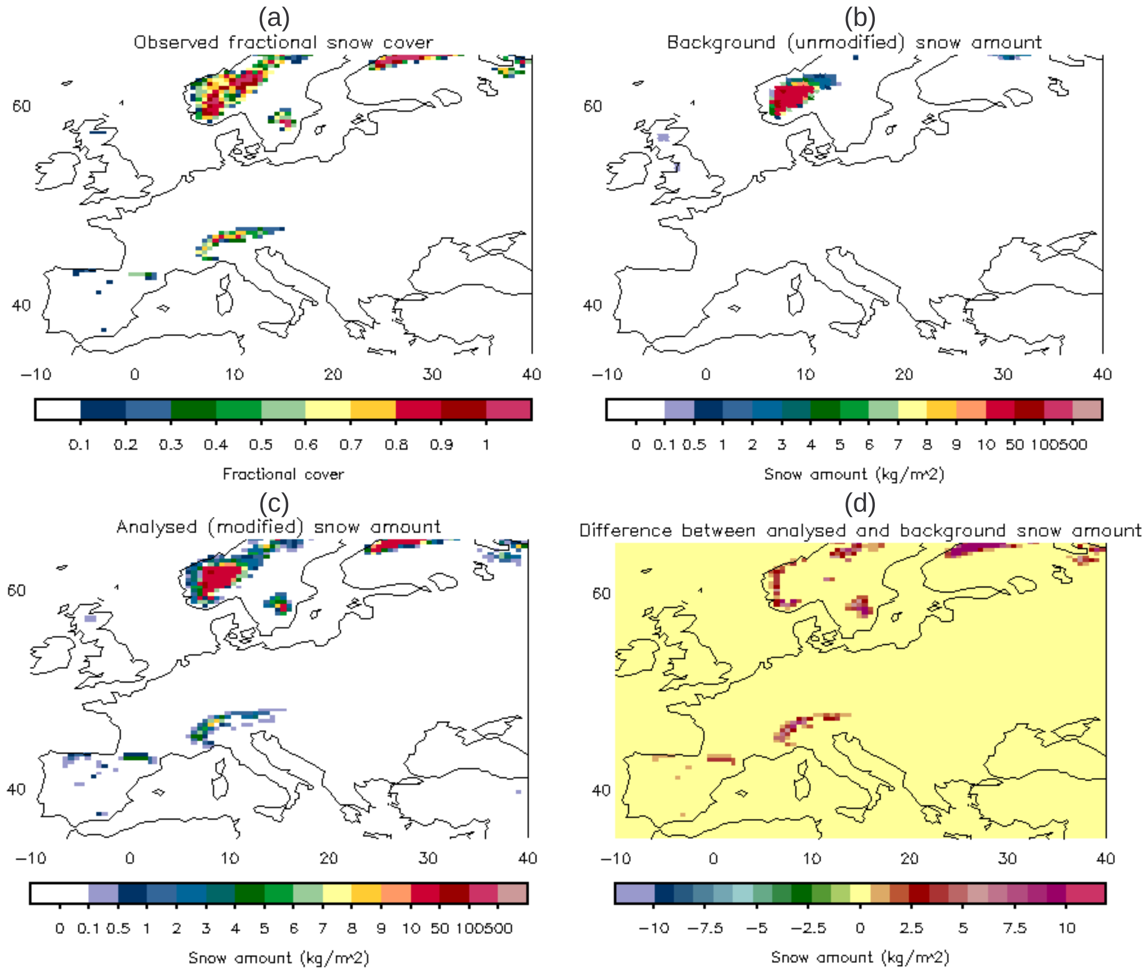

Figure 5. A snow analysis performed on 10th November 2008 over Europe, showing (a) the observed fractional cover, (b) the background snow amount field, (c) the analysed snow amount field, and (d) the snow amount increments.

A demonstration of the scheme is illustrated in Figure 5 where a snow analysis has been performed over Europe. Additions of areas of snow over the Alps, Northern Spain, and Southern Sweden are clearly shown in Figure 5(c) and (d) where none was present in the background snow field, but was present in the observations.

4. Trials

Global model trials have been run during the two main seasons that are affected by snow in the NH. A 1-month trial was run for December 2006, during snow accumulation, and a 3-month trial was run from March-May 2007, encompassing the majority of the snowmelt season. Both trials were run at N216L50 resolution with 3D-Var data assimilation, and included PS15 physics changes and soil moisture nudging. Figure 6 shows monthly snow maps, based on IMS, from Rutgers University Global Snow Lab[2] for the 2 trial periods, to illustrate the accumulation of snow throughout December 2006 and depletion from March to May 2007.

[2] http://climate.rutgers.edu/snowcover/

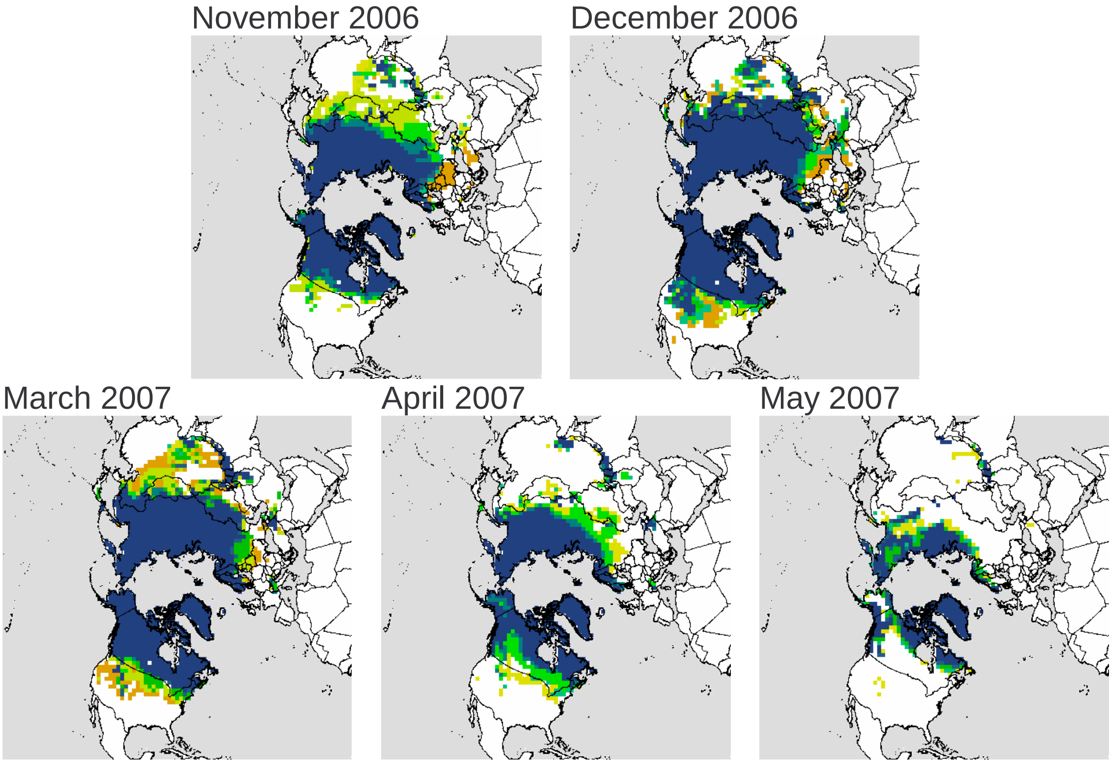

Figure 6. Average snow cover extents for the months marked, based on Rutgers Global Snow Lab analysis of IMS daily snow maps.

4.1 Behaviour of the snow analysis

Figure 7 and Figure 8 show time series of snow additions and removals by the snow analysis, and compare snow extent in analysis and background, for the NH winter and spring trials respectively. For the winter trial (Figure 7) snow was removed from approximately 3 times as many gridboxes as it was added to, by the analysis, and substantially more was removed after day 20 (18/12/06). The background contained more snowy points than the analysis throughout the entire period; in other words there was net removal of snow by the analysis each day. The background and analysis differed as to the presence of snow by an average of approximately 1% of NH grid points. For the spring trial (Figure 8) the snow extent decreased steadily throughout the trial. Initially snow was added to and removed from approximately the same number of grid points, but after day 34 (4^{th} April) the snow extent in background and analysis diverged as snow was added to increasingly large numbers of grid points, and snow removal decreased. This net addition of snow by the analysis as the spring progresses is consistent with previous reports (Cameron 2003) that the UM melts snow too rapidly in the spring.

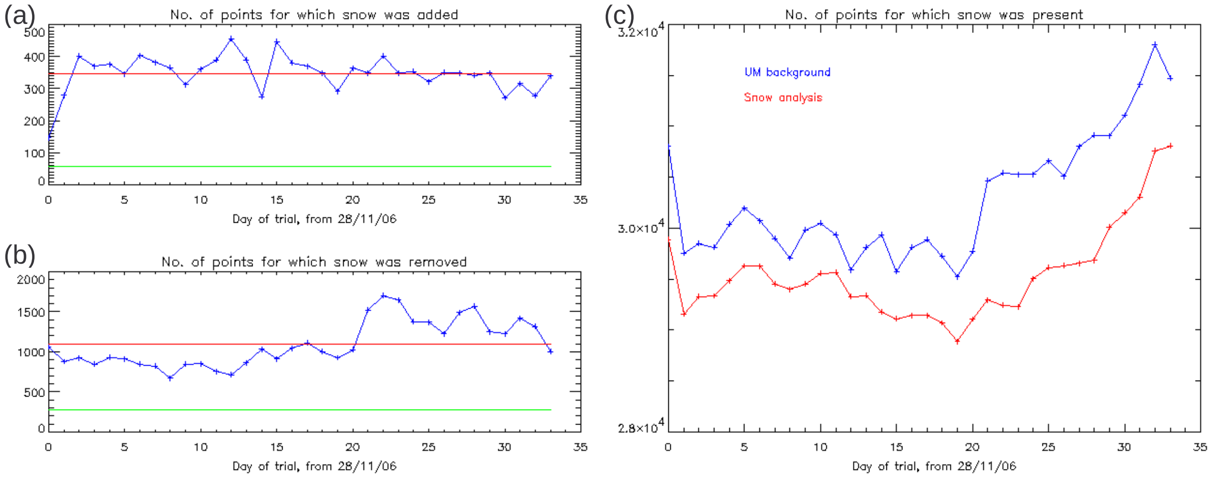

Figure 7. Time series of series of number of grid points for which snow was (a) added, (b) removed, and (c) present in both background and analysis, for the winter trial. Shown in red and green in (a) and (b) are the mean and standard deviation respectively.

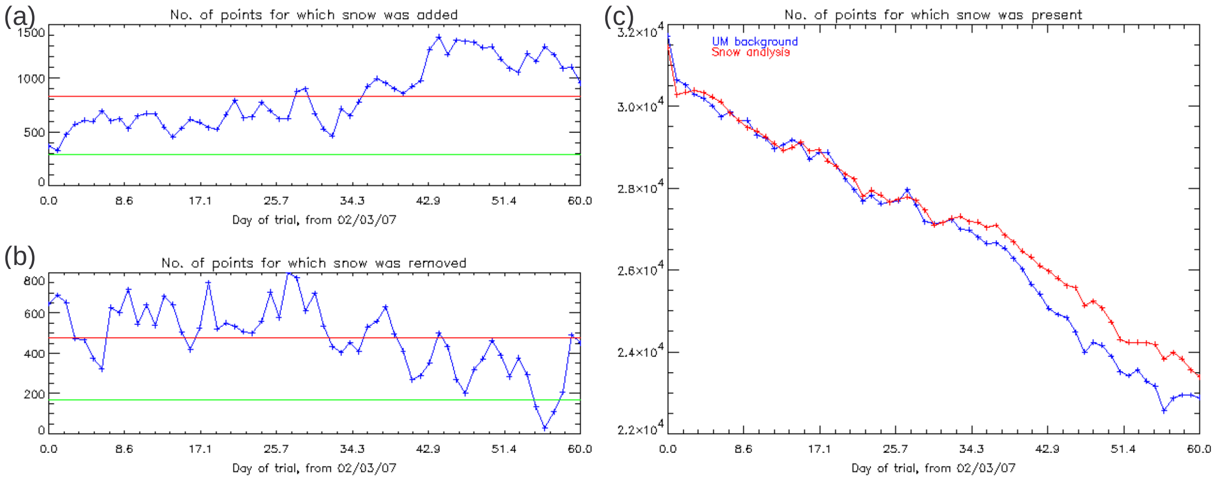

Figure 8. Time series of series of number of grid points for which snow was (a) added, (b) removed, and (c) present in both background and analysis, for the 1st 2 months of the spring trial. Shown in red and green in (a) and (b) are the mean and standard deviation respectively.

During December 2006 snow cover was initially fairly steady overall, though with increasing coverage of North American mountainous regions, but after 18th December, as seen in Figure 7 (c) there was a rapid increase as the snow field advanced westwards across Eastern Europe. Changes made by the snow analysis were either at snow field edges, or in regions of complex terrain. Snow was consistently added in the Sierra Nevada and Rocky Mountain ranges of North America, and removed in the region of the Tibetan Plateau, shown in Figure 9(a). Early in December snow was added along the edge of the snow field in a line from Eastern Scandinavia to the Caspian Sea, as shown in Figure 9(a), but later in the month large areas of snow cover tended to be removed from this region as in Figure 9(b).

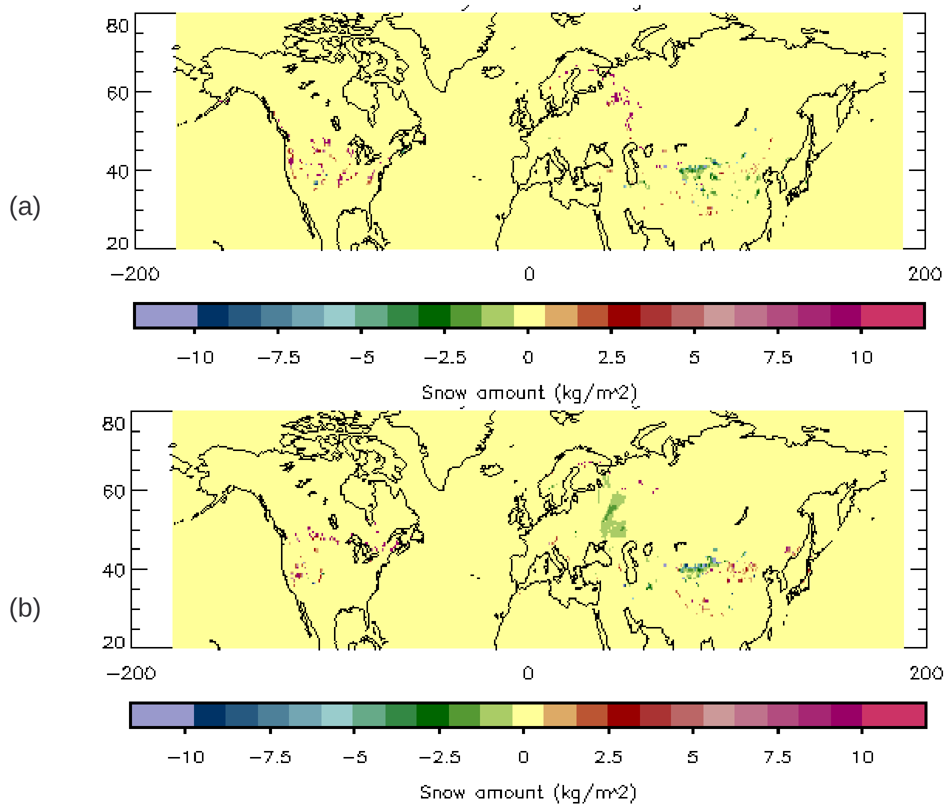

Figure 9. Snow analysis increments for (a) 9th and (b) 14th December 2006, from the winter trial.

Throughout the spring trial, as in the winter trial, snow was consistently added over mountainous parts of North America, and removed from the region of the Tibetan Plateau, suggesting that there is persistent model bias in these areas. At the start of the spring trial, there were generally small areas of snow addition by the analysis in Europe, Russia and around the North American Great Lakes, as in Figure 10(a), which became progressively larger as the spring advanced. These were situated at the edge of the snow field, where the UM snow melt was proceeding too rapidly and the analysis attempted to restore large areas of prematurely depleted snow cover, shown by Figure 10(b). The edge of the snow field moved gradually North-East in both North America and Eurasia as the spring progressed, and is illustrated by the North-Eastward movement of the areas of snow addition in Figure 10. Figure 10(d) shows the model background snow field on 26th April, to demonstrate the position of the model snow field edge relative to the increments in (c).

4.2 Validation of snow analysis trials

There are two aspects to validation of the snow analysis trials. As stated in Section 1 the main aim of implementing a snow analysis is to improve model analysed snow fields, and so the validation firstly concentrates on use of alternative snow observations to verify that the analysed snow fields represent snow cover better than the model background snow fields. Although no significant impact on forecast skill is anticipated, it is important to establish that the snow analysis has not degraded forecast skill significantly. The second aspect of the validation, therefore, concentrates on formal area-based forecast verification, to determine the impact on forecast skill overall, and for the main prognostic variables. Particular attention is paid to screen-level temperature and humidity forecasts, which could be beneficially affected by an improved snow cover analysis.

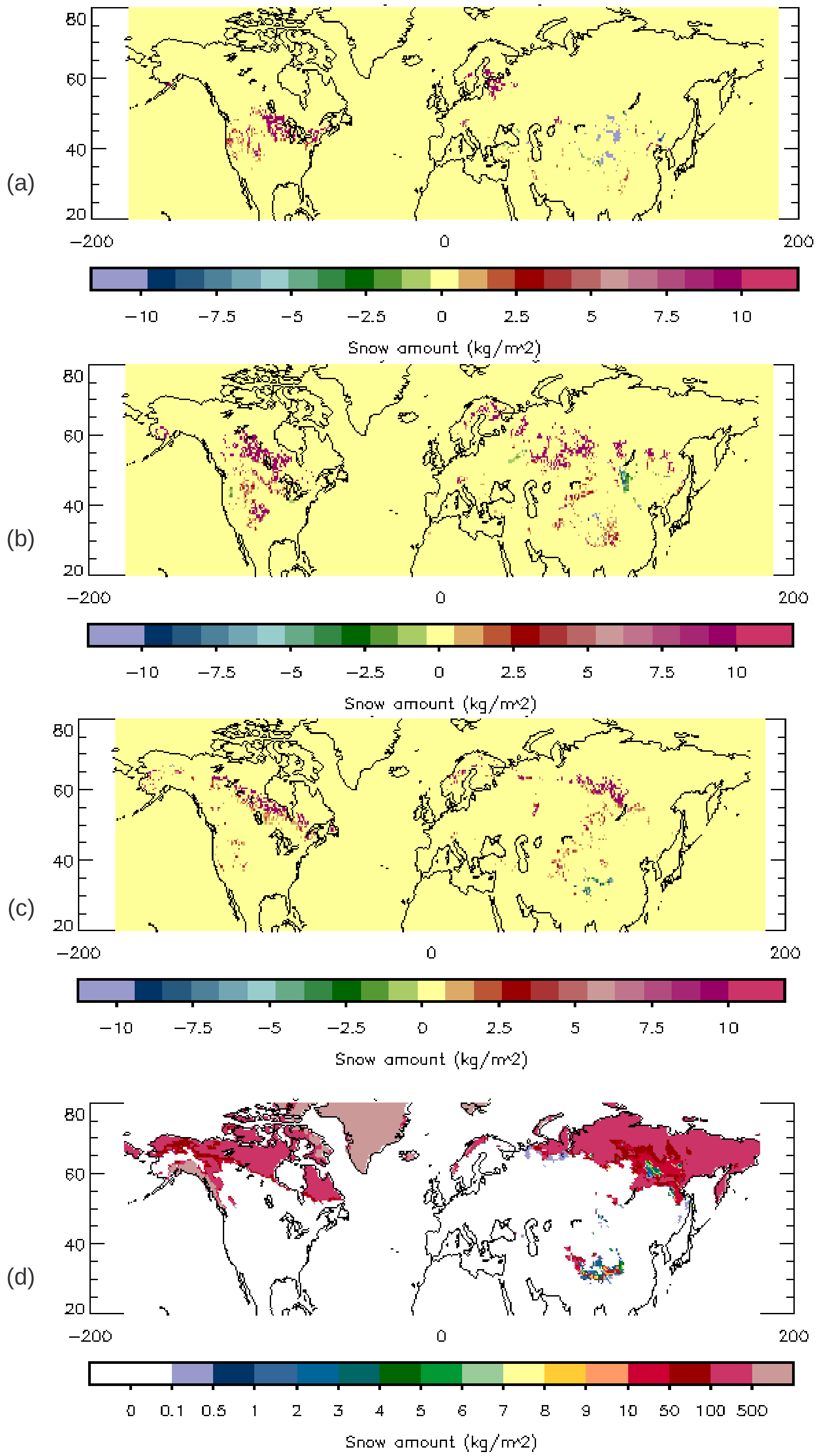

Figure 10. Analysis increments for (a) 13th March, (b) 15th April, (c) 26th April 2007, from the spring trial. (d) shows the background snow field for 26th April, to illustrate the position of the snow field edge.

4.2.1 Qualitative verification

The National Operational Hydrologic Remote Sensing Center (NOHRSC) produces operational daily snow maps, using ground-based, airborne, satellite, and snow model data for the coterminous United States and Alaska. Although not entirely independent, the NOHRSC products are often used to evaluate the accuracy of satellite-derived snow cover (e.g. Bitner *et al.*, 2002, Mauer *et al.*, 2003) and provide a convenient daily source of qualitative validation data in these trials.

Comparison of NOHRSC daily snow depth analyses with UM background (before modification) and analysed (after modification) snow amounts, in terms of presence or absence of snow, shows that there is generally good agreement between the NOHRSC product and UM analyses, in terms of snow coverage. This agreement is often, but not always, better than that between NOHRSC and UM background. In the winter trial the snow analysis increments were generally small and the UM background tended to represent the snow cover well, with some notable exceptions. Figure 11 shows comparisons for three dates that illustrate interesting features. The plots for 13^{th} December 2006 show two points of interest where the analysis has improved the comparison with the NOHRSC product. The analysis has added snow in the Sierra Nevada mountain range, which is absent in the background, and this change was seen frequently in both trial seasons. The analysis has also captured snow cover around the Great Lakes better than the background, although the extent may be overestimated. Changes made by the analysis often led to small degradations in the snow cover representation, for instance on 24^{th} December 2006 where the analysis has exacerbated a positional error in the background where the snow band across the mid-US intercepts the Great Lakes. However, in the spring trial, when the UM background tended to exhibit prematurely depleted snow fields, the snow analysis made huge improvements in the North American snow cover representation. The background snow field shows practically no snow cover over the mountainous western parts of the USA on most days after 14^{th} April. It is clear from the NOHRSC analysis that there is significant coverage, albeit patchy, over these regions throughout the period, and the cover is well captured by the analysed snow field.

On occasion, the analysis compared less favourably with the NOHRSC product, in a specific region, where areas of new snow cover in the background were removed by the analysis, and were not represented in the IMS data until a day or two later. This apparent time lag in the IMS data is discussed in Section 4.2.3 below.

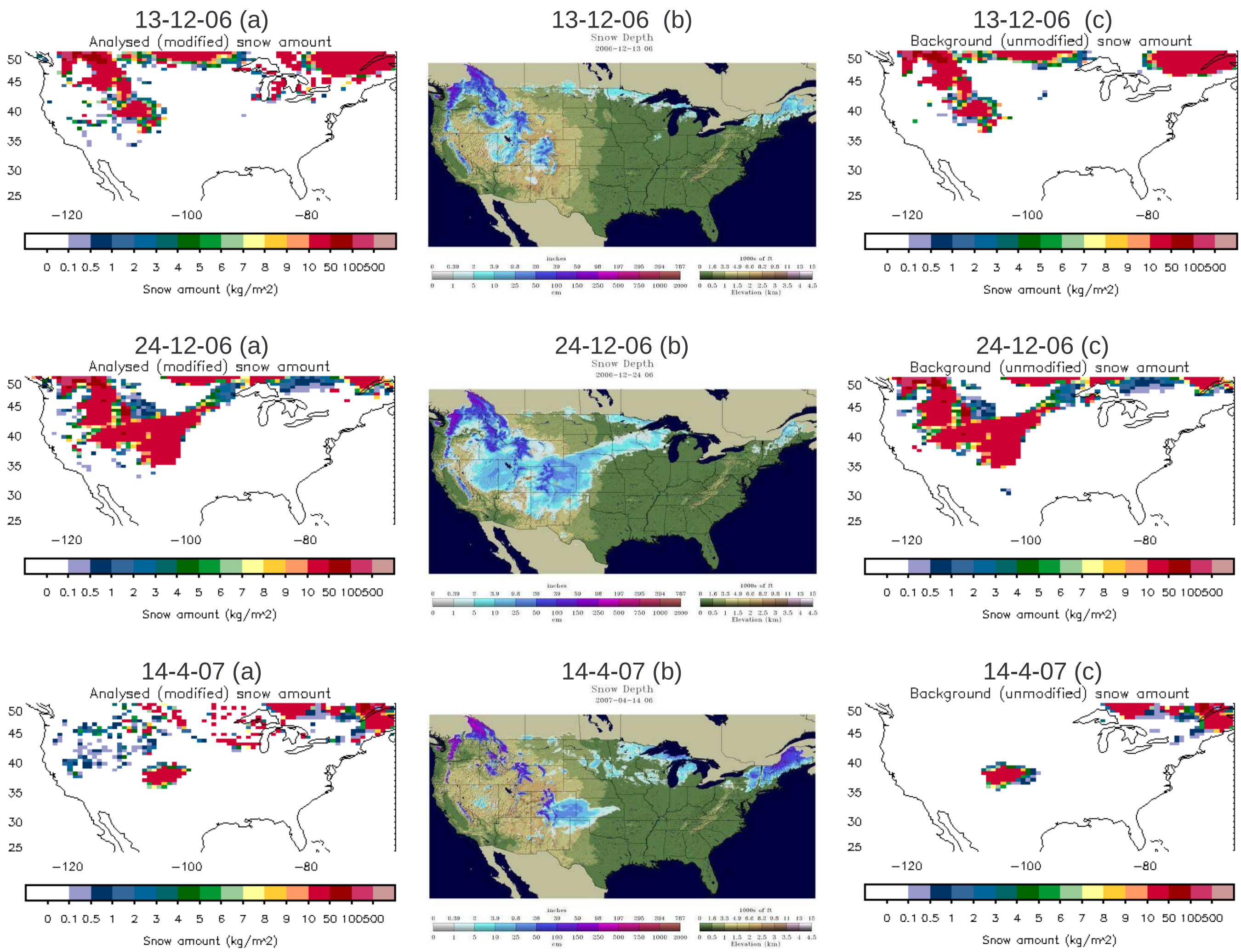

Figure 11. Analysed snow amounts (a), NOHRSC snow depth (b) and background snow amounts (c) for 13th and 24th December, 2006, and 14th April 2007, over the USA.

4.2.2 Quantitative verification

Quantitative verification of the analysed snow fields, in terms of snow cover, is problematic for a number of reasons. The IMS product comprises so many different data sources, including other analysed products, that it is very difficult to find an entirely independent dataset to use for verification. Ground station observations are often used as “ground truth”, but as point-scale, spatially sparse observations they are generally non-representative of the much larger footprint of a satellite-derived product. However, SYNOPS “state of ground” reports have been used here to give some measure of the effectiveness of the snow analysis in improving the model snow cover. The element GRND_STAT_IDNY has 20 different options for reporting ground state, 9 of which describe snow cover of some kind. Unfortunately only a subset of stations seems to submit this part of the report, and a missing data entry cannot be taken as a "no snow" report. This verification has therefore been carried out using only those stations that do report snow, and as such is rather one-sided as it tells us nothing about how well non-snowy points are represented (i.e. does not allow us to verify snow removal). Figure 12 below shows the SYNOP station data available in the MetDB for 7th December 2006, for Europe and North America. In red are those stations which have submitted a “state of ground” report for that day. There are so few stations submitting "state of ground" reports in North America at this time of year, and the coverage so non-uniform, that the results for North America are clearly not statistically valid.

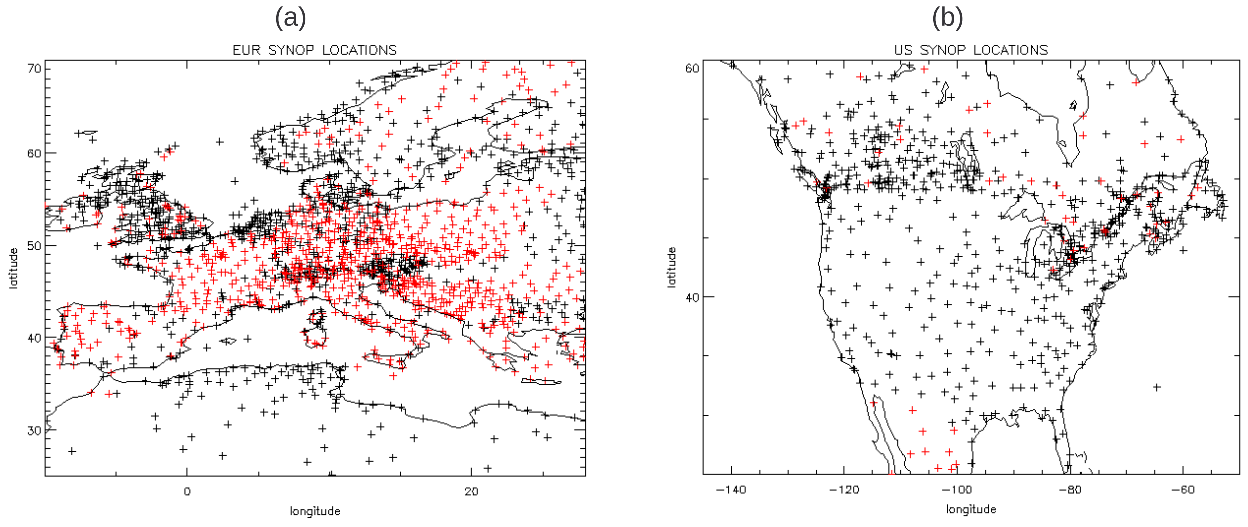

Figure 12. Positions of SYNOP stations in (a) Europe and (b) North America for which reports were received between 05Z and 07Z 7th December 2006. Marked in red are those stations which have reported on “state of ground”.

The verification therefore concentrates on Europe, where a large proportion of SYNOP stations submit a “state of ground” report, and compares the station data with model snow cover at 06Z daily for a period of 14 days within each trial. LNDSYN observations were retrieved from the MetDB for Europe, from 05Z to 07Z for each day of the comparison. The element GRND_STAT_IDNY was used to diagnose the presence of snow. The UM gridbox into which each SYNOP report fell was calculated, and multiple reports for a single gridbox were discarded. Model snow cover was diagnosed by snow amounts greater than 0.0 kgm^{-2}. The number of control and trial gridboxes in agreement with SYNOPS reports within them, as to the presence of snow, has been calculated. Figure 13 below shows the results for both trials, in percentage terms.

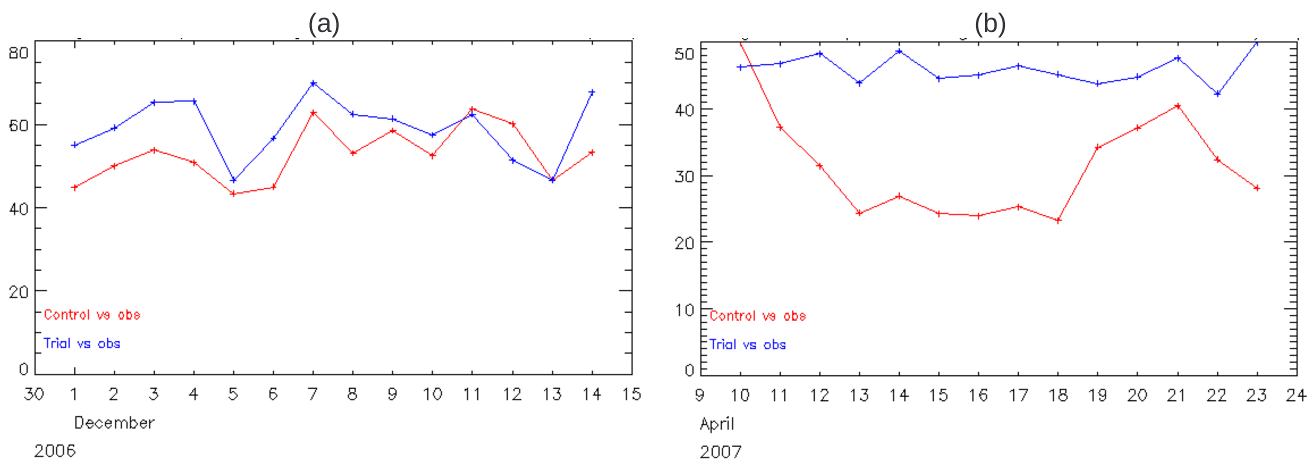

Figure 13. Percentage of model grid points, in Europe, with snow presence in agreement with SYNOPS snow reports within them for (a) 1-14th December 2006 and (b) 10-23rd April 2007. Control run, without snow analysis, is shown in red and trial run in blue.

During the winter trial the snow analysis led to an improvement in the agreement on most days, but a dramatic improvement was evident in the spring trial, with the percentage of gridboxes in agreement with the SYNOPS observations doubled on several days. Given that the predominant effect of the snow analysis in the winter trial was snow removal, especially over Europe, and that this method only allows us to verify snow addition, it is not surprising that the results were less convincing for the winter trial. However, both results do show a clear improvement in the agreement of the model snow with ground-based observations with the snow analysis in operation, and can be taken as evidence that the snow analysis has improved the model snow cover representation at analysis time.

4.2.3 Non-timeliness of observational data

In his investigations Cameron (2003) found that for an IMS snow cover map for a certain day, the best correlation was with the UM snow cover from the previous day. In fact he concluded that by the time the IMS data was available, it was lagging the UM by about 36 hours. Romanov *et al.* (2000) explains how the time lag between the IMS data and the NWP model into which it is assimilated arises, using North America as an example. Here surface reports can be included from any time in the 24-hour period leading up to the cut-off time of 1200 UTC. For the eastern US GOES observations are used from 1200-1700 UTC and for the western US images used are from 2000 UTC of the previous day to 0200 UTC of the analysis day. The analysis is then performed at 1800 UTC, acquired in the MetDB at 0300 UTC and used in the 06Z cycle of the global suite. This means that there is the potential for a time range of up to 29 hours in data used just within the US region of the IMS product, and for a difference of 42 hours between the validity time of an IMS data point and the UM snow field with which it is compared. Of course, this is an extreme example, which is unlikely to occur, since there will nearly always be multiple sources of data, and multiple satellite passes during the period that the IMS analyst draws information, but where cloud cover is present for a large period of that time, the available observations are considerably reduced and large time lags can develop for some regions of the IMS analysis.

The effects of such data time lags were sometimes apparent in the trials, especially in the winter season when changes in snow cover occurred on very short timescales (snowfall as opposed to snow melt). One striking case occurred on 30th November – 1st December 2006 when a large scale snowfall event over the USA occurred. The UM background captured the event well, verified against NOHRSC snow depth, but the IMS did not represent the snowfall until 2nd December, and so the snow analysis removed the snow from this area and degraded the model representation of the snow cover for these 2 days. The comparison of analysis and background against NOHRSC snow depth for 1st December 2006 is shown in Figure 14, with the large scale snowfall clearly visible, extending South West from the Great Lakes, in the NOHRSC and UM background plots ((b) and (c)), but absent in the analysis (a).

The effects of time lags in the data are much less evident in the spring, where the main changes to the snow field are due to seasonal melting, which happens on a longer timescale than winter snow storms. The data comprising the IMS snow cover product are perhaps also less likely to be cloud-covered, allowing more cloud-free data to be available to the analyst. Work is planned to mitigate the effects of such data time delays, and this is discussed in section 6 below.

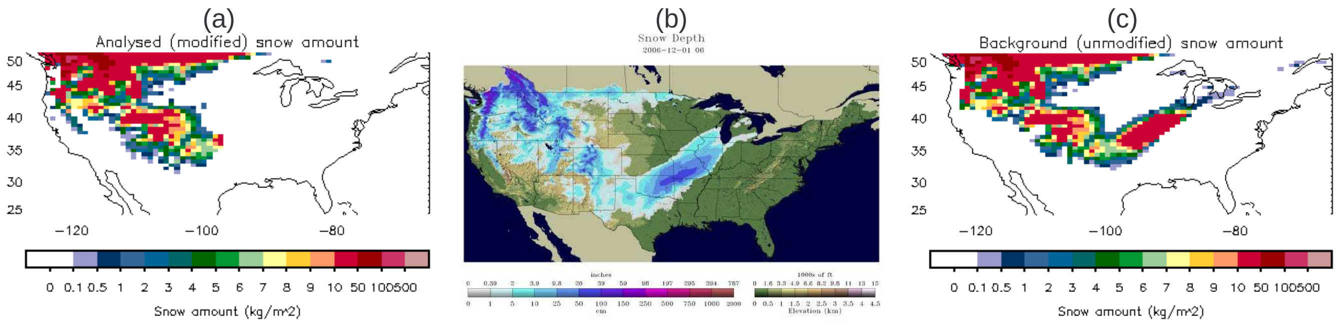

Figure 14. (a) analysed snow amounts, (b) NOHRSC snow depth, and (c) background snow amounts, for North America on 1st December 2006.

4.2.4 Non-retention of added snow

It is clear from examining the daily changes made by the snow analysis that many of the changes made are not retained by the model and must be made again by the subsequent analysis. This is particularly so for additions of snow to the model; if the model surface temperature is above freezing, the added snow quickly melts. As discussed in section 3.1, the same result has been found by others, and the hydrology could be adversely affected if a much greater quantity of snow was added, with the hope that some would remain.

Developments to the current UM snow scheme include the introduction of a multi-layer snow pack and representation of partial snow cover within a grid box. Both of these changes should make it easier to retain added snow in the future. Partial snow cover representation is addressed by the “Tibet snow” UM modification, as an interim solution. A short compatibility trial has been performed for the snow analysis along with the Tibet snow mod, and additionally incorporating screen-level temperature and relative humidity assimilation, which has been operationally implemented since the snow trials were run. There was no evidence of any adverse interactions between the snow analysis and the other changes, indeed the snow analysis appears to be facilitated. In general the model background contained more snow cover than in the original snow trial, and so less snow addition was required in the spring period. This effect may have been partly attributable to the action of the Tibet snow mod and suggests that springtime snow cover is able to be retained for longer in the model. Although retention times may not be significantly changed for snow added by the analysis, the problem itself is lessened as less snow addition is required.

4.3 Forecast verification

The NWP index scores, versus observations and versus analyses, are shown for both trials in Table 2 below. In the winter trial, when snow was building up, the impact of the snow analysis was slightly positive, and in the spring period, during snow ablation, the impact was slightly negative. Since snow was added by the analysis over increasingly large areas during the spring, and this added snow was not able to be retained, it is perhaps unsurprising that daily additions and subsequent melting of large areas of snow should have a negative impact on the forecast skill.

	Dec 2006	March-April-May 2007
Seasonal snow behaviour	Snow build-up	Snow melt
NWP Index vs Obs	+0.18	-0.12
NWP Index vs Anal	+0.05	-0.13
Net effect of analysis	Snow removal	Snow addition

Table 2. NWP index scores and main characteristics of the winter and spring snow analysis trials.

NWP Index impacts are small for all components, as shown by Figure 15, though it is interesting to note that the largest impacts are on tropical and SH components (where there is no direct action by the snow analysis). This is probably attributable to noise, rather than any genuine scientific effect, but it is worth noting that scientists have identified teleconnections between the snow pack in certain regions and subsequent meteorological conditions in other regions (Rodell and Houser, 2004), although the timeframe is likely to be somewhat longer than the trial periods considered here.

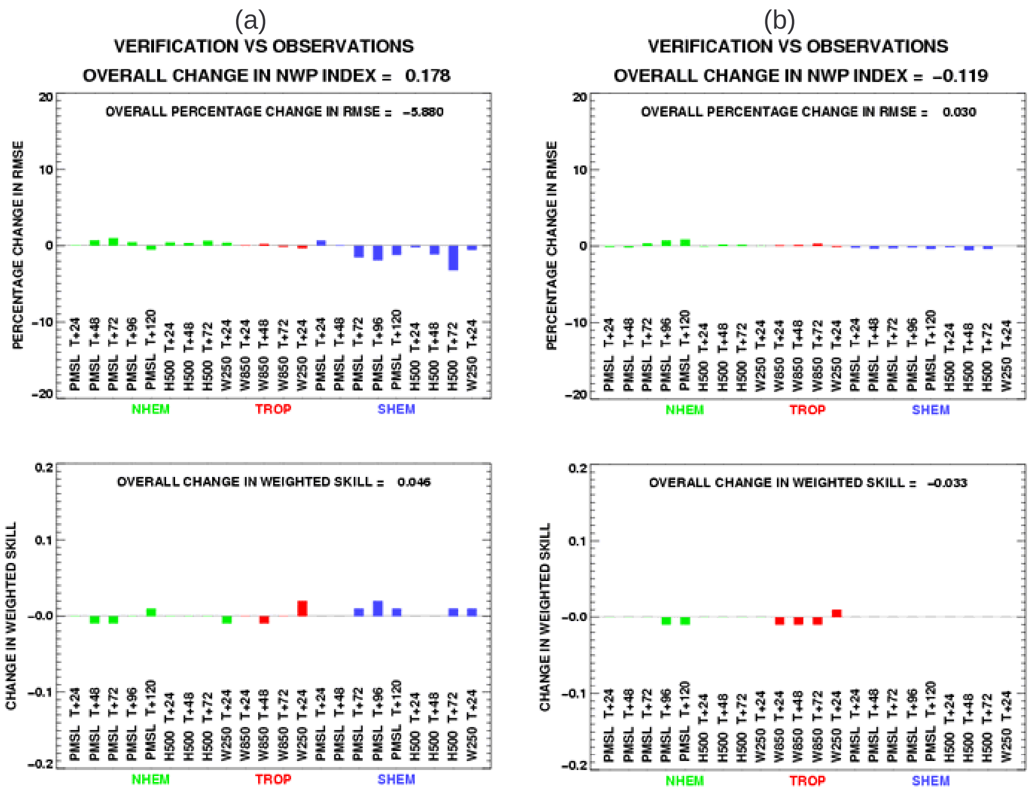

Figure 15. Impacts on forecast error and skill, verified against observations, for (a) the winter trial, and (b) the spring trial.

Regional verification has been performed for the main NH continental regions, since the snow analysis tends to affect different regions differently, depending on factors such as existing model biases, orographical characteristics, and typical weather patterns. The most noticeable changes are evident in Europe and North America, where the snow analysis behaves quite differently. In the winter trial, although snow was predominantly removed overall, there was more snow addition than removal in North America, and removal in Europe. In the spring trial there was net addition increasing throughout the period in both regions, but more so in North America.

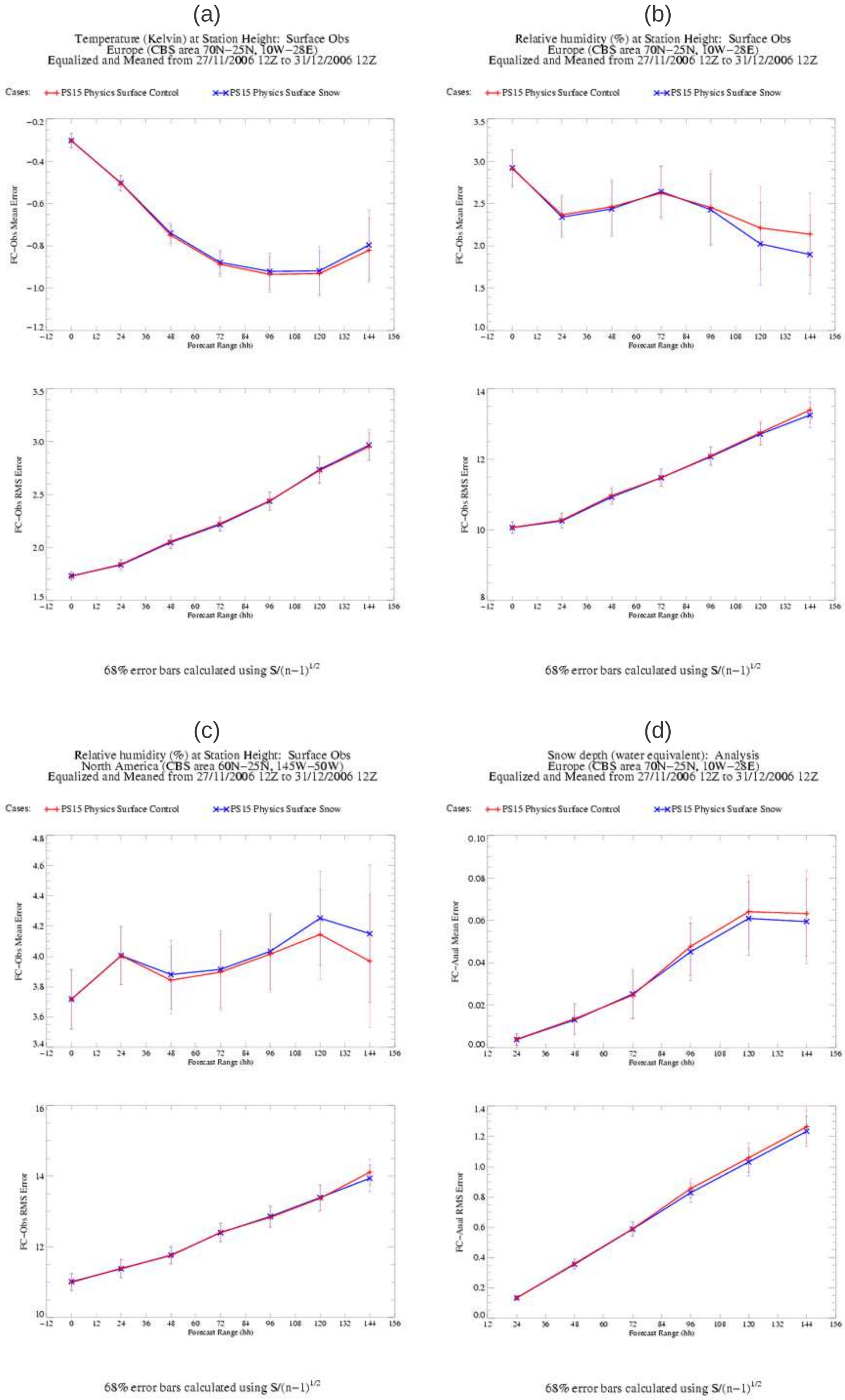

Figure 16. Impacts on surface variables during the December trial. Forecast mean (upper) and RMS (lower) error, verified against observations for (a) surface temperature over Europe, (b) surface relative humidity over Europe, and (c) surface relative humidity over North America, and verified against analysis for (d) snow depth over Europe. The trial run (with snow analysis) is shown in blue and the control run (with no snow analysis) is shown in red.

Though small, there is evidence of consistent improvements in surface and low level temperature and relative humidity (RH) forecasts in situations where snow is predominantly removed by the snow analysis. In the winter trial surface and lower level temperatures were generally slightly improved, with the most consistent improvements in Europe (see Figure 16(a)). Interestingly, surface relative humidity was improved for Europe but degraded for North America (Figure 16 (b) and (c)). This suggests that the repeated snow addition, seen in North America, and subsequent melting before the following daily snow analysis has degraded the surface RH forecast, by upsetting the surface hydrology. Improvements were seen in above surface RH, especially in North America, where the effects of the repeated snow melt are more remote.

In the spring trial changes were very small and mixed. Low level temperatures tended to be slightly improved, but not at the surface. This is consistent with the results of the winter trial, where surface temperatures could only be improved where snow was predominantly removed by the analysis. Rodell and Houser (2004) found similar benefit to forecast fields when removing snow. This scenario, which was typical of Europe in the December trial, also produced the only visible impact on snow depth forecasts, with a small improvement in mean and RMS error (Figure 16 (d)), verified against analyses.

5. Summary

A NH daily snow analysis, using NESDIS IMS snow cover data, has been developed and implemented in the operational global NWP model. This is the first introduction of observational snow data into the global model, and aims to improve the model representation of snow cover at analysis time. Global assimilation trials have been run during the two main snow-affected seasons for the NH: during December (2006) when snow is accumulating, and from March to May (2007) encompassing the majority of the snowmelt season. No significant impacts on forecast accuracy were expected and much of the validation focussed on the analysed snow field.

The effect on the NWP Index of introducing the snow analysis is largely neutral, with slightly positive impacts in the December trial, and slightly negative impacts in the spring trial. Throughout the December trial there was net snow removal by the analysis, with snow consistently being removed from Central Asia, and in the latter part of the trial, from Northern and Eastern Europe, where the UM has a tendency to build up snow cover prematurely. During the 3-month spring season trial there was a net addition of snow by the analysis, over increasingly large areas as the spring progressed. Large areas of snow cover were reinstated over North America and Eastern Europe, where the model had melted snow too early.

The changes made by the snow analysis generally verify well in qualitative terms, against other observational and analysed snow cover products, particularly the large-scale additions of snow made towards the end of the spring trial. In Europe, where SYNOP stations making use of snow reporting are sufficiently numerous, the number of model gridpoints in agreement with SYNOP reports of snow-covered ground increased when the snow analysis was used, in both seasons. This, along with qualitative comparisons of snow cover, gives clear evidence that the snow analysis has improved the analysed snow field, in terms of the presence or non-presence of snow.

Changes to all the components of the NWP Index were small, especially in the NH, but there is some evidence of improvements in surface and low level temperature and relative humidity forecasts. This was noted in situations where snow was predominantly removed by the snow analysis, with the most consistent improvement for Europe during the winter trial. Many of the changes made by the analysis were not retained, particularly in cases of snow addition. It is therefore unsurprising that positive impacts on forecast skill were not found where daily additions and subsequent melting of large areas of snow occurred. Future planned developments to the UM snow scheme physics are expected to help the retention of added snow. Further work to improve and develop the snow analysis is planned, and discussed in Section 6.

6. Future Work

One of the drawbacks noted in assimilating the IMS snow cover product is the potential time range of observational data comprising the IMS analysis, as discussed in section 4.2.3. Although it does not seem that forecast skill or mean fields are significantly affected by these data time delays, the consequences could be much more serious if the analysis was used by forecasters to determine where lying snow is present. A method is now being planned to mitigate the effects of a time delay in the IMS data. Information from the previous day's model background snow field will be used as a further constraint on the analysis system. For cases in which the UM has forecast a snowfall event well, and there is a significant time delay in the IMS data, the IMS data may be expected to compare better with the previous day's background snow field than the current one. Provided that the comparison with the previous day's background is good, it is reasonable to trust the UM representation of the snow event and make no change in the analysis. Used in this way this method would add an additional constraint to cases of snow removal (i.e. where IMS snow cover is zero, but the UM denotes snow) and reduce instances of incorrect snow removal by the analysis.

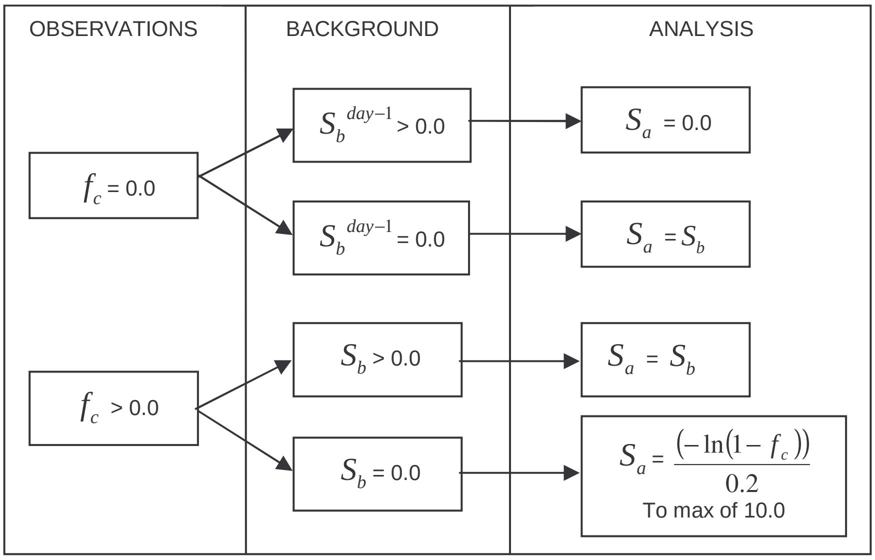

Figure 17. Schematic diagram showing how the upgraded snow analysis would work, where f_c = fractional cover, S_b = background snow amount and S_a = analysed snow amount.

In the longer term there are developments planned to the IMS product itself to tackle the time delay, and other data sources, such as the snow products from the Land Surface Analysis SAF, will become available for consideration. Helfrich *et al.* (2007) reports that there are plans to release a second IMS product each day over North America, to increase the timeliness of data in this region. There will also be available a file giving 'time of last observation' for the whole IMS grid, which will allow the data to be quality controlled based on their timeliness.

After some fine-scale analysis of some of the trial results, it emerged that there were some snow-free grid points to which snow should have been added by the analysis, but which were left unchanged. Further investigation revealed that the UM snow amount field often contains very small negative numbers instead of zero, which are treated as valid snow amounts by the analysis. Where the observed fractional cover is greater than zero, and the model background snow amount is zero, the analysis should add snow to the model at that grid point, however this does not happen if the model background snow amount is represented by a negative number. The result is that the snow analysis is not able to add snow at all the grid points it should. Snow removal is not affected and snow addition still validates well against observations, so the impact of the sub-optimal snow addition is not expected to be large. A correction will be tested for implementation at the first available opportunity for operational change.

Other plans for future developments of snow assimilation include making use of Southern Hemisphere snow cover observations, and assimilation of snow depth reports, from satellite and ground-based observations, for which an upgraded UM snow scheme is important.

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