443

ECMWF's global snow analysis: Assessment and revision based on satellite observations

Matthias Drusch, Drasko Vasiljevic
and Pedro Viterbo

Research Department

June 2004

Accepted for publication in J. Appl. Meteor.

For additional copies please contact

The Library
ECMWF
Shinfield Park
Reading, Berks RG2 9AX

library@ecmwf.int

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications.html

Abstract

Snow water equivalent and snow extent are key parameters for the Earth's energy and water budget. In this study, the current operational snow depth analysis (2-D spatial Cressman interpolation) at the European Centre for Medium-range Weather Forecasts (ECMWF), which relies on real-time observations of snow depth, the short range forecast and a snow depth climatology, is presented. The operational product is compared against satellite derived snow cover. It is found that the total area of grid boxes affected by snow is significantly larger in the analysis than in the NOAA / NESDIS (National Oceanic and Atmospheric Administration / National Environmental Satellite, Data and Information Service) snow extent product. The differences are persistent in time and space and cover the entire Northern Hemisphere. They comprise areas with intermittent and / or patchy snow cover, e.g. the Tibetan Plateau, the edges of snow fields and areas with a low density of observations, which are difficult to capture in the current operational analysis. We present a modified snow analysis, in which the operational NESDIS snow product is incorporated. The current and the revised analysis are compared to high resolution snow cover data sets derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and independent ground-based snow depth observations from the Meteorological Service of Canada (MSC). Using the NOAA / NESDIS snow extent data set in the operational analysis leads to a more realistic description of the actual snow extent.

1. Introduction

About 98 % of the global seasonal snow cover is located in the Northern Hemisphere (Armstrong and Brodzig 2001) with a mean maximum extent of nearly 50% of the land surface area (Robinson et al. 1993). In large areas, snow melt is a significant contribution to the surface water supply and the main cause of flooding. Variability in snow cover causes dramatic changes in surface albedo and consequently in the land surface energy budget. Therefore, global snow depth and snow extent are crucial parameters for the performance of numerical prediction models and for climate monitoring including re-analysis projects.

The current snow depth analysis of the European Centre for Medium-Range Weather Forecasts has been operational since 1987 with modifications made in 2001. It relies on in-situ observations, which are available in real-time, the 6 hour short range forecast of the Integrated Forecast System (IFS) and the snow climatology published by Foster and Davy (1988). During recent years, a number of global snow products derived from satellite remote sensing have been made available. For operational applications, the daily NOAA / NESDIS Northern Hemisphere snow cover product is of particular interest since it is produced in near real-time.

In order to quantify the potential of satellite remote sensing for the operational snow depth analysis, the ECMWF product is compared to the NOAA / NESDIS satellite product. Any comparison between model / analysis data and satellite derived products is limited by differences in spatial resolution. The analyzed snow water equivalent (SWE) on a Gaussian grid represents spectral T511 resolution (~ 0.35°), whereas the NESDIS snow extent is available with variable spatial resolution on 1024×1024 element grid on a polar stereographic projection. In order to bridge the differences caused by different spatial resolutions and projections both data sets are re-sampled to a regular 0.5° grid. Since the spatial resolution of the NESDIS snow extent product exceeds 0.5°, it is converted into a fractional snow cover data set. The different snow data sets used in this study (including ECMWF's operational analysis) are introduced in section 2; the comparison between the snow depth analysis and NOAA / NESDIS snow extent is presented in section 3.

In section 4 the revised version of the snow analysis, which includes the NOAA / NESDIS snow extent product, is described. In order to evaluate the current operational analysis and its revised version with respect to the snow extent, comparisons with MODIS derived snow cover are shown in section 5. An evaluation of the revised and operational analyses against independent ground-based measurements is performed using observations from the MSC (Meteorological Service of Canada) data set. In the discussion and conclusions section, the impact of the revised analysis on the current IFS is analyzed.

2. Data sets

2.1 ECMWF operational snow analysis

The number of reviewed publications regarding operational global snow depth analyses is small. A detailed description and validation of the analysis of the Canadian Meteorological Centre (CMC) are given in Brasnett (1999). The analysis method used by CMC is similar to the scheme presented in this paper. The current ECMWF snow depth analysis has been operational since 1987 and was modified in 2001. It is a 2-D sequential analysis performed every six hours using a successive correction method. The first guess or background field for the snow depth S^b [m] is estimated from the 6 hour model forecast of snow water equivalent W_s^b [m] and snow density ρ_s^b [kg m^{-3}]:

$$S^b = \frac{1000 \times W_s^b}{\rho_s^b} \quad [\mathrm{m}] \tag{1}$$

In the Integrated Forecast System the snow mass budget reads as:

$$\rho_w \frac{\partial W_s}{\partial t} = F + c_{snow}(E_{snow} - M_{snow}) \quad [\mathrm{m}] \tag{2}$$

with ρ_w the density of water [kg m^{-3}], F snowfall [kg m^{-2}s^{-1}], c_{snow} fractional snow cover and E_{snow} and M_{snow} snow evaporation and melting [kg m^{-2}s^{-1}], respectively. The quantities in equation (2) represent the entire grid square. For more details on the model and the first guess the reader is referred to http://www.ecmwf.int/research/ifs.

The snow depth analysis S^a is performed using a Cressman spatial interpolation (e.g. Daley 1991):

$$S^a = S^b + \frac{\sum_{n=1}^{N} w_n \left(S_n^o - S^{b'} \right)}{\sum_{n=1}^{N} w_n} \tag{3}$$

where S^o are the snow depth observations from N SYNOP reports and $S^{b'}$ is the background field at the observation point. w_n is the weighting function defined as:

$$w = H(r)v(h) \tag{4}$$

with $H(r)$ the weighting function dependent on the horizontal distance between observation and grid point and $v(h)$ a weighting function depending on the vertical displacement h (model grid point height minus observation height):

$$H(r) = \max\left(\frac{r_{\max}^2 - r^2}{r_{\max}^2 + r^2}, 0\right) \tag{5}$$

and

$$v(h) = \begin{cases} 1 & \text{if} \quad 0 < h \\ \dfrac{h_{\max}^2 - h^2}{h_{\max}^2 + h^2} & \text{if} \quad -h_{\max} < h < 0 \\ 0 & \text{if} \quad h < -h_{\max} \end{cases} \tag{6}$$

Model orography is derived from 30'' data (GTOPO30) by averaging. Source and target grids are overlaid, and weighted averages are computed by considering the fractions of source grid areas that cover the target grid square. The distances r_{max} and h_{max} are set to 250 km and 300 m, respectively, in the current operational analysis and the ERA40 (40-year ECMWF Re-Analysis) re-analysis. It should be noted that these values should ideally depend on model resolution and the density of observations. However, an r_{max} value of 250 km corresponds well with the e-folding distance of 120 km for the horizontal correlation function used by CMC in their global snow depth analysis. The weighting function *v(h)* ensures that snow depth reported from stations above the model grid point height is reduced to enable the analysis to represent snow covered mountains and snow free valleys. A correction for observations obtained at stations below the model grid point height is not applied. Brasnett (1999) shows that a substantial negative bias in the difference between station height and mean topography height at 0.33° resolution exists. This bias may result in too low SWE in the analysis in mountainous areas.

In addition to the preliminary quality control in the observational data base, a quality control and consistency check is performed following the Cressman interpolation analysis:

i) If the two meter air temperature (T_{2m}) is below 8° C, only snow depth observations less than 140 cm are allowed.

ii) This limit is reduced to 70 cm if T_{2m} exceeds 8° C.

iii) Snow depth analysis is limited to 140 cm.

iv) Snow depth observations are rejected if they differ by more than 50 cm from the background field.

v) When only one snow depth observation is available within the influence radius r_{max}, the snow depth increments are set to 0.

vi) Snow depth is set to 0 if below 0.04 cm.

vii) Snow depth increments are set to 0 when larger than (160 – 16 T_{2m}) mm (T_{2m} expressed in °C).

viii) If there is no snow in the background and in more than half of the observations within a circle of radius r_{max}, the snow depth increment is kept to 0.

In the quality checks the two meter air temperature T_{2m} refers to the background field. The tests outlined above reflect the large representativeness error of snow observations, but are purely empirical and based on a number of analysis experiments with different thresholds. Test no. 5 seems to be the strictest since it removes isolated observations. In combination with test no. 6, it prevents grid boxes along the snow edge from being updated using the information from a single observation, which might be more than 200 km away. Test no. 8, often called 'buddy checking', ensures that observations are compared against its neighbours within the radius r_{max}. In order to compensate for errors in the background in areas with no snow observations, a relaxation towards climatology S^{clim} is added:

$$S^a = (1-\alpha)S^a + \alpha S^{c\lim} \tag{7}$$

The snow depth climatology is taken from Foster and Davy (1988) and the relaxation coefficient α is set to 0.02, corresponding to a time scale of 12.5 days. The final SWE product is then calculated using equation (1). Areas of permanent ice cover are set to an arbitrarily high value of 10000 mm snow water equivalent. The operational SWE analysis product (OA) is derived on the Gaussian grid corresponding to the T511 spectral resolution, which is equivalent to a quasi-uniform 40 km grid point resolution. It is based on ~ 1500 real-time in-situ observations of snow depth, which are available every 24 hours. The ERA40 SWE product (E4) was derived at T159 resolution (equivalent to 125 km point resolution). Both analysis products are re-sampled to 0.5° resolution using a bi-linear interpolation scheme for the purpose of the assessment discussed in this paper.

2.2 IMS NOAA / NESDIS real-time snow cover

The Interactive Multisensor Snow and Ice Mapping System (IMS) is a workstation based application, which allows the analyst to process the various snow cover data in a manner timely enough to release a real-time daily product (Ramsay 1998). Northern Hemisphere snow cover maps are primarily based on satellite imagery comprised of time sequenced imagery from geostationary satellites including the Geostationary Operational Environmental Satellites (GOES), the Meteorological Satellites (METEOSAT), polar orbiting satellites including the Polar-orbiting Operational Environmental Satellites (POES) and imagery from the Special Sensor Microwave/Imager (SSM/I) and the Advanced Very High Resolution Radiometer (AVHRR). In addition, the analyst can rely on station data and the previous day's analysis. The different products are analyzed in approximately one hour's time and mapped into a 1024×1024 element polar-stereographic projection. Weekly charts were produced manually from 1966 to 1999. The daily IMS NOAA / NESDIS product has been available from 1997. For the comparisons with the ECMWF product and the MODIS data sets, the NESDIS product is aggregated to a regular latitude / longitude grid with a 0.5° resolution. Fractional snow cover for the 0.5° grid is calculated from the original 'snow free/100 % snow covered' binary information. In the revised snow analysis, the NOAA / NESDIS product is used at its original resolution.

2.3 MODIS Snow Cover

MODIS is operated on the NASA Earth Observing System (EOS) Aqua and Terra platforms in a sun-synchronous circular near-polar orbit. The larger number of bands (36 bands from .4 to 14 μm) and the higher spatial resolution (250 m, 500m, or 1000m) of the MODIS observations should result in a better snow cover detection under cloud free conditions compared to the NOAA / NESDIS product. A detailed description of the satellites and the instruments can be found under (http://modis.gsfc.nasa.gov/about/specs.html). The snow-mapping algorithm is based on the Normalized Difference Snow Index (NDSI) (Hall et al. 2001):

NDSI = (Band4 – Band6) /(Band4 + Band6).

Since snow is characterized by high reflectivity in the visible spectral region (Band 4 (545-565 nm)) and high absorption in the short wave infra red (Band 6 (1628-1652)) it can be distinguished from many other surface types. In general, most clouds show high reflectivities in the visible and the near infra red channels (Rossow and Garder 1993). However, optically thin cirrus clouds can be a problem in the snow retrieval. Generally, areas covered by more than ~50 % snow exhibit NDSI values exceeding 0.4. In addition, Band 2 (841-876 nm) reflectances are used to mask water.

For forest areas NDSI values below the 0.4 threshold can be obtained. In order to get reliable snow covers for forested regions the Normalized Difference Vegetation Index (NDVI) is calculated from Band 1 (620-670 nm) and Band 2. Following Klein et al. (1998), forested pixels are classified snow covered if NDSI and NDVI values are within an irregular polygon as determined from canopy-reflectance modelling. The results presented in this study are based on the Daily L3 Global 0.05 Deg Climate Modelling Grid (CMG) dataset (version 3). Based on a 0.05° land mask, derived from the University of Maryland 1-km global land data set, CMG cells are classified as land whenever the percentage of land cover exceeds 12%. For the daily CMG data set a binning algorithm maps the 500 m resolution snow and cloud cover product into corresponding cells of 0.05° resolution. Snow cover (SC) and cloud cover are computed based on the total number of observations of a class (snow and land) and the total number of land observations. The land / sea classification of the observations is performed in the snow detection algorithm using the MODIS land / water mask. The minimum snow cover in the CMG data set is 40 %. Grid boxes containing less than 40 % snow cover are labelled snow free. The confidence index (CI) is defined as the number of cloud free land pixels divided by the total number of land pixels. For further details on the snow mapping algorithm, the reader is referred to Hall et al. (2001).

For the comparisons with the snow analysis and the real-time daily NOAA / NESDIS product, the MODIS data set is aggregated to 0.5° resolution. To take into account the uncertainty in the snow cover estimates due to clouds, the confidence index is incorporated in the aggregation procedure. Grid boxes defined as snow covered with fractional values ranging from 40% to 100% are multiplied by the corresponding confidence index. The resulting snow cover value represents the minimal fractional snow cover at 0.05° resolution. For snow free grid boxes at 0.05° resolution, (1 - CI) was added to represent the maximum fractional snow cover. The resulting values were averaged to 0.5° resolution. The frequency distribution of snow cover is slightly changed through this aggregation procedure since the number of snow free grid boxes (0%) and completely snow covered grid boxes (100%) is reduced. In parallel, the aggregation from 0.05° to 0.5° was performed using the nearest neighbour technique, which conserves the normalized frequency distribution. The resulting global snow cover maps at 0.5° do not show significant differences when compared to the maps derived from snow cover and confidence index.

2.4 MSC Snow Depth Observations

Operational snow analyses at ECMWF have to rely on real-time data. Observations, which are not exchanged in real-time through the Global Telecommunication System (GTS), are an independent source of information for calibration and validation studies. The collection and quality check of independent global snow observations is time consuming and can not be done operationally at ECMWF. For this study, DLY04 data from the Canadian snow depth database are used to evaluate the operational and the revised analyses. DLY04 data comprise data that is keypunched from either the volunteer climate observing form or from the Summary of the Climatological Day from observing stations at airports (Brown, personal communication).

The data are quality controlled and processed at MSC (Brown and Braaten 1998). The station network, which comprises several hundred stations, concentrates in southern latitudes and has a low elevation bias in mountainous areas. Although the snow depth observations are point measurements and do not represent the surrounding terrain and vegetation cover, it was found that the observations exhibit realistic temporal and spatial variability (Brown and Braaten 1998, Brown and Goodison 1996). For more details on the snow data the reader is referred to Brown and Braaten (1998).

3. Assessment of the analysis of snow depth observations

NOAA / NESDIS snow cover and the SWE OA and E4 products are compared for a two year period comprising 2001 and 2002 based on corresponding daily 0.5° data sets. Equations (3) to (6) indicate that analyzed SWE is an effective value, which characterizes the grid box at fractional snow cover of 100%. Fractional snow cover can not be analyzed separately from sparsely distributed snow depth observations. This is a limitation in any comparison with satellite derived snow extent. In this study, satellite derived snow extent is calculated from the area of a grid box multiplied by its fractional snow cover, while ECMWF analyzed snow extent is based on the area of grid boxes containing snow water equivalent larger than zero.

From the data sets presented in this study, the most accurate value for Northern Hemispheric snow extent can be calculated from area weighted NOAA / NESDIS fractional snow cover at 0.5° resolution. This snow extent is shown as the thick solid line in Fig. 1. Values are normalized with the total land area. The shaded area in Fig. 1 depicts the range between the area of grid boxes affected by snow (the area of grid boxes with fractional snow cover larger than zero) and the area of grid boxes with 100% snow cover for the NOAA / NESDIS data set.

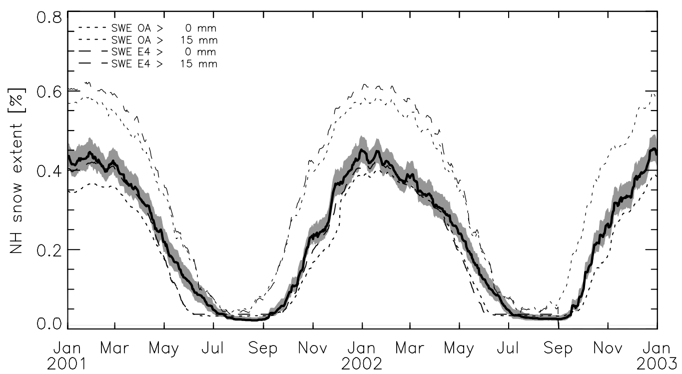

Figure 1 Temporal evolution of Northern Hemispheric snow extent based on 0.5° resolution data. The shaded area represents NESDIS snow extent for fractional snow cover larger than 0% and less equal 100%. ECMWF snow extent is shown as a function of snow water equivalent (SWE).

The relationships between fractional snow cover and snow depth or SWE are not generally well known. Ideally, a reliable global relationship between analyzed SWE and remotely sensed fractional snow cover should depend on a large number of parameters, e.g. land use, fractional vegetation cover, orography, model resolution, observation density, sensor resolution, wavelength and viewing angle. Consequently, the ECMWF analyzed snow extent defined through SWE > 0 mm (OA and E4) and the area of grid boxes characterized by fractional snow cover exceeding 0% (NOAA / NESDIS) are the only quantities which can be compared directly. In the ideal case of a perfect analysis and a perfect sensor, which is not influenced by clouds and which is able to detect very low fractional snow cover, the number and area of grid boxes affected by snow should be identical. Figure 1 shows that the E4 and OA data sets show systematically higher values for the area of snow affected grid boxes when compared to the NOAA / NESDIS data set. The difference between E4 and OA is due to the different model resolutions of 1.125° and 0.35°, respectively, and the interpolation of the original resolution to 0.5°. During the melting period from the beginning of May onwards, the differences between NOAA / NESDIS and both analysis products decreases and the rate of depletion in the ECMWF analyses is larger than the observations indicate. This pattern in SWE in the analyses is primarily due to the hydrological model in the Integrated Forecast System. In a study based on data from the Mackenzie River basin Betts et al. (2003) found that the model snow melts too soon, which is partly compensated in data assimilation by positive snow increments.

It was found in previous studies (e.g. Hall et al. 2001) that fractional snow cover below 40 to 50% (at 500 m resolution) may not be correctly detected by algorithms based on visible and infrared measurements. Therefore, it can be assumed that the area of grid boxes affected by snow is underestimated by the NOAA / NESDIS product. However, the quality check in the analysis (criteria (5), (6), and (8)) also lead to an underestimation of grid boxes characterized by low SWE values. In addition, the accuracy of the analysis with respect to fractional snow cover and consequently low SWE depends on the density and distribution of observations within a grid box. There needs to be at least two observations to represent fractional snow cover with an accuracy of 50%. In addition, quality check criterion (8) limits the analysis to fractional snow cover exceeding 50% independently from the number of observations if the background field contains no snow. Given the fact that the model melts snow too fast, this criterion alone leads to a negative bias in the melting season.

Figure 2 shows the frequency of occurrence of cases where the NOAA / NESDIS product indicates snow free grid boxes and the ECMWF analysis had SWE values exceeding 0. The three images are based on the daily data for March, May, and December 2002, respectively. It can be seen that the operational ECMWF analysis overestimates snow cover systematically over the globe. The differences are most pronounced at the snow edge. The southern snow edge moves northward during the season as snow melt starts (Fig. 2a and b). One particular area of interest in March is a band stretching from the South-eastern part of the Baltic Sea to the Caspian Sea, an area adequately covered with observations. However, since SYNOP stations are not required to report a snow depth of zero, the spatial interpolation in the OA produces snow in this area. The NOAA / NESDIS data and the absence of reports in the operational data base indicate snow free conditions. In addition, it is interesting to note that even in areas with dense observation networks, e.g. Central and Northern Europe, the differences in snow extent can be significant. In December, the North American region in between 40 and 50 latitude exhibits large differences between NOAA / NESDIS snow cover and the operational analysis. The Tibetan Plateau is another area where the operational ECMWF analysis shows systematically larger snow extents than the NESDIS data set in March, May, and December. According to Armstrong and Brodzig (2001) the Plateau is characterized by intermittent and patchy snow cover. Consequently, the absence of reliable real-time observations and a questionable climatology make this area extremely difficult to analyze by the ECMWF scheme.

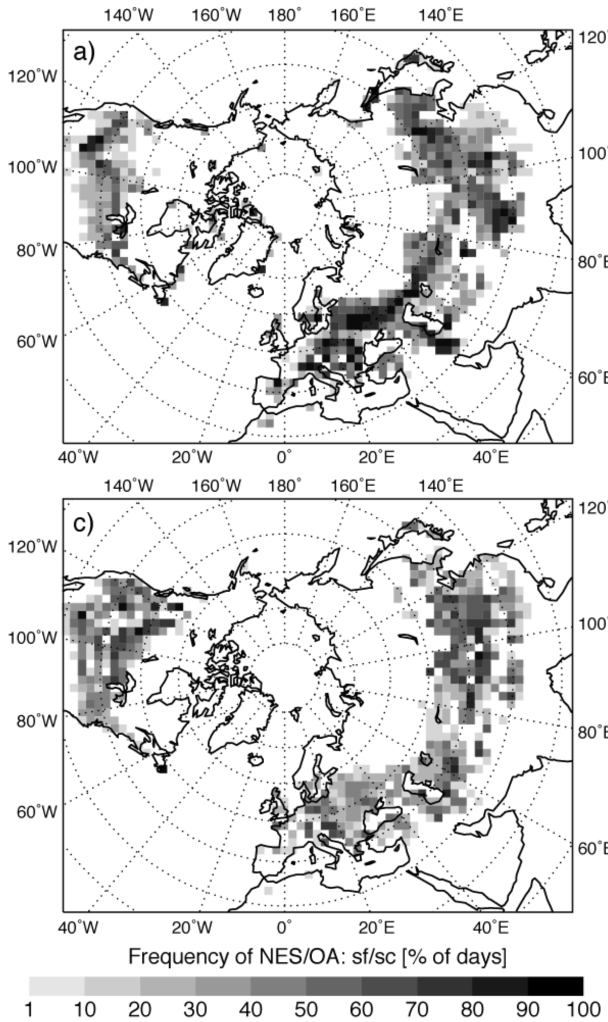

Figure 2 Frequency of occurrence of snow free (sf) NESDIS data and a snow water equivalent larger zero (sc) for March (a), May (b), and December (c) 2002. The number of days for every grid box is normalized with the total number of day available (29, 31, and 29 in March, May, and December, respectively).

4. Towards a revision of the snow analysis using NOAA / NESDIS snow extent

Different ways exist to incorporate NOAA / NESDIS snow cover in a snow depth analysis. NCEP's (National Centers for Environmental Prediction) Environmental Modeling Center (EMC) uses the NESDIS snow cover product to quality control the snow depth analysis, which is based on the 47 km daily Air Force analysis. Both data sets are interpolated to 0.5° resolution. For the interpolated NESDIS data set, a 50% threshold is applied to discriminate between snow and snow free grid boxes. In cases where NESDIS indicates no snow, the snow depth in the analysis is set to zero. Snow free grid points in the EMC analysis, for which NESDIS exhibits snow cover, are set to an arbitrary value of 2.5 mm SWE. For more details the reader is referred to http://www.emc.ncep.noaa.gov/gmb/pan/snow.html. The EMC quality check as outlined above assumes that the satellite product is true and the analysis is false. The revised ECMWF snow analysis described in the following section ensures a more sophisticated treatment of uncertainties, which arise through fractional snow cover and its representation in observations and satellite data sets.

In areas where the OA analysis has no snow and the satellite product exhibits snow, an arbitrary value has to be assigned since a snow cover product contains no information on snow depth. From the remote sensing point of view, one could argue that this snow depth value has to be larger than 20 mm, which is the threshold for snow detection in the NOAA data set (Robinson et al. 1993; Brown 2000). From the atmospheric modeler's point of view, the value should be higher. Since the update in the OA snow analysis through the NOAA / NESDIS product is performed once a day, it has to be ensured that the snow introduced does not melt within the next hours. Anderson (1976) reported a reduction of ~ 90 mm SWE within a 2.5 day period for Danville, VT. On the other hand, too high snow depth values may have a significant impact on the local terrestrial water balance and result in an overestimation of runoff. For the revised snow analysis, a snow depth of 100 mm was chosen according to the results by Anderson (1976). Since the horizontal resolution of the Integrated Forecast System (i) depends on the application (re-analysis, operational forecast, research mode) and (ii) the operational horizontal resolution increases periodically as part of the development of the forecasting systems, the NOAA / NESDIS snow cover product is incorporated at its original resolution. Only snow free IFS model grid boxes, for which 100% snow cover is obtained from the NOAA / NESDIS product, are updated with a snow depth value of 100 mm. This update is performed at the very beginning of the analysis in the first guess field Sb, since the accuracy of the satellite derived snow depth of 100 mm is supposed to be much lower than the accuracy of the actual observations used in equation (3).

Grid points in the NOAA / NESDIS snow product which are snow free, are incorporated as regular observations SO in equation (3) with a snow depth value of 0 mm at the geographic position in the corresponding polar stereographic grid. The corresponding height in equation (6) is based on IFS orography, which was interpolated and transformed to the 1024 ´ 1024 element grid in polar stereographic projection. For the results presented in this study, the satellite data were introduced at 12 UTC. Therefore, ground-based measurements and satellite observations get a similar weight in the analysis. Low fractional snow cover, which may be labeled snow free in the NOAA / NESDIS product but is captured through ground-based observations, is treated in a consistent way. The relaxation towards climatology (equation. 7) is omitted in the revised analysis.

The different satellite data sets and the corresponding operational analysis products for March 1, 2002 are compared in Figure 3. The OA product (Fig. 3a) shows almost homogeneous snow water equivalent for large parts of North America, Central and Eastern Europe and Asia. Even the Northeastern part of Spain, the South of France and large parts of Italy are snow covered. The NOAA / NESDIS product for this particular day reveals very different patterns. Snow cover is patchier for large parts in the Western USA and large parts of Asia, especially the Tibetan Plateau (Fig. 3b). The Central US and large parts of Eastern Europe are snow free and snow cover in Europe is limited to mountain areas. Incorporating the NOAA / NESDIS snow cover analysis in the operational Cressman snow depth analysis changes the output significantly. Small scale features from the NOAA / NESDIS analysis can now be found in the OA product. Snow in South and West Europe is limited to mountain regions and the Western US and the Tibetan Plateau are characterized by patchy snow fields (Fig. 3c). The snow free area in Eastern Europe (30° E, 50° N) in the NOAA / NESDIS product can be identified in the updated analysis. The corresponding MODIS image supports the results of the updated Cressman analysis for the cloud free regions. From Fig. 3d it can be seen that large parts of the Tibetan Plateau, Eastern Europe, and the US East Coast are snow free, which corroborates the validity of the revised analysis.

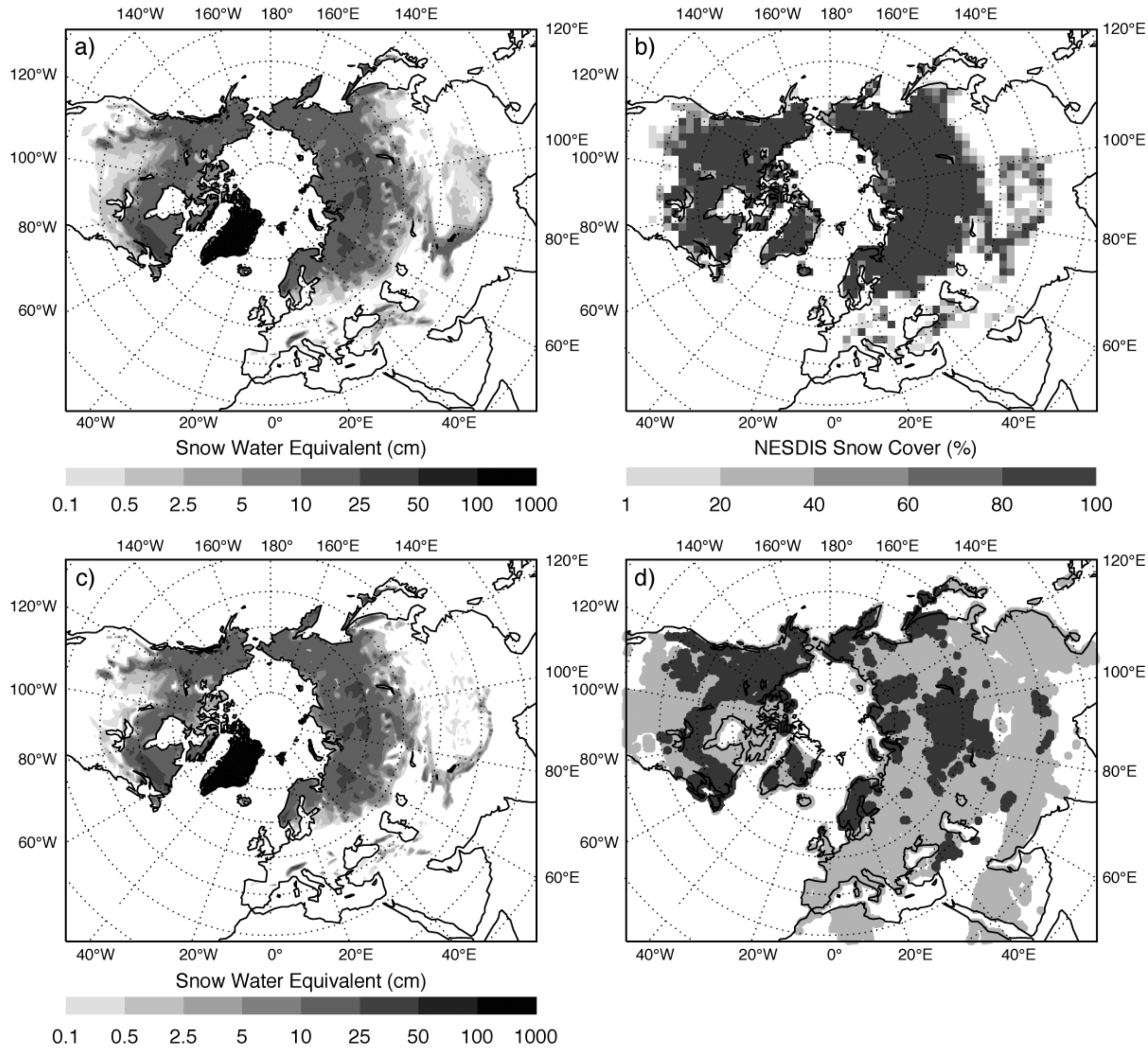

Figure 3 Northern Hemispheric snow parameters for March 1, 2002: (a) Snow water equivalent as analyzed by the operational ECMWF system. (b) NOAA / NESDIS snow extent re-sampled to 0.5° resolution. (c) Revised ECMWF analysis using the NOAA / NESDIS product. (d) MODIS derived snow extent (white: snow free; light grey: clouds; dark grey: snow cover larger 50 %).

It is likely that the large scale impact of the satellite data on the analysis could be achieved through the EMC quality check as well. The advantage of the revised ECMWF analysis is most significant on smaller scales and can be discussed using the Central US area in Figs. 3 as an example. The MODIS snow cover product indicates cloud cover for almost the entire area. In the NOAA / NESDIS product, large parts between 90° W and 105° W are labelled snow free. In contrast, the operational analysis indicates large scale SWE values up to 10 mm. Since the accuracy of the NESDIS product is reduced due to complete cloud coverage, it is desirable to take into account the information from the first guess (i.e. the short range model forecast) and ground-based observations. The revised analysis exhibits a reasonable blend of information with large parts of the Central US being snow free. A narrow band of snow stretching in the East-West direction can partly be found in the NOAA / NESDIS product. However, a major contribution in the revised analysis for this area originates from the first guess (not shown).

5. Evaluation

A direct comparison between the revised analysis after one cycle and the operational analysis for March 1, 2002 is shown in Figs. 4a, b. It can be seen that the entire range of snow water equivalent values is influenced by the satellite-based NOAA / NESDIS data set (Fig. 4a). However, the most significant changes occur below values of 400 mm and in general the revised analysis has less SWE than the OA; the largest number of grid boxes influenced by the satellite data can be found below 100 mm SWE. A more detailed description of the differences between OA and revised analysis is presented in Fig. 4b. Approximately 27.000 grid boxes were changed by an absolute amount of less than 10 mm SWE. These changes primarily occur in the range of 0 to 500 mm SWE. Negative differences below 10 mm absolute (13,169 cases) are almost as frequent as positive differences below 10 mm (13,415 cases). For higher changes the frequency distribution is shifted towards positive differences. Consequently, the revised analysis contains significantly less snow than the OA product. The mean difference per 0.5° grid box between the OA and the revised analysis is 8.6 mm SWE, the total sum of changes is 291,268 mm SWE. It can be concluded from the results shown in Fig. 4a, b that the method proposed in this study leads to significantly different results from those of EMC's quality check, in which the NOAA / NESDIS data set is assumed to be true.

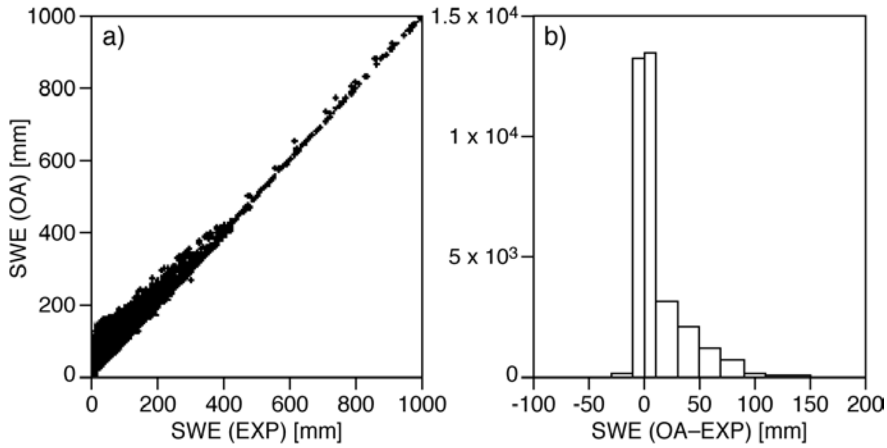

Figure 4. Snow water equivalent SWE as analyzed in the operational analysis (OA) and the revised analysis (EXP) using the NOAA / NESDIS data set for March, 1, 2002: (a) absolute values, (b) frequency distribution of the differences between OA and EXP.

In order to evaluate the impact of the NESDIS data set on the analysis, the MODIS snow cover product is used in this study. The data set itself and the aggregation method are presented in section 2c. Again, the frequencies of occurrence of cases where the MODIS derived snow cover product indicates snow free grid boxes and the analysis is characterized by SWE exceeding zero mm are compared. For both months, March and May 2002 (Fig. 5), the spatial patterns are very similar to those obtained from the NESDIS data comparison presented in Fig. 2. In March 2002, the areas characterized by differences in frequency of snow occurrence are almost identical to those obtained through the NESDIS – OA comparison. Even small scale patterns, e.g. differences in Ireland, Scotland and South Sweden, are present in both data set comparisons (Figs. 2a and 5a). The May comparison (Figs. 2b and 5b) reveals similar differences for most areas of the world. Differences between the OA comparisons with MODIS and NESDIS can be found for Alaska and Northwestern Canada, where the NESDIS data set exhibits larger snow extents than the MODIS data. When the revised analysis is compared with the MODIS data for March 2002, the structures discussed in Figs. 2a and 5a change significantly. In general, the pattern of snow free MODIS scenes, which coincide with analyzed snow depths larger than zero, is patchy. Large scale structures of differences between the analysis and the satellite product such as the band stretching from the Baltic Sea towards the Caspian Sea, or snow covered areas in South Sweden, Italy and the Southern-central US, as shown in Figs. 2a and 5a, are removed through the use of the NOAA / NESDIS data in the revised analysis (Fig. 5c). For May 2002, the effect of the NOAA / NESDIS snow extent analysis on the revised snow depth analysis is not as pronounced as in March (Fig. 5d). Again, the overall pattern of differences is patchier and the frequency of occurrence in general is reduced. The most significant improvement can be found in the Baltic Sea area.

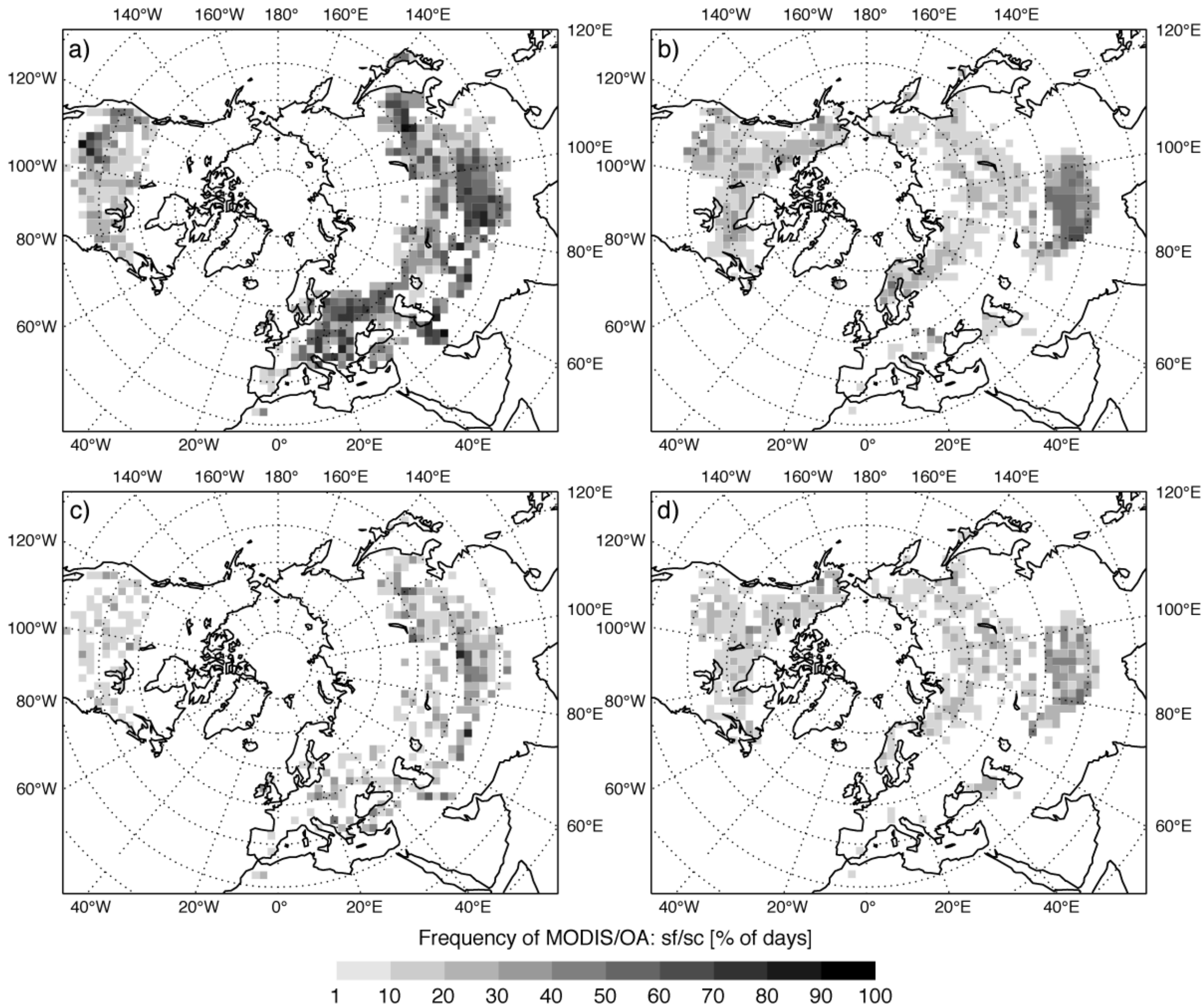

Figure 5. Frequency of occurrence of snow free MODIS data (fractional snow cover below 50 %) and a OA snow water equivalent larger zero for March (a) and May (b). The number of days for every grid box is normalized with the total number of day available (17 and 31 in March and May, respectively). Figures (c) and (d) show the corresponding images for the revised analysis for March and May, respectively.

Due to the lack of independent observations, it is difficult to validate the revised and the operational snow depth analyses on the global scale. However, for this study MSC daily snow depth observations as described in section 2.d are analyzed for March, May, and December 2002. For the evaluation of the impact of the NOAA / NESDIS snow extent, the Heidke Skill Score (HSS) is computed from a two class contingency table. Following Heidke (1926) the HSS for finite sample sizes can be written as:

$$HSS = (N_{sc/sc} + n_{sf/sf} - E)/(N - E) \tag{8}$$

and

$$E = \left(\left(n_{sc/sc} + n_{sf/sf}\right)\left(n_{sc/sc} + n_{sf/sc}\right) + \left(n_{sf/sc} + n_{sc/sf}\right)\left(n_{sf/sf} + n_{sc/sf}\right)\right)/N \tag{9}$$

$$N = n_{sc/sc} + n_{sf/sf} + n_{sc/sf} + n_{sf/sc} \tag{10}$$

with $n_{sc/sc}$ ($n_{sf/sf}$) the number of cases with snow (no snow) at an individual station and at the corresponding analysis grid point. $n_{sc/sf}$ and $n_{sf/sc}$ are the numbers of cases where the analysis had a SWE larger 0 mm and the station was snow free and vice versa. N is the number of realizations and E is an estimate of the expected number of correct random forecasts. A perfect analysis would result in a HSS of 1 while two randomly generated data sets would be characterized by a HSS of 0. If there is perfect reverse reliability, that is, the analysis shows snow wherever the observations indicate no snow and vice versa, the HSS would be -1 if both classes (snow and no snow) are equally likely (von Storch and Zwiers 1999).

The Heidke skill scores for March, May, and December 2002 are shown as time series in Fig. 6. For every day, the HSS is computed based on the MSC observations and the corresponding 0.5° grid boxes of the 12 UTC analyses. The highest skills of the operational analysis are obtained for March, when Southern Canada is characterized by fairly homogeneous snow cover, and towards the end of May, when the snow edge is moving northward. For both periods the differences between the operational analyses and the NOAA / NESDIS product are comparably small for this particular area (Fig. 2a, b). In December, the operational analyses are characterized by HSS values around 0. This fact might be explained by intermittent and / or patchy snow cover, which would be well represented in the observations and the NOAA / NESDIS (Fig. 2c) product but not in the operational analyses. The skill of the revised analysis is systematically higher when compared to the skill of the operational analysis (Fig. 6). For the second half of May the pattern changes and the operational analyses exhibit higher skills. However, due to the snow melt during this period, the number of correctly analyzed grid boxes ($n_{sf/sf}$ and $n_{sc/sc}$) is very high and exceeds the number of incorrectly analyzed grid boxes ($n_{\mathrm{sf/sc}}$ and $n_{\mathrm{sc/sf}}$) by a factor of 12 in both analyses.

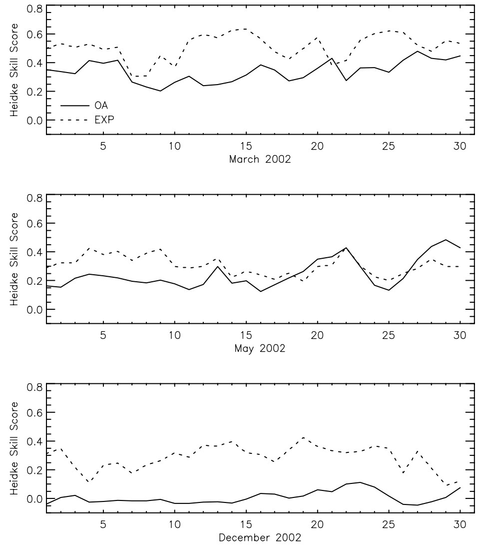

Figure 6 Heidke skill scores (HSS) based on 2 class contingency tables (snow / no snow) for MSC observations and analyses (operational analysis OA: solid line, revised analysis EXP: dashed line).

6. Discussion and conclusions

A well-posed analysis is a better estimate of the true state than either the background (a-priori) information or the observation data sets available. Consequently, the operational snow depth analysis is a useful product in itself as a comprehensive diagnostic part of the cryosphere. Analysis or re-analysis products are used for scientific applications comprising the development of parameterizations, retrieval algorithms and calibration/ validation studies. For numerical modeling applications and weather forecasting, the analysis products are used as the initial state and can also be used for quality checks for other observations.

The results presented in the previous section clearly show that the operationally analyzed snow extent, as defined through grid boxes containing SWE larger than zero, is significantly larger than the corresponding satellite derived NOAA / NESDIS product. Cloud cover and irregular updates of the satellite product will introduce errors. However, the analysis of MODIS high resolution data, which contain a cloud mask and a confidence index for the fractional snow cover retrieval, leads to the same conclusion. Equation (5) shows that snow extent in the spatial analysis depends on the maximum radius of influence. A value of 250 km was found to produce reasonable SWE maps for various horizontal model resolutions and a spatially varying density of observations. However, for patchy and intermittent snow cover and at the edges of snow fields the spatial interpolation with a maximum radius of influence of 250 km will produce persistent areas with low SWE values, which are not realistic. The snow climatology by Foster and Davy (1988) is not very reliable in remote areas and does not capture intermittent or patchy snow cover; in addition, relaxation to climatology artificially reduces interannual variability. In order to resolve local effects and provide an accurate snow field for a wide range of scientific applications, it would desirable to improve the operational analysis using satellite data.

In this study, it is demonstrated that satellite derived data sets have the potential to correct errors in the operational analysis. Incorporating the high resolution information leads to a more realistic snow extent. The method presented uses the satellite derived snow cover product at its original resolution. Consequently, the analysis scheme can cope with different horizontal model resolutions and with high resolution satellite data sets, which may become available in the future. The maximum radius of influence in the Cressman analysis was kept at 250 km in order to avoid patchy snow fields in remote areas with low observation densities, which are best characterized by complete snow cover.

An improved snow analysis will not automatically result in an improved weather forecast. In contrast, the land surface module of the IFS is a well calibrated system with respect to the analyzed geophysical parameters. Consequently, the impact of the revised snow analysis including the NOAA / NESDIS data on the forecast quality has to be quantified. In the Centre's Integrated Forecast System fractional snow cover c_{snow} is computed from the analyzed SWE W_s following:

$$c_{snow} = \min\left(1, \frac{W_s}{W_{cr}}\right) \tag{11}$$

with W_{cr} equal 0.015 m. As already stated earlier, SWE in the analysis and the snow mass budget as given through equation (2) is an effective value representing the entire grid box. The snow energy budget in the physical model relies on snow depth D_s, which represents the snow covered part of a grid box only and is calculated after:

$$D_s = \frac{\rho_w}{\rho_s} \frac{W_s}{c_{snow}} \tag{12}$$

with ρ_w the density of water in kg m^{-3}. In the reviewed literature, a number of parameterizations similar to equation (11) exist for global modeling applications (e.g. Marshall et al. 1994; Sellers et al. 1996; Yang et al. 1997). Most of the relationships are empirical and do not depend on the horizontal model resolution. Equation (11) is optimized for use with the current operational snow analysis product. The parameterization published by Sellers et al. (1996) applied to the operational analysis product would result in snow extents, which are far too small compared to the MODIS or NOAA / NESDIS data sets. The impact of snow water equivalent on the forecast is therefore determined by the analysis itself and the parameterization linking SWE and fractional snow cover.

In order to quantify the forecast skill for the revised analysis, ten-day forecasts were performed for March and December 2002 based on IFS version 26R1, which was operational from April to October 2003. The forecasts based on the revised analysis are compared to forecasts based on the operational analysis. It is assumed that changes in the forecast would be most pronounced in low level temperatures, which are directly linked to the surface albedo. For the 1000 and 850 hPa temperature forecasts, anomaly correlations c_j have been computed following Simmons et al. (1995):

$$c_j = \frac{\overline{(f_j - c)\times(a-c)} - \overline{(f_j - c)}\times\overline{(a-c)}}{\sqrt{\left[\overline{(f_j - c)^2} - \overline{(f_j - c)}^2\right]\times\left[\overline{(a-c)^2} - \overline{(a-c)}^2\right]}} \tag{13}$$

with f_j the forecast for day j, c the climatology and a the analysis. The overbar denotes an average over area and over all forecasts for day j in a particular period. Figure 7 shows the anomaly correlations for four areas, namely the Northern Hemisphere, North America, Europe and Northern Europe. Again, the individual c_j are based on 60 forecasts for March and December 2002. In general, the differences in temperature forecast skill between the control runs (operational snow analysis) and the experimental runs (revised analysis) are very small for both pressure levels. It can be noted for the 1000 hPa level that the revised analysis yields slightly lower correlations for the Northern Hemisphere for days one to seven. In contrast, the performance of the revised analysis is better for North America, Europe, and Northern Europe for days seven to ten, days four to seven, and days three to seven, respectively. However, none of the differences are statistically significant when the F-test or the run test is applied. Forecasts resulting in correlations below 60% are not considered to have any significant skill.

To investigate possible impacts on the local scale, the forecast skill is evaluated using 2 meter air temperature observations for Italy for December 2002, where significant changes in snow extent are obtained in the revised analysis. Since the NOAA / NESDIS data are introduced at 12 UTC, six hour forecasts for screen level temperature are compared with observations at 18 UTC. The rms errors between the 6 hour forecasts and the observations and the maximum differences for 85 stations are shown in Figure 8. The quality of the forecast remains unchanged when the revised analysis is introduced. The mean rms errors for both sets of forecast are 3.36 K. The mean maximum differences between the forecast and the corresponding observation are 5.85 K and 5.84 K for the operational snow analysis and its revised version, respectively. A similar comparison was performed for the 2 meter temperature forecast and the corresponding analysis. No significant changes between the experimental and the operational run were found. The values of the rms and the maximum differences were lower.

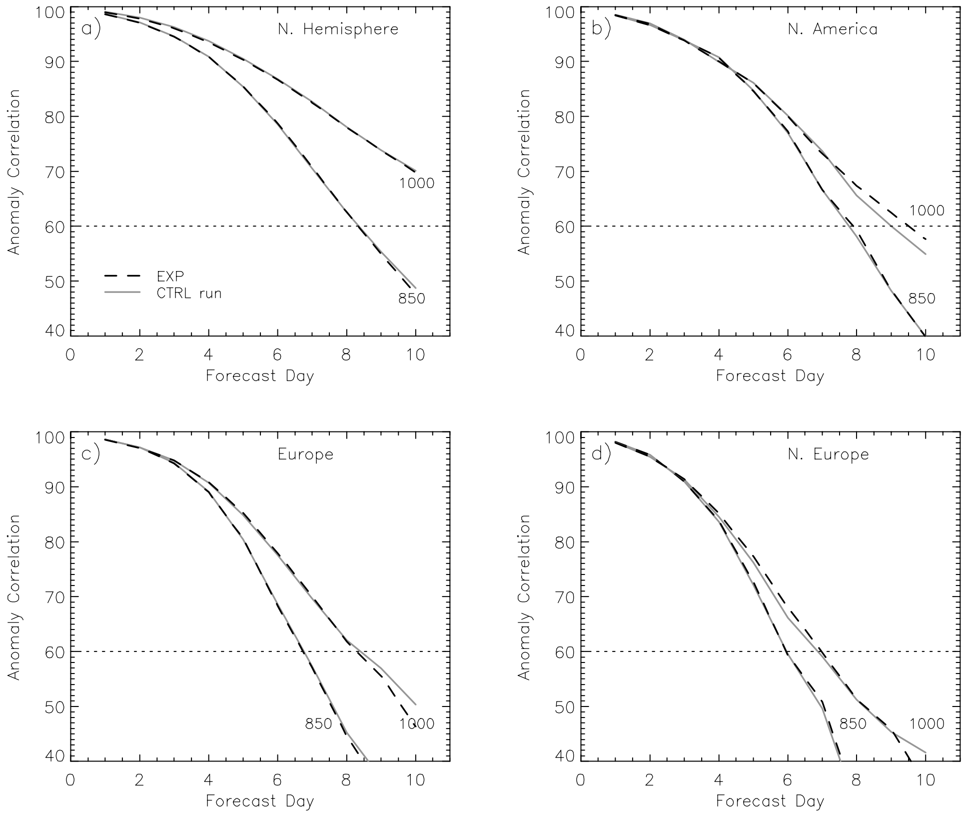

Figure 7. Anomaly correlations for 1000 and 850 hPa temperatures computed from forecasts for days one to ten. Calculations are based on 60 model runs (May 1st-30th and December 1st-30th, 2002) for the Northern Hemisphere (a), North America (b), Europe (c), and Northern Europe (d).

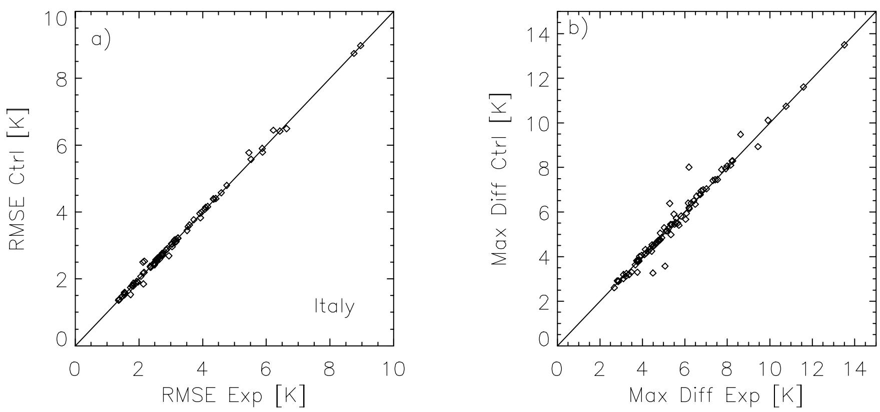

Figure 8. Root mean square errors (a) and maximum differences (b) for 2 meter temperature computed from the 6 hour forecast for 18 UTC and station observations in Italy. Forecasts are based on the revised snow analysis (Exp) and the operational analysis (Ctrl).

It is demonstrated that the revised analysis has a neutral impact on the forecast skill of the Integrated Forecast System with its present parameterizations in the land surface module. It is expected that the satellite derived snow extent can be used in the analysis to replace the role of snow depth climatology in correcting for the model bias. However, due to their computational costs, multi-year experiments can not be performed off-line. Results from the application of the revised analysis in operations have to be analyzed to quantify the benefits on long time scales.

Acknowledgments

The MODIS data were obtained through the National Snow and Ice Data Center (NSIDC). The authors would like to thank Brad Mc Lean from NSIDC User Services for his support. The Canadian snow depth observations were provided by Ross Brown (MSC). The paper benefited from many discussions with Erik Andersson and Sami Saarinen (ECMWF). The authors would like to thank three anonymous reviewers for their helpful comments. We would like to thank Rob Hine (ECMWF) for his help with the preparation of the figures.

References

Anderson, E.A., 1976: A point energy and mass balance model of snow cover. Silver Spring, MD: U.S. National Oceanic and Atmospheric Administration NOAA Technical Report NWS-19

Armstrong, R.L. and M.J. Brodzig, 2001: Recent Northern Hemisphere snow extent: A comparison of data derived from visible and microwave satellite sensors. Geophys. Res. Lett., 28 (19), 3673-3676

Betts, A.K., J.H. Ball and P. Viterbo, 2003: Evaluation of the ERA-40 surface water budget and surface temperature for the Mackenzie River Basin. J. Hydromet., 4 (6), 1194-1211

Brasnett, B., 1999: A global analysis of snow depth for numerical weather prediction. J. Appl. Meteor., 38, 726-740

Brown, R.D. 2000: North American snow cover variability and change 1915-97. J. Climate, 13, 2339-2355

Brown, R.D. and R.O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depth, 1946-1995. Atmos.-Ocean, 36, 37-45

Brown, R.D. and B.E. Goodison, 1996: Interannual climate variability and snowpack in the Western United States. J. Clim., 9, 1299-1318.

Daley, R., 1991: Atmospheric Data Analysis. Cambridge University Press, Cambridge, UK, 457 pp

Foster, D.J. and R.D. Davy, 1988: Global snow depth climatology. U.S. Air Force Environmental Tech. Applications Center/TN-88/006, 48 pp

Hall, D.K., G.A. Riggs, V.V. Salomonson, 2001: Algorithm Theoretical Basis Document (ATBD) for the MODIS Snow and Sea Ice-Mapping Algorithms. 53 pp, available through: http://modis-snow-ice.gsfc.nasa.gov/atbd01.html

Heidke, P., 1926: Berechnung des Erfolges und der Güte der Windstärkevorhersagen im Sturmwarnungsdienst. Geogr. Ann. 8, 301-349

Klein, A.G., D.K. Hall, and G.A. Riggs, 1998: Improving snow cover mapping in forests through the use of a canopy reflectance model. Hydrological Processes, 12, 1723-1744

Marshall, S., J. Roads, and G. Glatzmaier, 1994: Snow hydrology in a general circulation model. J. Climate, 7, 1251-1269

Ramsay, B., 1998: The interactive multisensor snow and ice mapping system. Hydrological Processes, 12, 1537-1546

Robinson, D.A., K.F. Dewey, and R.R. Heim, 1993: Global snow cover monitoring: an update. Bull. Amer. Meteor. Soc., 74 (9): 1689-1696

Roesch, A., M. Wild, H. Gilgen, and A. Ohmura, 2001: A new snow cover fraction parametrization for the ECHAM4 GCM. Climate Dyn., 17, 933-946

Rossow, W.B. and L.C. Garder, 1993: Validation of ISCCP cloud detection. J. Climate, 6 (12), 2370 – 2393

Sellers, P., D. Randall, G. Collatz, J. Berry, C. Field, D. Dazlich, C. Zhang, G. Collelo, and L. Bounoua, 1996: A revised land surface parameterization (SiB2) for atmospheric GCMs, Part I: model formulation. J. Climate, 9, 676-705

Simmons, A.J., R. Mureau, and T. Petroliagis, 1995: Error growth and estimates ofpredictability from the ECMWF forecasting system. Quart. J. Roy. Meteor. Soc., 121, 1739 – 1771

von Storch, H. and F.W. Zwiers, 1999: Statistical analysis in climate research. Cambridge University Press, Cambridge, UK, 484 pp

Yang, Z.-L., R. Dickinson, A. Robock, and K. Vinnikov, 1997: Validation of the snow submodel of the biosphere-atmosphere transfer scheme with Russian snow cover and meteorological observational data. J. Climate, 10, 353-373