SNOWGRID – A new operational snow cover model in Austria

Marc Olefs[1,*], Wolfgang Schöner[1], Martin Suklitsch[1], Christoph Wittmann[1], Bernd Niedermoser[4], Alfred Neururer[2] and Arnulf Wurzer[3]
[1]ZAMG – Central Institute for Meteorology and Geodynamics, Vienna, Austria.
[2]ZAMG – Regional office of Tyrol and Vorarlberg, Innsbruck, Austria
[3]ZAMG – Regional office and Avalanche Warning Service of Styria, Graz, Austria.
[4] ZAMG – Regional office and Avalanche Warning Service of Salzburg, Salzburg, Austria.

ABSTRACT: We present first results of the newly developed, physically-based and spatially distributed snow cover model SNOWGRID. The model is driven with gridded meteorological input data of the integrated nowcasting model INCA (8.1 – 17.7°E; 45.8 - 49.5°N) that uses remote sensing and radar data as well as ground observations and is operated by the Austrian weather service ZAMG. Additional data from remote sensing and ground measurements are used to validate and calibrate the model output consisting mainly of snow height and snow water equivalent maps in a spatial resolution of 100 m and a time resolution of 15 minutes in near real-time. Its energy balance mode contains partly newly developed schemes (e.g. radiation, cloudiness) based on high quality solar and terrestrial radiation data, satellite products and ground measurements. Snow physical properties and snow cover dynamics are currently incorporated in the model based on a simple 2-layer scheme, as the primary focus of the model are fast calculations on the large grid and to accurately represent the spatial distribution of the snow mass and depth (and not its detailed microstructural behavior), which is of great interest for authorities and the general public. Snow extent from SNOWGRID together with satellite data is also used to evaluate the effect of initializing a numerical weather prediction model such as AROME using a real snow distribution instead of climatological estimates as it is operationally done. As the model is still in development, the results and methods shown here are preliminary and not complete yet.

KEYWORDS: Snow cover model, climate services, avalanche warning, INCA, nowcasting, numerical weather prediction.

1 INTRODUCTION

For an efficient and accurate snow cover model that is able to operate in near real-time on large grids in high spatial resolution, it is necessary to fill the gap between sophisticated multi-layer snow cover models, part of which also consider the snow microstructure (e.g. CROCUS (Brun et al., 1989), SNOWPACK (Bartelt and Lehning, 2002) or SNTHERM (Jordan, 1991) and spatially distributed energy balance models that do not fully consider the atmosphere-snow energy exchange as well as snow cover internal mass and thermal processes (e.g. AMUNDSEN (Strasser et al. 2004) or models that do not consider the energy balance components (e.g. SeNorge (Endrizzi and Skaugen, 2009; Saloranta, 2012)). Additionally, all those models (a part maybe from SeNorge) are especially suited (due to performance reasons and/or used parameterizations) to be fed with meteorological point measurements rather than with gridded meteorological or remotely sensed input data with a very large number of grid cells as is required in the present operational nowcasting case at high spatial resolution. The newly developed snow cover model SNOWGRID tries to incorporate the advantages of all these model groups, at costs of some compromises.

2 METHODS

SNOWGRID is entirely written in the widely used open source programming language Python and has a flexible modular structure, making it easy to add new or to extend existing modules. SNOWGRID can be run in either a simple mode incorporating a typical positive degree day approach or a (more complex) mode that resolves the entire energy balance. As an upper boundary condition to the snow cover, SNOWGRID is driven with gridded meteorological input data from the Integrated Nowcasting through Comprehensive Analysis (INCA) system (Haiden et al., 2011) and additionally from the STRAHLGRID radiation model (Olefs and Schöner, 2012) for the energy balance mode.

2.1 Modeling domain and topography

The standard SNOWGRID modeling domain consists of the INCA-Large (INCA-L) domain that extends approximately from 8.09° to

Corresponding author address: Marc Olefs, ZAMG - Central Institute for Meteorology and Geodynamics, Vienna, Austria.
tel: +43 1 36 0 26 2233; fax: +43 1 369 12 33;
email: marc.olefs@zamg.ac.at

17.73°E and 45.77° to 49.48°N. respectively. For SNOWGRID applications, the standard INCA spatial resolution of 1x1 km is increased to 100x100 m. Thus, the model domain consists of 7001 x 4001 grid cells (roughly 28 m. points). For the moment, all meteorological input data from INCA is interpolated to the 100 m grid using bilinear interpolation. We use a digital elevation model (DEM) that is derived by void filling of the original NASA SRTM3 version 2.1 data (Farr et al., 2007) with high quality data from Jonathan de Ferranti (http://www.viewfinderpanoramas.org/dem3.html#alps) that were created manually from Russian and local maps (both at 90 m original resolution). The final DEM grid was then obtained by bilinear interpolation to the 100 m INCA-L mesh and is shown in Fig.1 together with the ground station locations that are used for SNOWGRID model validation and calibration later. Different functions from the excellent free and open source package GRASS GIS (*GRASS Development Team, 2012*) where then used to derive a few parameters from this DEM that are needed for important, topography-relevant calculations in SNOWGRID. Those parameters are for every grid cell: slope, aspect, ground- and sky view factors as well as horizon elevations in 360 degrees azimuthal directions.

2.2 The INCA nowcasting system

INCA was especially developed for use in mountaineous terrain and is described in detail in Haiden et al. (2011). The basic idea is to complement and improve numerical weather prediction (NWP) output in the nowcasting range (0-6 h) for a range of variables (e.g. temperature, humidity, precipitation, cloudiness) using realtime observations and high-resolution topographic data. Its analysis part combines surface station data with remote sensing data in such a way that station observations at the station locations are reproduced, whereas the remote sensing data provide the spatial structure for interpolation. After 2 to 6 hours of forecast time the nowcast is blended into a downscaled NWP forecast. Cross correlation derived accuracies of the INCA analysis part are variable dependant: Temperature is analyzed with an average accuracy of 1°-1.5°C (1.5°-2.5° in Alpine valleys), the precipitation analysis which is a combination of radar and rain gauge data and parameterized elevation effects is in the order of 50%-100% (15-min amounts). Future improvements are most likely to come from improved remotesensing and NWP data. For SNOWGRID applications we currently only use the INCA Analysis

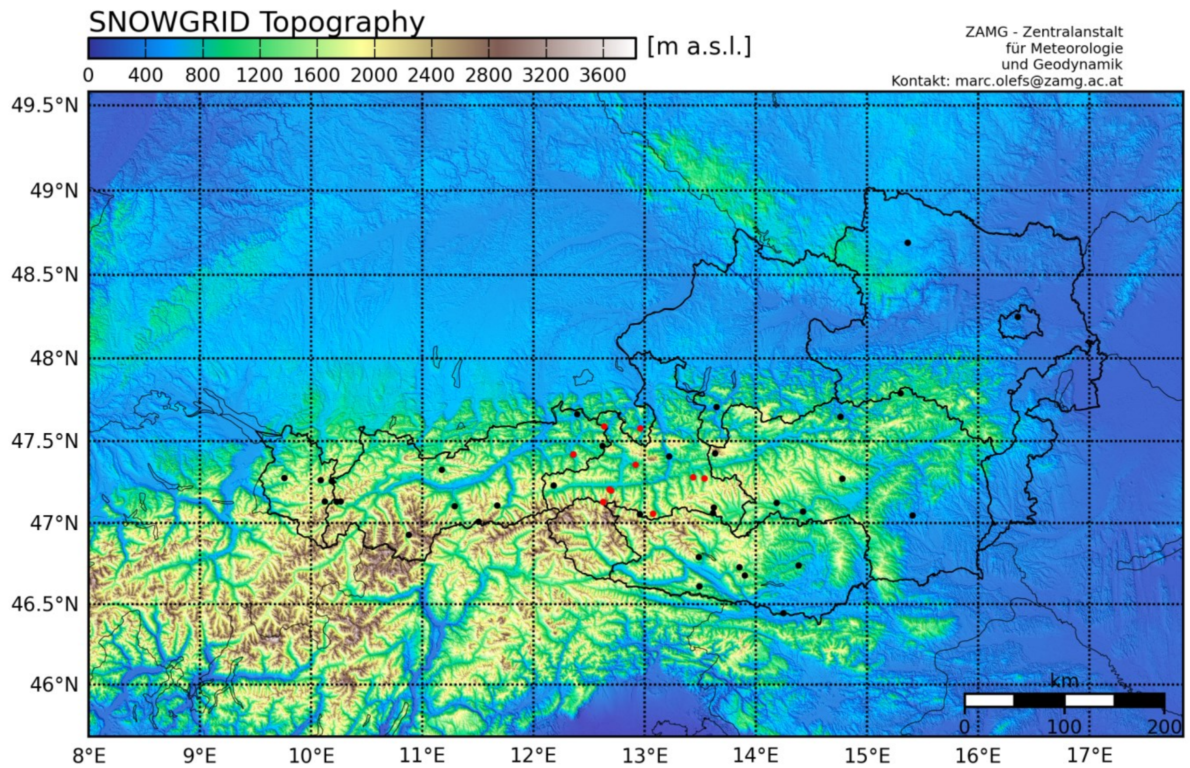


Figure 1. Topography of the SNOWGRID domain and locations of the ground truth stations as red (stations from the avalanche warning-services of Salzburg/Bavaria) and black (ZAMG stations) dots.

fields, namely: 2 m Air Temperature, relative humidity, precipitable water, wind, precipitation, cloudiness, snowfall line and the newly derived “HIM_ratio” that parameterizes the cloudiness effect of diffuse solar radiation. The time resolution of these fields is 15 minutes (cloudiness, HIM_ratio, precipitation) and 1 hour (all other fields), respectively. All fields are linearly interpolated to a common timestep of 15 minutes which is used for all SNOWGRID calculations.

2.3 STRAHLGRID Radiation model

The STRAHLGRID model is a parametric solar radiation model and is briefly described in Olefs and Schöner (2012). It calculates direct and diffuse solar radiation separately in the (shortwave) 0.3 to 3 µm spectral range (broadband) and is based on equations of diverse authors, following partly the method of Corripio (2003).

It accounts for atmospheric turbidity, cloudiness, terrain shading, multiple and terrain effects and ground albedo feedbacks. To reproduce temporal changes of atmospheric turbidity at best, we use precipitable water (water vapour transmittance) from INCA and monthly broadband aerosol optical depth values from MODIS, both interpolated to the 100 m grid using bilinear interpolation.Cloudiness effects are treated separately for direct and diffuse solar radiation. For direct radiation an improved version of the standard INCA cloudiness raster as described in Haiden et al. (2011) is used as input, where meteosat second generation (MSG2) cloudtypes are calibrated against sunshine duration data from the Austrian meteorological measurement network TAWES including a station dependant daily climatology of effective sunshine duration

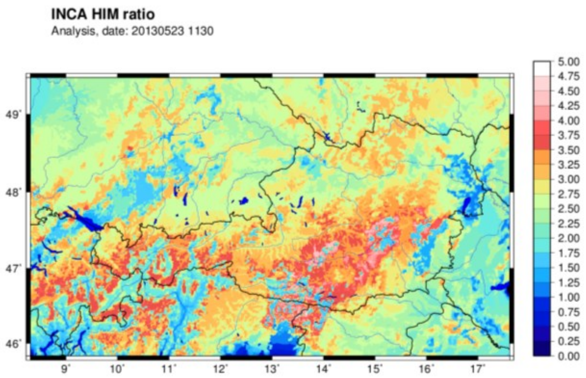


Figure 2. Newly derived INCA HIM_ratio Parameter for 23 May 2013, 1130 UTC

at high accuracy. The TAWES measurement network consists of more than 250 stations today, with a mean horizontal station distance of 18 km. As diffuse radiation changes differently in function of the cloud amount and type than does direct solar radiation (Dirmhirn, 1964) and sunshine duration is much better correlated with direct than with diffuse radiation, it was necessary to derive an additional cloudiness parameterization for diffuse radiation: The new INCA “HIM_ratio” parameter was derived recently within the SNOWGRID project. HIM_ratio attributes every MSG2 cloudtype to a ratio between all-sky observed and clear sky STRAHLGRID calculated diffuse radiation values using a lookup table. The table was derived by comparison of MSG2 cloudtypes with this ratio using all-sky measured diffuse radiation values at 4 ARAD stations (radiation station network following BSRN standard, Olefs et al.,2012) over a period of 2 years and is month-, time of the day and elevation dependant. Additionally, INCA relative humidity (RH) fields are used. In case of high absolute values of RH, a low spatial variability and a low or very low stratus-type cloudtype, the HIMratio value is additionally reduced as a function of RH. This technique considerably improves modelling of all-sky diffuse radiation in case of fog or elevated fog events. The mean standard error of the entire STRAHLGRID model is 19 W/m² based on 10-minute average values of global radiation. Fig.2 shows an example of the spatial structure and distribution of HIM_ratio and Fig.3 the performance of the old and new diffuse cloudiness parameterization scheme against measured global radiation data. Fig. 4 shows that the high spatial resolution of the used DEM data (100 m) dramatically increases the models ability to reproduce observed clear sky global radiation in the complex Alpine terrain. This is also confirmed by the decrease of the mean daily absolute differences of STRAHLGRID modelled vs. observed clear sky effective sunshine durations at station Innsbruck University from 0.5 to 0.1 hours using the described 100 m DEM vs. the 1 KM GTOPO30 DEM as used e.g. in INCA.

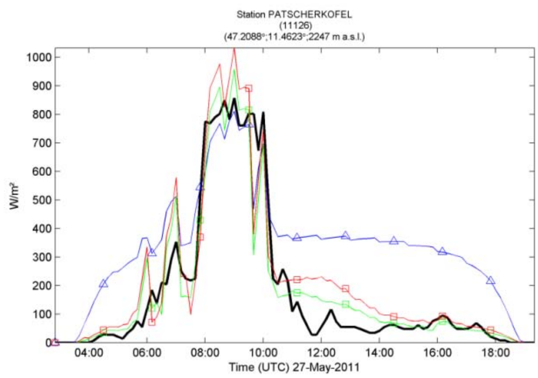


Figure 3. Calculated (coloured lines) vs. measured (black line) global radiation at station Patscherkofel (2247 m a.s.l.) using the old (blue line) vs. the new (green line) cloudiness parameterization scheme for diffuse solar radiation.

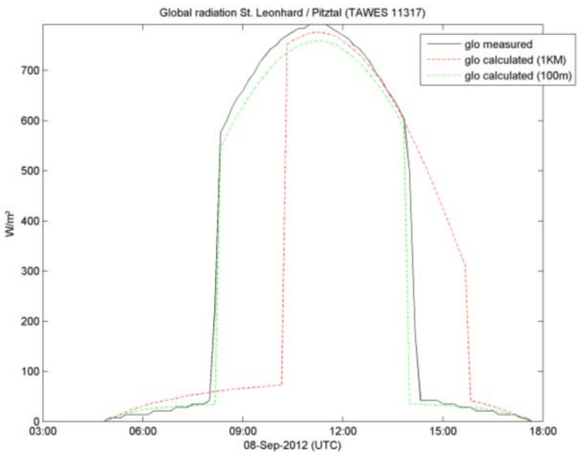


Figure 4. Calculated (coloured lines) vs. measured (black line) global radiation at valley station St. Leonhard/Pitztal during a clear sky day using the 1 KM (red) vs. the 100 m (green) spatial resolution of STRAHLGRID.

2.4 Other energy balance components

The implementation of the other energy balance components is current work in progress.

To reproduce incoming longwave radiation, a modified version of STRAHLGRID is currently in development, testing and incorporating the best performing parameterizations as described in many review studies (e.g. Flerchinger et al., 2009; Sedlar and Hock, 2009).

For turbulent fluxes of sensible and latent heat we will use bulk transport parameterizations using a bulk transfer coefficient and temperature and vapour pressure differences between the snow surface and the air temperature and humidity at reference height, respectively.

2.5 Snow model

The snow model that is currently used in SNOWGRID is an upgraded version of a model originally developped by Scheppler (2000) that was already applied in a daily resolution to Austrian data and the 1 KM INCA domain by Schöner and Hiebl (2009). Recently it was successfully used to derive daily grids of snow depth and snow water equivalent in the framework of the CARPATCLIM Project (Hiebl, 2012). The reported mean standard error of modelled snow depth was in the order of 0.035 m. In the current project SNOWPAT at ZAMG it is used for analysis and gap filling of long-term snow-depth time-series. A model evaluation using snow-depth data of 30 Austrian longterm stations shows a mean absolute error (MAE) and squared correlation coefficient (rs) of calculated snow depths of 0.2 m and 0.65, respectively (MAE=0.15 m and rs=0.58 for stations below and MAE=0.29 m and rs=0.8 for stations above 1500 m a.s.l.) (personal communication, Koch, R.). The model is explained in detail in the work of these authors.

Here we focus on the main processes and the modifications as used in SNOWGRID. The model simulates the accumulation and ablation of the snow cover, whereby the accumulation processes are the same for both the degree day mode and the energy balance one, whereas the degradation of the snow cover is modelled differently in the two modes. In the current model setup, the snow cover is divided into a maximum of 2 layers, whereby the 2nd layer only exists if the total SWE of the deposited snow cover exceeds 200 mm w.e.. For each layer, grid point and time step, the state variables snow density, snow water equivalent and average snow temperature are calculated and stored and characterize the snow cover. Thermal loss and gain of the snow cover are determined depending on the mode used and will be described for the degree day mode only, as the energy balance model is still not finished.

A snow cover is accumulated using the INCA fields precipitation and snowfall line. In INCA, precipitation is derived from a combination of station measurements and radar data (for details see Haiden et al., 2011). Snowfall line is defined in INCA as being the altitude where the wet-bulb temperature T_w is the first time > T_{wcrit} when marching downward the vertical model levels. The snowline is then calculated from linear interpolation between that level and the one above. T_{wcrit} corresponds to a value of T_w = 1.5 °C which has been found empirically to correspond closely to the rain/snow limit (Steinacker, 1983). Currently there is no mixed precipitation type used in SNOWGRID, we use this hard limit to decide between snow or rain. In a defined grid cell snow accumulates if the precipitation amount is greater zero and the snowline from INCA is equal or below the DEM elevation of that cell. New snow density ρ_{new} (kgm^{-3}) is calculated as a function of air temperature T_a $(°C)$ using an algorithm that is used in the North American Mesoscale model NAM (Koren et al., 1999;http://www.meted.ucar.edu/nwp/pcu2/etsnow2c.htm):

$$\rho_{new} = (0.15 + 0.01T_a + 0.0002^{T_a}) * 1000 \qquad (1)$$

After fresh snow has deposited, the new snow added at this time step is considered as a separate layer before it is aggregated to the existing one from former time steps. Next, the snow cover settles. Settling of the snow cover is divided into a part that results from destructive metamorphism of the freshly-fallen snow crystals that break up after deposition (the only settling mechanism for the fresh snow layer) and one that is due to the overburden pressure of the

snow cover. The eventually existing snow layer below the new one is applied both settling mechanisms. The contribution of destructive metamorphism to total settling is continuously reduced for snow densities greater than 150 kgm^{-3}. To calculate these settling effects we use the methods and formulas as described in Jordan (1991) and used in the SNTHERM89 model, with the difference that we neglect the melting term of the compaction rate.
Temperature of the freshly fallen snow is set equal to the 2-m wet-bulb temperature at that time step as used in many other snow models. When the new layer is aggregated with the old underlying one, the new combined layer will have the weighted average temperature of both layers in function of their SWE and temperature values.
To account for the thermal state of the snow cover and to better reproduce processes between the snow cover and the atmosphere, the cold content of the snow cover is calculated in the following simple way (Scheppler, 2000): Directly after accumulation, a preliminary snow water equivalent SWE_{prelim} and snow temperature Ts_{prelim} of the new together with the old snow layer are determined. They equal the solid precipitation amount in the current time step plus an eventually existing old SWE and the weighted average of the snow temperature from the new and old layer, respectively. A preliminary cold content qcc_{prelim} of the entire snow layer is calculated in units of (mm w.e.) as follows:

$$qcc_{prelim} = \frac{SWE_{prelim} * Ts_{prelim}}{160} \quad (2)$$

Note that 160 in (2) equals the ratio of the latent heat of fusion and the specific heat capacity of snow (assumed as constant and equal to 2090 J/kg/K by Scheppler (2000)). In contrast to reality this neglects the volumetric fraction dependant contributions of the specific heats of water and air in the snowpack. In a next step, and with the aid of a seasonally dependant degree day factor and a cooling factor, potential melt or effective cooling are calculated depending on whether T_a is above or below freezing. Then, qcc_{prelim} and potential melt/effective cooling together determine the amount of effective melt and decrease of the cold content (T_a > 0°C) or the increase of the cold content (T_a < 0°C). Effective melt subtracted from SWE_{prelim} gives the final output variable SWE. The cold content applied to the final SWE allows the calculation of the final snow temperature. If the total SWE exceeds 200 mm w.e. the snow cover is then split-up into two and the state variables are again calculated for those 2 layers, whereby the upper layer is not allowed to exceed the value of 200 mm w.e. In SNOWGRD, all snow depth and settling calculations are made after the snow mass of the new and old layer were determined.

2.6 Validation dataset

In order to calibrate and validate the SNOWGRID model we use both point ground measurements (time-series), remote-sensing data on a daily basis (MODIS fractional snow cover) and manual point measurements of some important snow physical properties (snow depth, snow water equivalent (SWE), and average snow density.
A total number of 49 ground stations is used (see their locations on the map in Fig. 1). Ten-minute average values of snow depth are recorded at all of these stations using either a Laser (35 stations, Jenoptik SHM30) or an ultrasonic sensor (14 stations, Sommer USH-8) as well as some basic meteorological parameters. Additionally, SWE is measured at 2 stations using a snow pillow (Sommer) and snow surface temperatures using infrared sensors at 3 stations, both in the same time resolution of 10 minutes.
For the measurement uncertainties of the basic meteorological quantities see Haiden et al. (2011), concerning snow depth, the uncertainty is given as 0.005 m for the laser and as 0.1 % for the ultrasonic. Several intercomparison studies between laser and ultrasonic snow depth sensors (e.g. Mair and Baumgartner 2010) have shown that the laser sensor has several advantages and a higher performance compared to the ultrasonic sensor, the biggest being its independency from temperature (less noisy signal) and its better performance with low snow depth values due to a well-defined and visible measurement point on the snow surface. For the measurement of SWE (snow pillow), the manufacturer gives an uncertainty of 0.25 %.
Concerning snow remote-sensing data we use the fractional snow cover product from MODIS, provided on a daily basis with a spatial resolution of 250 m by the GMES project Cryoland (www.cryoland.eu, Bippus and Nagler, 2012). Due to the inherent nature of optical satellite data, these informations are only available in cloud-free sky situations. This data is interpolated on the 100 m INCA-L grid using the nearest-neighbour method.
To complement all these data we also make use of a total number of 155 manual point measurements of snow depth, SWE and average snow density across Austria in the period Oct 2011 to May 2013 that are carried out by ZAMG on a regular basis for snow load measurements. The values are determined by weighting a defined volume of snow using the tube technique

(Kaser et al., 2003) which is also widely used in glacier mass balance measurements.

2.7 NWP initialization

The ALARO5 and AROME-Austria NWP models at ZAMG are using the ISBA and ISBA-SURFEX schemes (Noilhan and Planton, 1989) to simulate soil processes and the snow parameterization scheme after Douville (1995). Relevant prognostic variables are SWE, snow albedo and snow density. As the snow cover plays a very important role in the surface energy balance (albedo, longwave emission) and also impacts the water balance of the soil (liquid water absorption in the snow cover, melting of the snow cover) or both (sublimation) it can especially impact predicted near-surface temperatures but also precipitation amounts. In the present operational NWP model versions used at ZAMG, the initialization snow cover is deduced mainly from SWE of the previous model run (modelled precipitation) corrected with a monthly climatology. If 2-m temperature is above freezing, SWE is reduced correspondingly. The main shortcoming of this approach is that errors in calculated precipitation amounts from the previous run propagate into the current snow initialization which is only slightly corrected with the methods described before. Thus, a more realistic snow cover is needed as input.

As the SNOWGRID model is still in development we test these more realistic initializations with a satellite product during a few selected days with low cloud amount. The same fractional snow cover product of MODIS as described in section 2.6 is used here but with a different domain corresponding to the model domains of ALARO5 and AROME-Austria, respectively.

3 RESULTS AND DISCUSSIONS

3.1 SNOWGRID validation

The validation results presented hereafter are preliminary and not complete yet. Figure 5 shows that SWE, snow depth and the timing of most snowfall events at station Kühroint is well modelled apart from one event in early December 2011 which propagates through the rest of the month. In Tab. 1, three of the 5 presented manual snow measurements are overestimations from the model in terms of SWE and snow depth, one is closely matched and one underestimated. Fig. 6 shows that the general spatial pattern of snow covered area is already well represented.

In this early stage of model development, these differences may come from (in decreasing order of importance) : errors in the meteorological input fields (especially precipitation), errors in the SNOWGRID model itself, uncalibrated model parameters, lack of a snow redistribution scheme, use of a degree-day instead of an energy balance scheme for snow ablation.

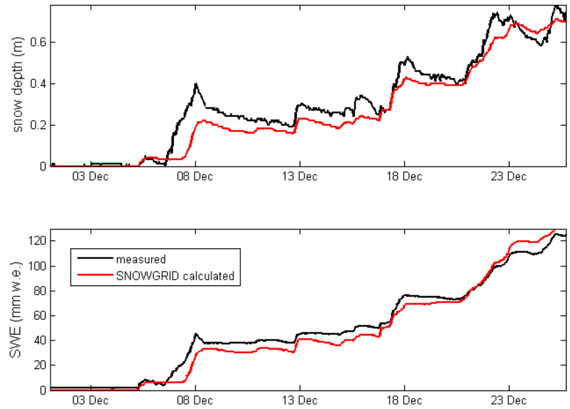


Figure 5. Hourly extracted 15 min. average values of SNOWGRID calculated (red) vs. measured (black) snow depth (top) and SWE (bottom) at station Kühroint (avalanche warning service Bavaria, 47.5769°N; 12.9613°E; 1420 m a.s.l.) for the period 1 Dec – 25 Dec 2011.

Site	Time (UTC)	Lat	Lon	Alt (m a.s.l.)	SD (m)	SWE (mm w.e.)	rho (kg/m³)
Ochsengarten	10:30	47°13.635	10°55.884	1513	0,56 (0,56)	80 (97)	143 (173)
Kühtai	10:15	47°12.682	11°00.667	1947	0,98 (0,2)	165 (39)	168 (195)
Holzleitensattel	11:45	47°18.467	10°53.284	1116	0,75 (0.98)	103 (175)	137 (179)
Leutasch	13:10	47°22.279	11°08.908	1131	0,78 (1.07)	114 (178)	147 (166)
Seefeld	14:15	47°19.486	11°10.525	1182	0,69 (1,03)	93 (175)	135 (170)

Tab 1. Manual measured (black) vs. SNOWGRID calculated (red) point values of snow depth and SWE for 22 Dec 2011 at different locations in Tyrol.

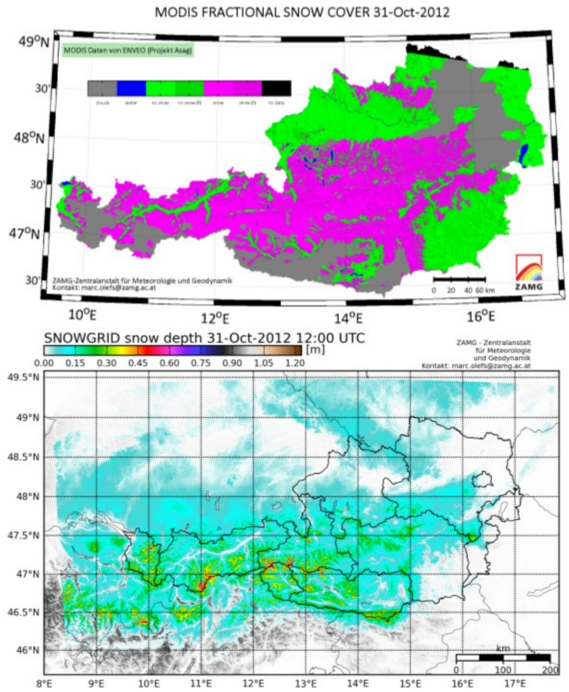
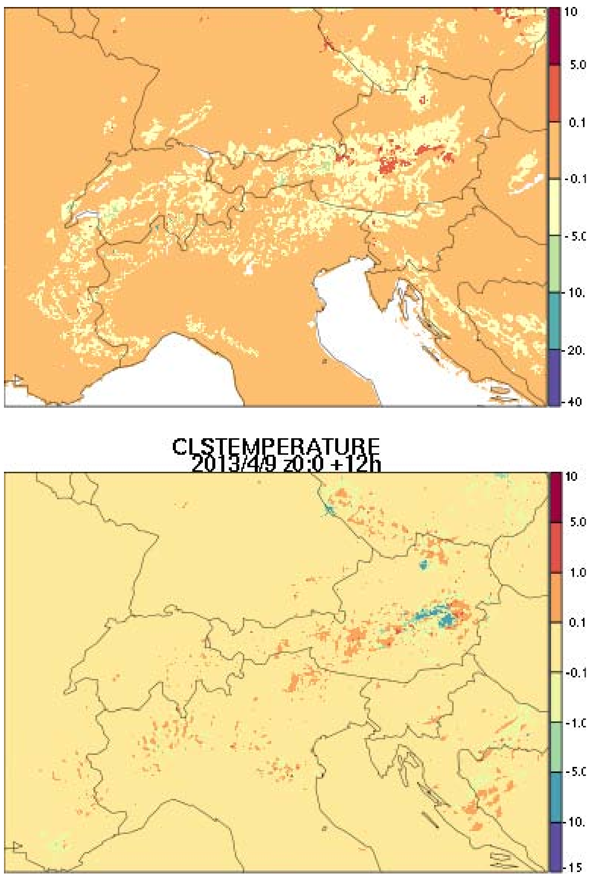


Figure 6. Observed MODIS Fractional snow cover for the national territory of Austria (Top) vs. SNOWGRID calculated snow depth in the INCA-L domain (bottom) for 31 Oct 2012. In the top image purple represents snow covered,

green snow-free area, clouds are shown in grey, water surfaces in blue. In the bottom image snow-free areas are grey shaded.

3.2. NWP initialization

Two case studies in January and April 2013 show a positive effect of the MODIS FSCA initialized ALARO5 and AROME NWP model runs vs. the operational snow initialization. Differences in 2-m air temperature are up to 10 K on 31 Jan 2013 in a valley of south tyrol (not shown). As can be seen in Fig. 7 added snow in southeastern Austria locally decreases air temperatures by more than 5 K due to an increased ground albedo. Fig. 8 shows an improvement of the +24h precipitation forecast due to the more realistic snow cover compared to the INCA precipitation analysis. Generally, with increasing forecast time, local differences due to the snow modification propagate in space. One drawback of the satellite method beside cloud obstruction is the sometimes wrong classified snow cover (clouds are detected as snow) which leads to new errors in the NWP models. At least one of these shortcomings can be eliminated with the use of the SNOWGRID model which is current and future work in progress.



Fgure 7. Difference of initialized SWE (kg/m^2) AROME-Austria run with minus without snow modifications for 9 Apr 2013 0 UTC+0h (top) and difference of T2m (K) at an integration time of 12 h (9 Apr 2013 12 UTC).

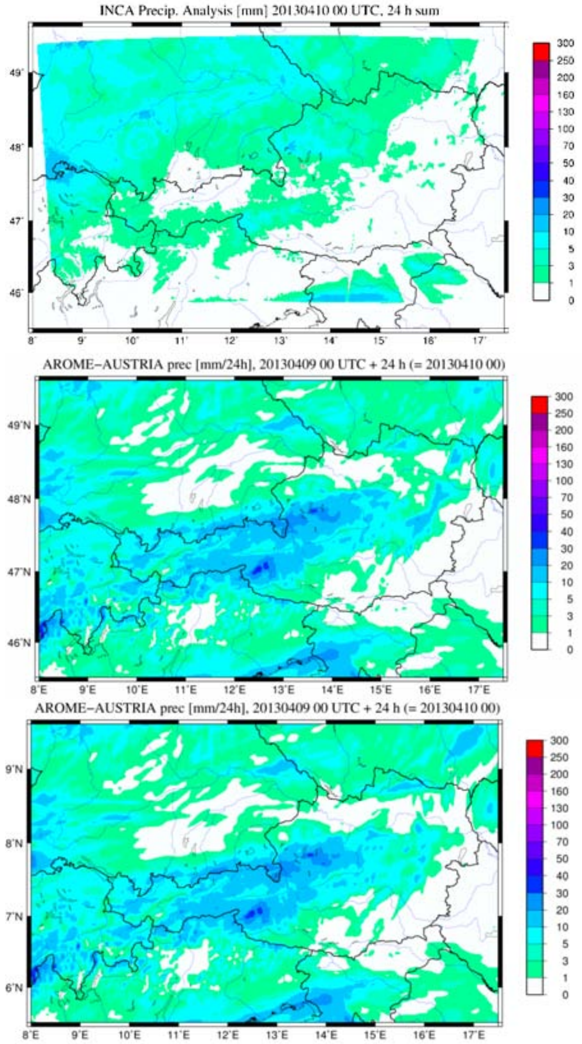


Figure 8. INCA analysis (top), AROME-Austria (middle) and AROME-Austria with modified snow cover (bottom) for 24h precipitation sums 9 Apr 2013 0 UTC – 10 Apr 2013 0 UTC.

4 CONCLUSIONS

Presented preliminary results of the SNOWGRID model are promising, more complete and extensive validation results, and performance of the energy balance version are shown at the conference.

10 REFERENCES

Bartelt, P. and Lehning, M., 2002. A physical SNOWPACK model for the Swiss avalanche warning; Part I: numerical model. Cold Reg. Sci. Technol., 35(3): 123-145.

Bippus, G. and T. Nagler, 2013, Monitoring Snow and Land Ice using Satellite data in the GMES project CryoLand. Poster, EGU 2013, Vienna, Austria.

Brun, E., Martin, E., Simon, V., Gendre, C., Coleou, C. (1989), An energy and mass model of snow cover suitable for operational avalanche forecasting. Journal of Glaciology 35 (121), 333-342.

Corripio, J. G., 2003, Modelling the energy balance of high altitude glacierised basins in the Central Andes, PhD Thesis, University of Edinburgh.

Dirmhirn, I., 1951, Untersuchungen der Himmelsstrahlung in den Ostalpen mit besonderer Berücksichtigung ihrer Höhenabhängigkeit, Arch.Met.Geoph.Biokl.B. Bd.II, H.4.

Douville, H., J.-F. Royer, and J.-F. Mahfouf, 1995, A new snow parameterization for the Meteo-France climate model, Climate Dynamics, 12, 21-35.

Endrizzi, S. and Skaugen, T., 2009. Snow Simulation and forecasting through all Norway: the SeNorge model. In: Proceedings ISSW 2009. International Snow Science Workshop, Davos, Switzerland.

Farr, T. G., et al., 2007, The Shuttle Radar Topography Mission, Rev. Geophys., 45, *RG2004, doi:*10.1029/2005RG000183.

Flerchinger, G. N., W. Xaio, D. Marks, T. J. Sauer, *and* Q. Yu, 2009, Comparison of algorithms for incoming atmospheric long-wave radiation, Water Resour. Res., 45, *W03423, doi:*10.1029/2008WR007394.

GRASS Development Team, 2012. Geographic Resources Analysis Support System (GRASS) Software, Version 6.4.2. Open Source Geospatial Foundation. http://grass.osgeo.org

Haiden, T., Kann, A., Wittmann, C., Pistotnik, G., Bica, B., Gruber, C., 2011, The Integrated Nowcasting through Comprehensive Analysis (INCA) System and its Validation over the Eastern Alpine Region. Weather and Forecasting, 26, 166-183. DOI: 10.1175/2010WAF2222451.1

Hiebl, J., 2012, Gridding of snow depth and snow water equivalent. In: Szentimrey, T. et al., Final report on the creation of national gridded datasets, per country, CARPATCLIM report.

Jordan, R., 1991, A one-dimensional temperature model for a snow cover: Technical documentation for SNTHERM.89, Spec. Rep. 91-16, Cold Reg. Res. and Eng. Lab., Hanover, N. H.

Kaser, G., Fountain, A., and Jansson, P., 2003. *A Manual For Monitoring the Mass Balance of Mountain Glaciers*. IHP-VI Technical Documents in Hydrology No. 59, UNESCO-IHP, Paris.

Koren, V., J. Schaake, K. Mitchell, Q. Y. Duan, F. Chen, J. M. Baker, 1999: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models. J. Geophys. Res., 104, 19569-19585.

Mair, M., and D.J. Baumgartner, 2010: Operational experience with automatic snow depth sensors – ultrasonic and laser principle. Paper presented at TECO 2010. WMO, 30/8/2010-1/9/2010, 2010, Helsinki, Finland.

Noilhan, J. and S. Planton, 1989: A simple parameterization of land surface processes for meteorological models. Mon. Wea. Rev., 117, 536-549.

Olefs M., Schöner W.: A new solar radiation model for research and applications in Austria. In: EGU General Assembly 2012. Vienna, Austria, 22 April–27 April 2012.

Olefs M., Baumgartner D., Obleitner F., Weihs P.: The ARAD Project: New radiation initiatives in Austria. In: 12th BSRN Scientific and Review Workshop. Potsdam, Germany, 01Aug2012.(http://www.bsrn.awi.de/en/other/workshop_2012/).

Saloranta, T.M., 2012, Simulating snow maps for Norway: description and statistical evaluation of the seNorge snow model. The Cryosphere, 6:1323-1337.

Scheppler, P. 2000: Schneedeckenmodellierung und Kalibrationsmöglichkeiten für ausgewählte Beobachtungsstationen. Bern: University of Bern, master thesis, 111p.

Schöner W. and Hiebl J., 2009: webklim.at. Präsentation hochauflösender Klimainformation im Internet am Beispiel von Lufttemperatur, Niederschlag und Schneedecke. Vienna: ZAMG, project report, 36 p.

Strasser, U., Corripio, J., Pellicciotti, F., Burlando, P., Brock, B., Funk, M., 2004: Spatial and temporal variability of meteorological variables at Haut Glacier d'Arolla (Switzerland) during the ablation season 2001: measurements and simulations, J. Geophys. Res., 109, doi: 10.1029/2003JD003973.

Steinacker, R., 1983, Diagnose und Prognose der Schneefallgrenze, Wetter und Leben, 35, 81-90.