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Analysis of Different Snow Products Available at JRC-MARS Unit

Contribution to the Development of MARS Crop Yield Forecasting System

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Abstract

Snow cover information is currently used in the modelling of frost kill damage of winter cereals at JRC-MARS. The intended improvements can exploit snow data information leading to more precise simulations in the crop models and soil moisture simulations resulting more precise crop yield forecasts. As a first step, the main characteristics and constrains of ground-based snow depth measurements and remote sensing based snow observation were discussed. Comparison of SnowMaus model and ECMWF snow products was performed for 20 meteorological stations of Russia, Ukraine, Poland and Sweden. The results indicated good agreement in case of both model for start and termination of snow cover. SnowMaus model can be useful in the data quality control, but local calibration is needed for reliable snow depth values especially in case of deep snow cover. The ECMWF model provided the best estimates/results of snow depth by the help of snow water equivalent and simulated snow density parameters. Evaluation of shallow snow cover data (<20 cm) confirmed that the ECMWF based snow data are most suitable for winter frost kill analysis.

Contents

Introduction

Snow cover can modify the physical properties of the land surface, altering the energy and water transfer and affecting significantly the infiltration and storage of precipitation, influencing the runoff properties of the ground and delaying the replenishment of soil moisture during the winter season (Trnka et al., 2010). Therefore, snow cover plays an important role in agro-meteorology. For instance, thick snow cover provides thermal insulation against severe frost events, thus, protecting winter crops from winter kill (frost kill) losses.

Snow cover information is mainly used within the JRC-MARS Crop Yield Forecasting System (MCYFS) in the modelling of frost kill damage of winter cereals. The importance of snow data is expected to increase for the JRC-MARS activities in the near future, due to the need for achieving more reliable crop simulations during the dormancy period of winter crops as well as for increasing the accuracy of the model simulation of:

- soil moisture content
- run-off
- infiltration
- movement of moisture in the soil,
- soil moisture profile
- albedo
- soil thermal conductivity
- heat exchange processes
- energy balance
- soil temperature

These improvements can lead to more reliable soil moisture and crop model simulations, improve pest and disease models, and result in better crop yield forecasts.

Main snow parameters and definitions

The nomenclature and definitions related to snow measurements are not unique and commonly accepted; therefore it is important to list and define the main snow parameters here.

Snow is a solid form of precipitation, formed in clouds and falling in form of flakes or ice crystals to the land surface. If the ground temperature is below or close to the freezing point, snow can accumulate on the ground.

Snow Cover (SC) can be defined as the total amount of *snow* accumulated on the ground in a given place originating from snowfall and/or snowdrift (Armstrong et al., 2009). Snow cover is characterised by its depth and spatial extent (Sturm et al., 1995).

Snow Depth (*SD*) is the total height of snow cover involving the old and fresh fallen snow. It is usually expressed in centimetres (*cm)*.

Snow Cover Extent (*SCE*) is the total land area covered by snow. It is measured in square kilometres (km^2) (Armstrong et al., 2009).

Snow Water Equivalent (*SWE*) is the amount of water stored/contained in the snow cover. It can be considered as the depth of water that would result, if the whole snow cover were instantaneously melted with neither evaporation nor sublimation. It can be measured either in kg/m^2 or mm of water depth. Applications based on SWE are frequent in hydrology (e.g., surface runoff and soil moisture models), climatology, meteorology (weather forecast), agro-meteorology, etc.

Snow Density (S_DEN) is the mass of snow per unit volume. Generally, snow density is expressed in kg/m^3. Snow density has a wide range of variability (see Table 1).

Table 1 - Typical snow density values (Cuffey and Paterson, 2010)

Snow type	Density in kg/m^3
New snow (immediately after falling in calm, but highly temperature dependent)	50-70
Damp new snow	100-200
Settled snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Very wet snow and firn	400-600

Snow density can be also derived by using the following equation:

S_DEN = SWE/SD

Snow Fraction (SF) is the ratio of the snow covered area to the total area. SF is a dimensionless parameter which varies between 0 (no snow) and 1 (complete coverage). It is important in the case of fractional snow cover (primarily in autumn and spring). SF has special importance in the implementation of snow cover in global climate models as well in the remote sensing of the snow cover extent.

Main features of snow cover

- Very high spatial variability as a result of the interaction of several spatially highly variable factors like:
    - precipitation
    - temperature
    - air humidity
    - wind
    - orography
    - soil conditions and
    - vegetation (e.g. forests)
- Complex physical processes during the development, existence and termination of snow cover, including sublimation, evaporation, snow-drift and melting as well as temporal changes of the main physical characteristics of snow (albedo, heat conductivity, density, etc.).
- Complex physical processes acting within the snow layer (e.g., change of structure, mixed and changing aggregate state, mixed recrystallization) that makes difficult the modelling of snow cover.

Main features of ground-based snow depth measurements

- Point measurements at weather stations with high accuracy, but with a limited spatial representativeness.
- Lower representativeness on heterogeneous terrain/surface (the estimated uncertainty of SYNOP snow depth data can reach a global average of 12 cm (Takala et al., 2011).
- Snow depth is not everywhere measured.
- Frequently no snow data is sent into the Global Telecommunication System of the World Meteorological Organization (WMO GTS).

- Most stations do not report 0 cm snow depth when snow is not present, therefore it is difficult to distinguish between the no snow condition and no snow report situation (data gap).
- Several countries have sparse snow measurements in their national meteorological network; e.g. the Asian part of Russia, China, Argentina (de Rosnay, 2013). This problem exists also in Europe, especially in Sweden, the eastern part of Russia and in mountainous regions of Europe (see Fig. 1).
- There are dedicated national snow depth measurement networks (e.g. SNOTEL, SNOWDAS and COOP in USA), but their data do not circulate in the WMO GTS.
- Some improvements have been noticed in Europe; for instance, the snow observation network of the Swedish Meteorological and Hydrological Institute has been present in the WMO GTS since 2010.

Main features of remote sensing (RS) based snow observations

- Remotely sensed snow measurements (primarily snow cover extent and SWE) at the global scale.
- RS products deliver most frequently snow cover extent information.
- SWE products are based on passive microwave measurements, but they are less common and have limited accuracy, particularly for large values of snow depths (Takala et al., 2011).
- Several uncertain parameters (e.g. snow grain size, snow liquid water content, etc.) come up in the snow depth and snow water equivalent parameter estimation.
- The new European Space Agency (ESA) Earth Explorer CoReH2O mission is designed to reach high spatial resolution and accuracy in RS based SWE observation (the satellite launch time is scheduled for 2019-2020).
- Snow cover fraction and snow cover extent can be estimated with good accuracy from visible and near infrared measurements. Moderate Resolution Imaging Spectroradiometer MODIS satellites provides daily observations of global snow cover with 5.6 km spatial resolution (0.05°; NASA, 2013).
- NOAA/NESDIS (National Environmental Satellite, Data, and Information Service) Interactive Multi-sensor Snow and Ice Mapping System (IMS) combines ground observations, geostationary and polar orbiting satellite data from microwave and visible sensors and provides daily information about snow cover extent at the global scale with 4 km resolution.

Current state and processing of snow data within the MCYFS

JRC-MARS Crop Growth Monitoring System (CGMS) is based on weather observations. Snow depth on the grid of CGMS Europe is currently generated by inverse weighted distance (IWD) interpolation procedure of snow depth (SD) values from individual weather station observations. No other auxiliary data are involved in the calculation. Snow extent (SE) maps are available in the CGMS remote sensing component, e.g. METOP snow cover information. However, this data is used neither during the snow depth interpolation nor for the evaluation of snow presence.

In CGMS there are extended areas in Scandinavia and Russia with no snow information (Fig. 1) due to the lack of reported snow data and/or not transferred to the WMO GTS. Additionally, the currently used interpolation technique produces patchy maps with sharp borders. Thus, the reliability/accuracy is often questionable.

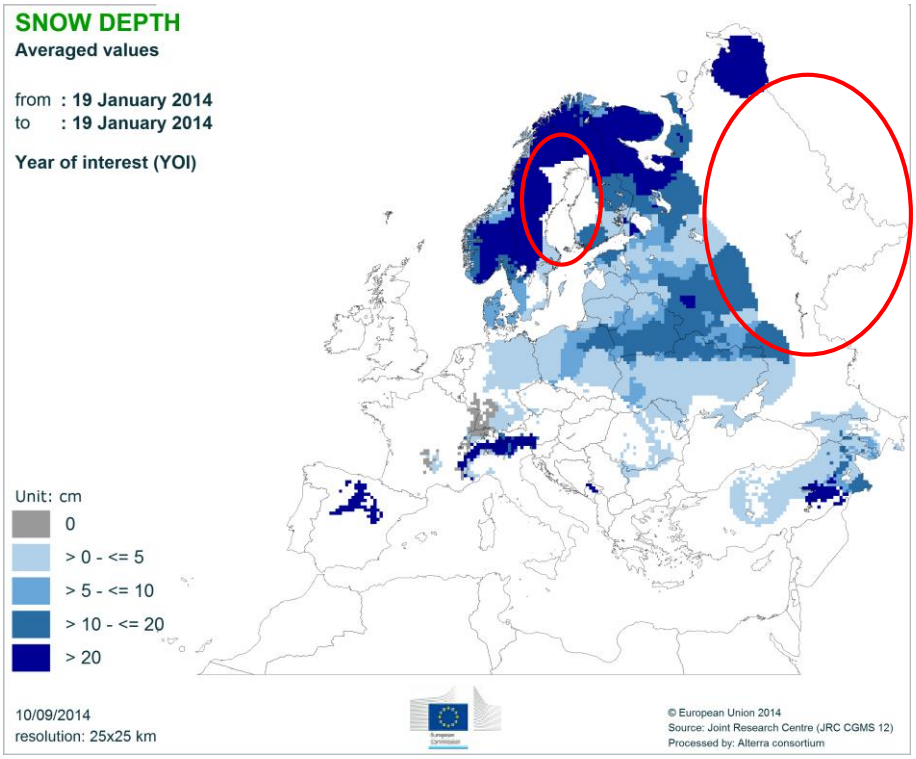

Fig. 1 - An example of snow depth map for the 25th of December 2012 based on weather station measurements (CGMS EUR, on 19/01/2014). Red ellipses identify areas with no snow information.

Another serious problem is the temporal discontinuity of the CGMS snow dataset. The current quality check and interpolation procedures of snow data do not take into consideration the persistence of snow cover. Due to gaps in measurements, there are temporal fluctuations and missing snow cover data. For example, Polish, Ukrainian, and Russian weather stations suffer from this problem (Fig. 2), although these are not the only affected. These discontinuities can cause problems in the estimation of frost kill (Annex 1), because the current frost kill model can simulate severe damages in a 3-4 days period with no snow cover and low temperatures.

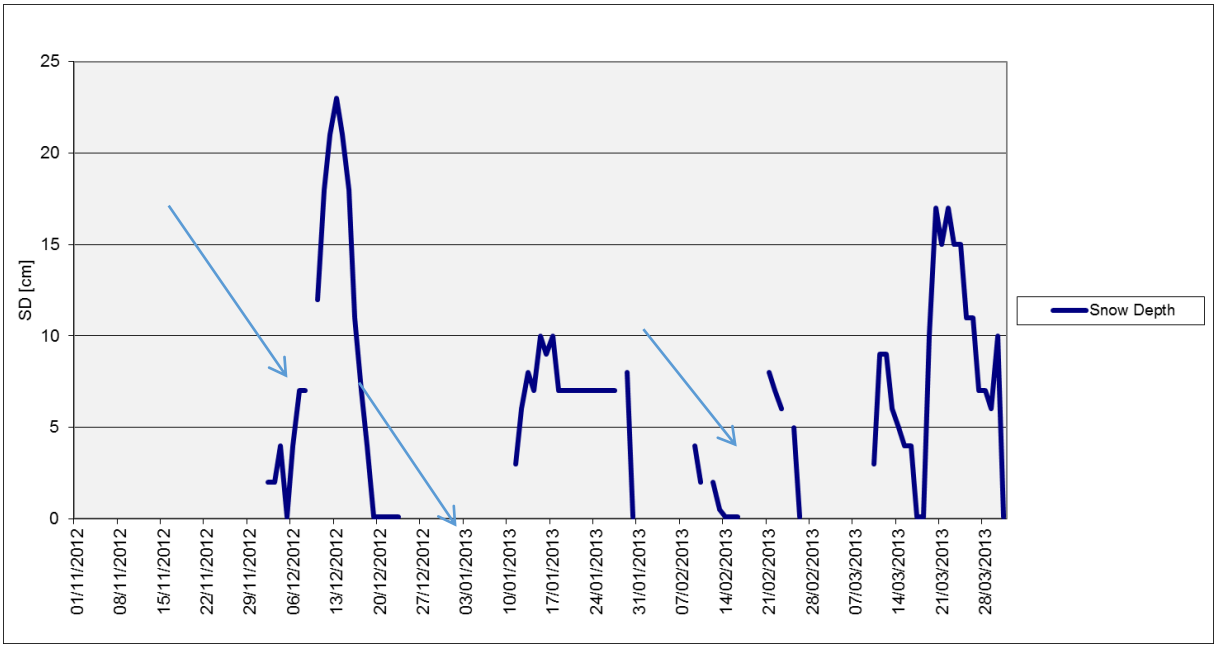

Fig. 2 - Example of discontinuities in the snow depth [cm] data series of Kołobrzeg (PL) during the winter of 2012/2013.

ECMWF Snow Products

In global weather prediction models, the surface–atmosphere interaction processes have great importance. They are simulated by the help of land surface models, which describe the water and energy fluxes at the soil-plant-atmosphere surface layers, as well as the changes of soil moisture and snow cover. Several studies have proved the significant impact of soil moisture and snow cover conditions on the weather forecast skill at short, medium and seasonal range (de Rosnay et al, 2012).

Snow-cover is characterised by a high albedo (typically 0.65-0.98; Cuffey and Paterson, 2010), low thermal conductivity, and additionally it constitutes a substantial water storage. The energy and water balance as well as the surface–atmosphere processes and interactions are therefore significantly modified. The initialisation of snow conditions has a large impact on the atmospheric forecast accuracy. This explains why ECMWF elaborated a sophisticated snow analysis method as part of the H-TESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchange over Land) land surface model (Dutra et al., 2010). H-TESSEL is a single-layer model, which simulates the accumulation and depletion periods of the snow pack.

The ECMWF snow parameterisation used for numerical forecasting accounts for (Dutra et al., 2010):

- snow water equivalent,
- new snow density formulation as a function of wind speed and air temperature (ECMWF, 2010),
- snow cover fraction.

The current ECMWF snow model describes well the duration of snow cover, but there are uncertainties in terms of snow accumulation due to inaccuracies in the meteorological forcing and imperfect model parameterisations (de Rosnay et al., 2012). Data assimilation approaches, by optimally combining model results and observations, provides better estimates of snow conditions (Pullen et al. 2011).

In 2010, the Cressman (1959) interpolation method, used in the snow assimilation analysis, was replaced by the 2D optimal interpolation method (de Rosnay et al. 2011). This method calculates the weighting functions of vertical and horizontal distances between observations and model grid points as well as covariance matrices of background and observations errors. Thus, it can provide an optimal combination of model background and observations (de Rosnay et. al, 2012). This new method provides higher accuracy than the previous one and has been implemented in ECMWF deterministic model (ECMWF HIS and OPE products). However, the Cressman method is still in use in the ERA-Interim reanalysis.

The ECMWF operational snow modelling applies a two-step procedure (de Rosnay, 2012). In the first step, the Interactive Multisensor Snow and Ice Mapping System (IMS) of the National Oceanic and Atmospheric Administration (NOAA) snow extension information is used. The snow-free grid points of the ECMWF model are initialized with a constant 10 cm snow depth and 100 kg/m^3 snow density values when NOAA remote sensing product identifies existence of new snow cover. In the second step, ground station observations and snow-free grids of satellite observations are also included and assimilated into a snow parameter field with the 2D optimal interpolation and introduced as input parameters into the ECMWF weather forecast models.

2D Optimal interpolation performs better versus Cressman method due to the disappearance of unrealistic snow patterns, a smoother snow field and a more accurate reproduction of SYNOP snow depth values (de Rosnay et. al, 2011).

Incorporating ECMWF based snow products into MCYFS

The ECMWF-based snow depth parameter of the MARS Crop Growth Forecasting System for Europe (CGFS EUR) was analysed and compared with the snow information of CGMS EUR system. While the snow depth data of CGFS cover southern Sweden and eastern part of European Russia (Fig. 3), in CGMS EUR these areas suffer from data gaps (Fig. 1). At the same time, the snow cover extent in CGFS could

differ from CGMS like in our example in Germany and southern Ukraine. The absolute values in CGFS are realistic (Fig. 3) and similar to CGMS (Fig. 1). The underestimation of CGFS w.r.t. CGMS EUR is caused by a problem that was corrected in September 2013.

Snow cover is a difficult variable to simulate with numerical weather prediction models, and the requirements in terms of snow depth and extension accuracy are different for agro-meteorological and weather prediction purposes. CGFS and CGMS snow maps were compared with daily NOAA IMS remote sensing products. As expected, the actual NOAA IMS image (Fig. 4) has a snow distribution similar to the one of CGFS (Fig. 3), because it is used as input data for ECMWF snow simulation. Since NOAA IMS images are based on the previous day measurements there is a delay of one day in the ECMWF snow modelling. Thus, the NOAA image of 20/01/2014 (Fig. 4) has similar snow cover extent compared to the CGFS map of 190/12/2012 (Fig. 3) in Germany and Poland. Contrarily, the lag NOAA image of 20/01/2014 (Fig. 5) shows analogy with real measured snow cover extent of CGMS map of 19/01/2014 (Fig. 1). EUMETSAT sensor Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat Second Generation (MSG) satellites (MSG-SEVIRI) products are also available at JRC-MARS, but with dekadal snow cover class data instead of daily snow cover information (Fig. 6). Since all snow products have strengths and weaknesses, the concurrent usage of different products could represent an optimal strategy.

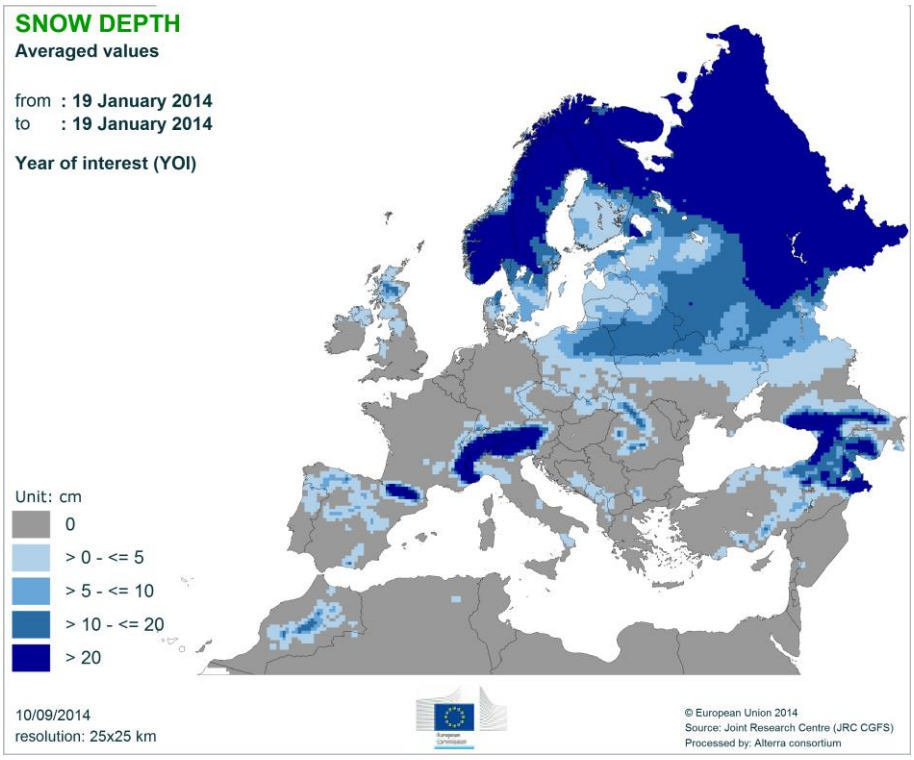

Fig. 3 - Snow depth map based on ECMWF SWE product (CGFS EUR, on 19/01/2014).

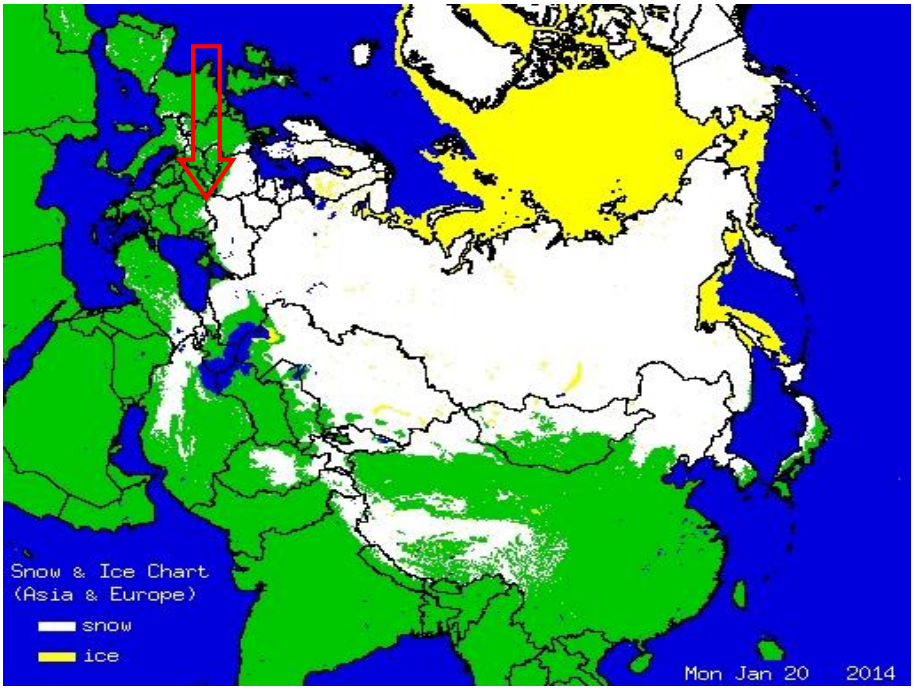

Fig. 4 - NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) snow/ice extent image of Europe/Asia (dated on 19/01/2014) (NOAA, 2014). (Red arrow indicates the change of snow cover in the southern half of Ukraine)

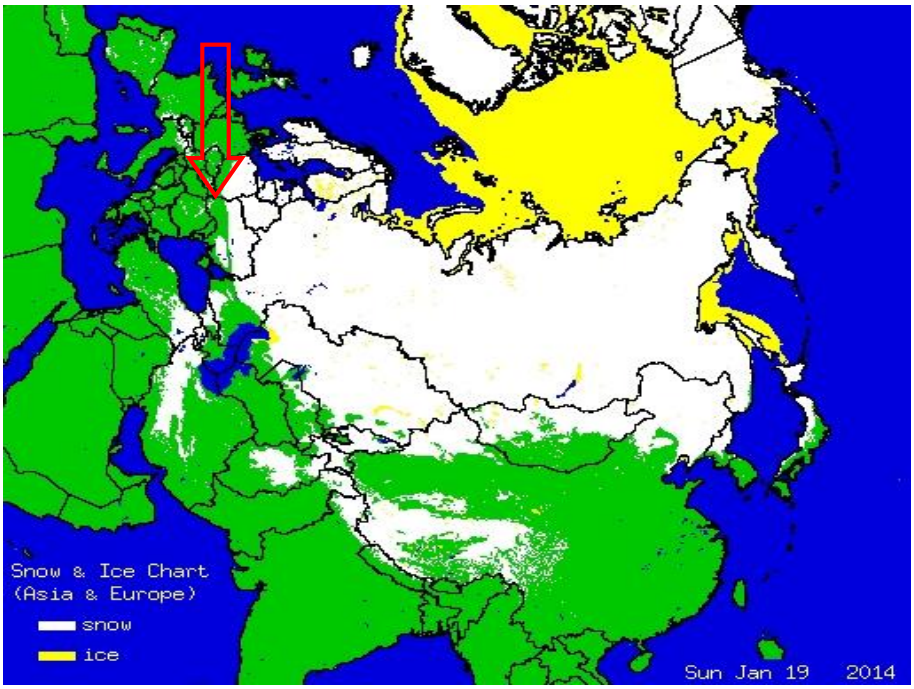

Fig. 5 - NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) snow/ice extent image of Europe/Asia (dated on 20/01/2014) (NOAA, 2014). (Red arrow indicates the change of snow cover in the southern half of Ukraine)

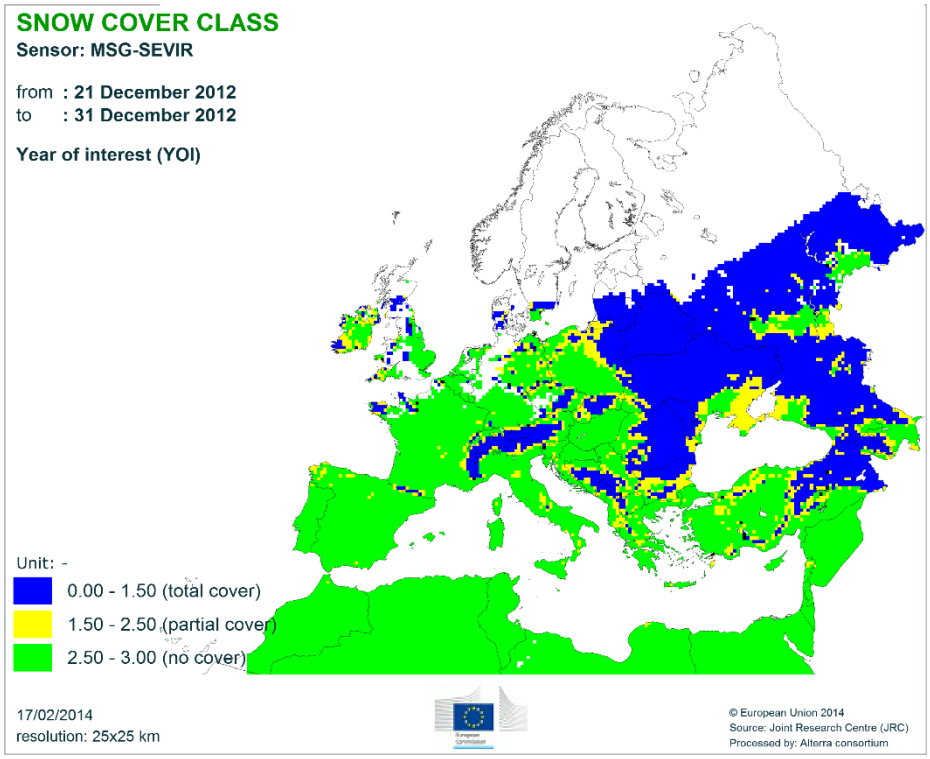

Fig. 6 - Snow cover classes of last decade of December 2012 (EUMETSAT MSG-SEVIRI sensor).

In CGMS Asia snow data is currently based on results of the ECMWF deterministic forecast model and contains only information on snow water equivalent. Snow density information is unavailable. It would be beneficial to derive snow depth from SWE. There are no meteorological observations of ground weather stations in the current version of CGMS Asia, but there are plans to include them in the next phase of the system development (MARSOP4). No remote sensing information of snow (e.g. geographical border of snow extent) exists in CGMS Asia.

SnowMaus Model

The SnowMaus model was published by Trnka et al. (2010).

This simple snow model simulates snow water equivalent and was mainly elaborated for agro-meteorological purposes. The model uses daily minimum and maximum temperatures and precipitation data as input parameters. It is downloadable from http://www.snowmaus.wz.cz/index.php?page=snowmaus&section=download as compiled running executables, but the source code/algorithm is not available on the associated webpage. Albeit the original article contains some errors in the explanation of the thawing algorithm, the original algorithm of the compiled program was completely reproduced at JRC-AGRI4CAST by using an artificial input data set (see Annex 2).

The SnowMaus model was implemented and tested in JRC-AGRI4CAST and plausible estimates were obtained for the dates of appearance and disappearance of snow cover. Consequently, the duration of snow cover also agrees well with snow observations.

One of the main features of SnowMaus is that it simulates snow water equivalent. Therefore the implementation of this model for deriving snow depth information requires the estimation of snow density (snow water equivalent/snow depth ratio). Snow density of freshly fallen snow can be assumed to be equal to 100 kg/m^3 (de Rosnay et al., 2012).

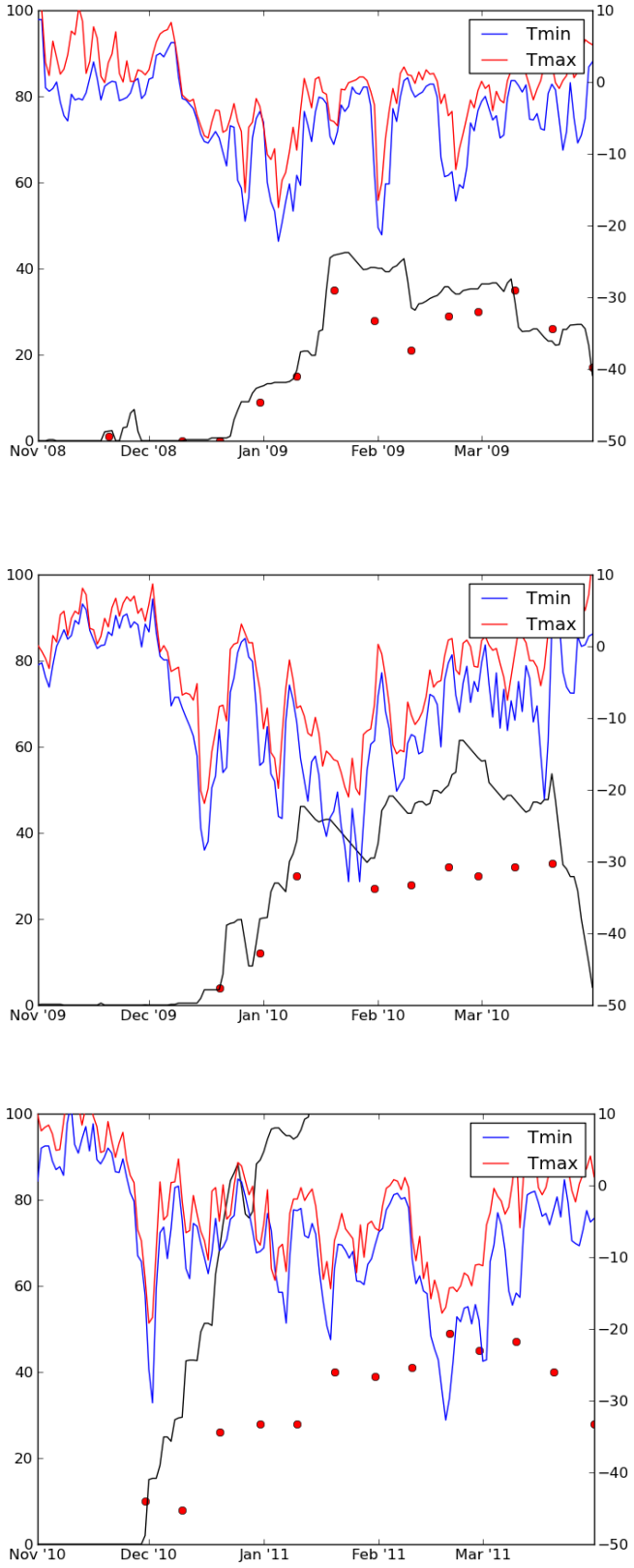

Fig. 7 - Comparison of calculated daily snow depth [cm] of SnowMaus model (solid black line) and measured snow depth (red dots) in Mtensk (RU) station during the winters 2008/2009 (upper), 2009/2010 (middle) and 2010/2011 (lower panel) respectively. The maximum (solid red line) and minimum (solid blue line) temperatures [°C] are also displayed as main driving factor of snow formation and melting process. (MOCCCASIN, 2013).

With this assumption SnowMaus model results were analysed w.r.t. snow depth observations by Allard de Wit (2012, personal communication) in the frame of the MOCCCASIN project (MOCCCASIN, 2013) for three winters in 2009-2011 for the Mtensk station (Russia, Orlovskaya oblast, N 53 16' 12'', E 36 33' 17''). As shown by Figure 7, definitive conclusions cannot be drawn. The SnowMaus model estimated reasonably well snow depth both in 2009 and 2010, with absolute mean error of 4.2 and 12.6 cm, respectively (Fig. 7). Although the winter 2011 experienced more precipitation and consequently higher snow depths than the two previous years, the model over-estimated snow depths at an unrealistic rate. The mean absolute error of winter 2011 reached 61.5 cm (Fig. 7). Indeed, the SnowMaus model can overestimate the snow depth when the temperature is close to the freezing point and the real snow density is higher than the applied constant value. Additionally the milder thermal conditions led to more compact snow cover and consequently shallower real snow depth.

Comparison of different snow products within the MCYFS

To perform a comparison of different snow products, 20 meteorological stations from Eastern and Northern Europe (Russia, Ukraine, Poland and Sweden) were selected. The stations are listed in Table 2. The analysis covered the period from October 1, 2011, until March 31, 2012. The main selection criterion was the availability of daily observed precipitation (Pcp), maximum (Tmax) and minimum (Tmin) temperatures on a minimum of 95% of days during the considered period (Table 2). The observed overall ratio of gaps is equal to 1.685%, all time series included. The strict weather station selection criterion didn't included the availability of snow data observations. Furthermore, the selection was focused on agricultural areas; only one mountainous weather station (Skole, Ukraine) was chosen. The other stations have moderate altitude, typically below 200 m.

Table 2 - List of weather stations used in the snow analysis.

Weather station	Country	Latitude	Longitude	Altitude	Nr. of data gap [day]
Astrahan'	Russia	46.28	47.98	-21	7
Gotska sandoen	Sweden	58.40	19.20	17	0
Kiev	Ukraine	50.40	30.57	167	14
Kirov	Russia	58.57	49.57	158	0
Krakow	Poland	50.08	19.80	242	1
Krasnodar	Russia	45.03	39.15	34	6
Moscow	Russia	55.83	37.62	157	3
Olevsk	Ukraine	51.22	27.67	183	0
Orel	Russia	52.93	36.00	196	2
Poznan	Poland	52.42	16.83	88	3
Rostov-Na-Donu	Russia	47.25	39.82	82	1
Skole	Ukraine	49.03	23.52	549	2
Smolensk	Russia	54.75	32.07	238	4
St.Peterburg	Russia	59.97	30.30	6	3
Stockholm	Sweden	59.18	17.92	45	0
Uman'	Ukraine	48.77	30.23	216	3
Vilkovo	Ukraine	45.40	29.60	2	2
Volgograd	Russia	48.78	44.37	134	5
Voronez	Russia	51.70	39.22	149	3
Yampol	Ukraine	49.97	26.25	282	0

The ECMWF data used in this comparison refer to the HIS/OPE deterministic forecast model. Data of the nearest grid point of the CGMS system were used for the calculations at each time step.

The following snow data and products were involved in this comparison exercise:

1. Measured snow depth at weather station.
2. CGMS Europe snow depth data interpolated on regular 25x25 km grid.
3. Snow depth of SnowMaus model (calculated using the simulated SWE and fixed S_DEN=100 kg/m^3).
4. Snow depth based on SWE of ECMWF OPE model (calculated using the SWE product of ECMWF OPE model and fixed S_DEN=250 kg/m^3 following the description of ECMWF (2001)).
5. Snow depth based on SWE and S_DEN parameters of ECMWF OPE model.

Measured snow depth was used as reference parameter, in spite of the frequent errors and gaps in the snow time-series. Some key results of this comparison are shown in the following Figures (8-16).

Measured snow depth versus SWE based on snow depth of the SnowMaus model

Dates of snow cover initiation and termination are well estimated by the SnowMaus model. The forming phase is mostly realistic (Fig. 8). On the contrary, the simulated melting phase is slower and sometimes delayed with respect to the measurements. The estimated maximum snow depth seems to be realistic at Polish and Ukrainian stations, whereas the depth of snow is significantly overestimated in case of Russia (Fig. 9). The magnitude of deviation (overestimation) depends on the geographical location, time and snow pack amount. Due to the cold climate of Russia the melting usually takes place only in spring-time therefore thick snow cover could be formed during wet winters. Compaction increases the density of the snow cover, primarily in winters when a deep snow cover exceeding approximately 300 mm of SWE at peak accumulation, is experienced. Therefore, the model needs an additional calibration for an extended use over Russia. Gaps in precipitation data or weather reports with consecutive 0 mm precipitation can also cause unreliable low values simulated by the snow model.

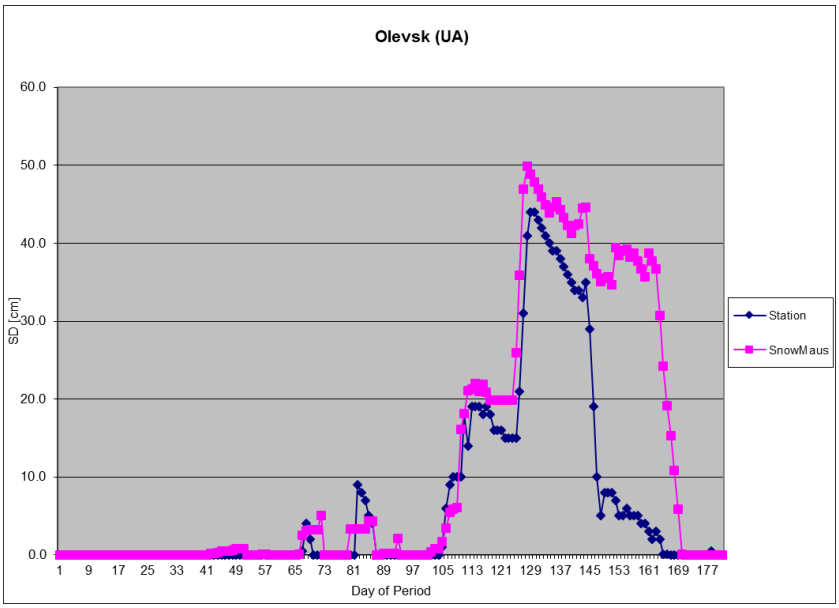

Fig. 8 - Snow depth [cm] simulated by SnowMaus model for Olevsk (UA) for period from October 1, 2011 until March 31, 2012. (Station – measured, SnowMaus – simulated data).

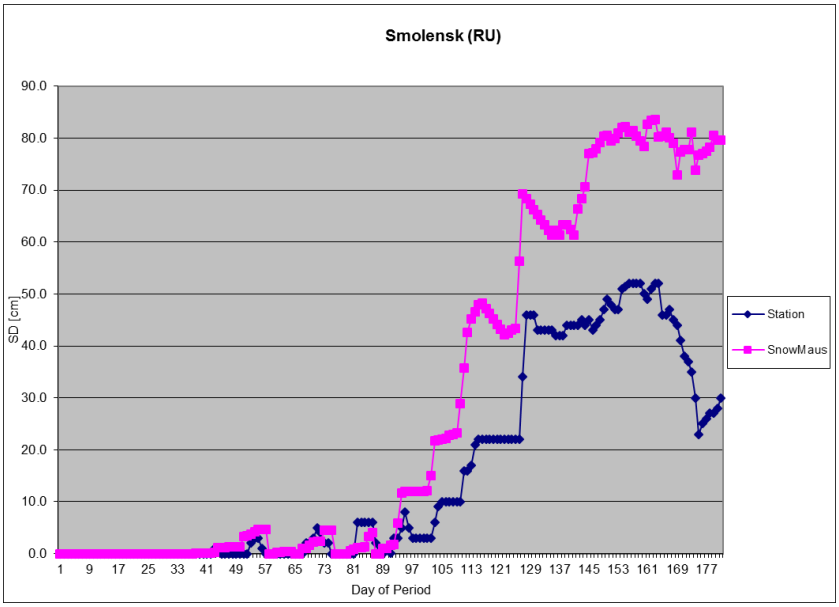

Fig. 9 - Snow depth [cm] simulated by SnowMaus model for Smolensk (RU) for period from October 1, 2011 until March 31. (Station – measured, SnowMaus – simulated data).

Finally, the SnowMaus model simulated unrealistic, approximately 5 times higher, snow depth for the mountainous region of Skole (UA). The estimated snow depth reached 341.7 cm against the real 67.0 cm value, probably due to the snow density fixed on a very low value. Therefore, it is highly recommended to test, verify and if needed re-calibrate the SnowMaus model before its use in a given place/region/country with no previous experience.

The SnowMaus model can be also used as an auxiliary tool to identify stations or time-periods with no snow reports (Fig. 10) and therefore contribute to data quality control.

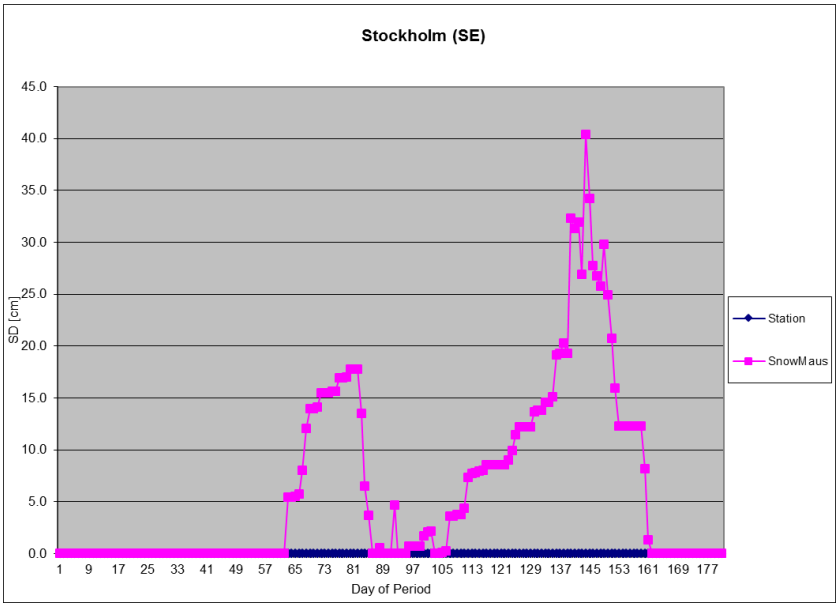

Fig. 10 - Snow depth [cm] simulated by SnowMaus model for Stockholm (SE) for period from October 1, 2011 until March 31. (Station – measured, SnowMaus – simulated data).

Measured snow depth versus interpolated snow depth from CGMS Europe

The interpolated snow depth of the nearest grid point to the station and the measured weather station data itself are equal or very similar when continuous weather observations are available. This is the obvious consequence of the interpolation method used in CGMS system. There are no appreciable differences among the interpolated snow values and the station values (for a station located within the specific grid box, climatologically representative and with available snow data). An example is provided for Volgograd (Fig. 11). Days with no meteorological observations (e.g. 13/03/2012, 26/03/2012 and 30/03/2012) cause gaps in the database, because there is no reliable neighbouring station to involve in the interpolation process. If there are no weather observations/reports at a given station and there are no other sources of snow information in the neighbourhood, then both data series can contain no snow information (0 value). This is well visible in the aforementioned regions of Scandinavia and Russia (Fig. 1).

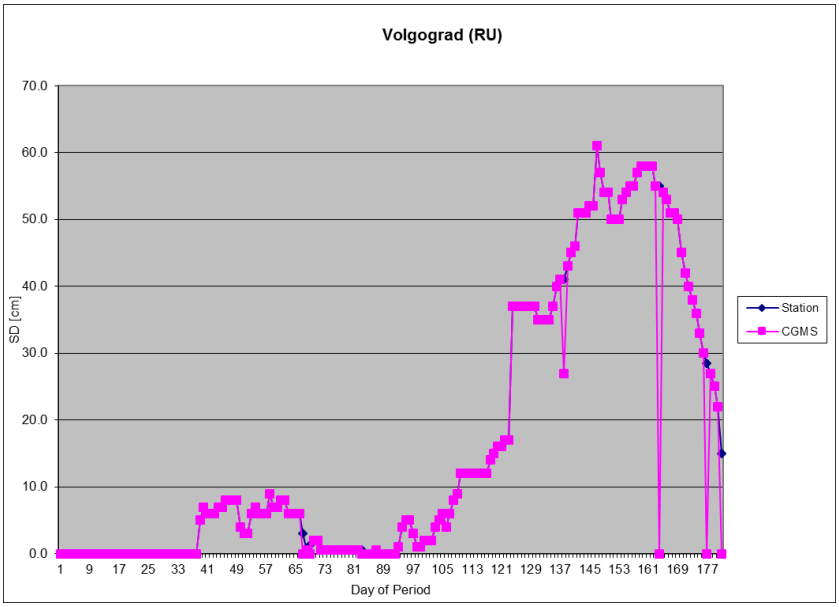

Fig. 11 - Example of good agreement between measured and CGMS Europe snow data for Volgograd (RU) for the period October 1, 2011 - March 31, 2012 (Station – measured, CGMS – CGMS Europe interpolated snow depth [cm]).

The interpolation can partly compensate (e.g., Astrakhan, RU, in Fig. 12) or mostly compensate (Rostov, RU; Fig. 13) the lack of snow reports. As shown in Figure 12, the sporadic (with a questionable reliability of the transmitted information in the WMO GTS) snow reports from the station of Astrakhan (Fig. 12) affect the interpolated values. The interpolation can compensate the data deficiency when reliable weather stations are available nearby, like in case of Rostov (Fig. 13).

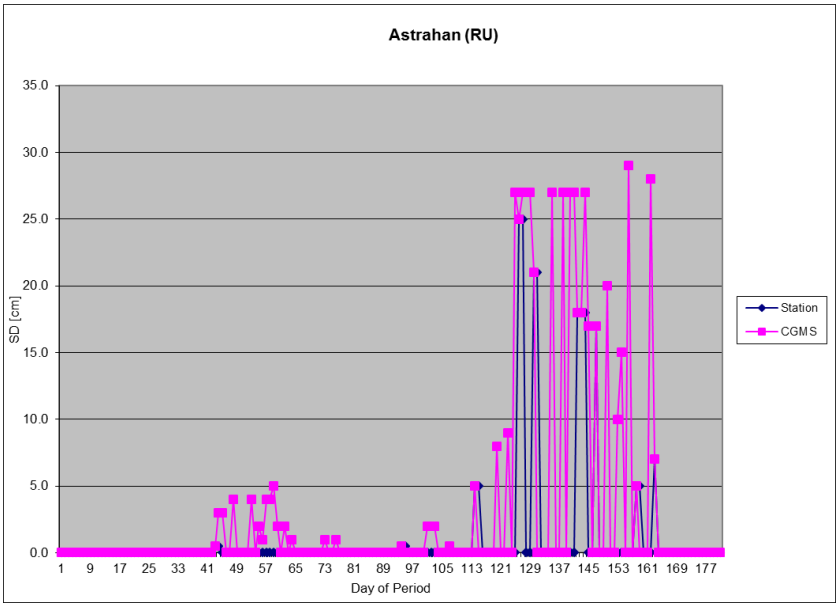

Fig. 12 - Interpolated snow depth data of CGMS can partially recover the lack of snow observation/ data transmission. The graph shows an example for Astrakhan (RU) for period from October 1, 2011 until March 31. (Station – measured, CGMS – CGMS Europe interpolated snow depth [cm]).

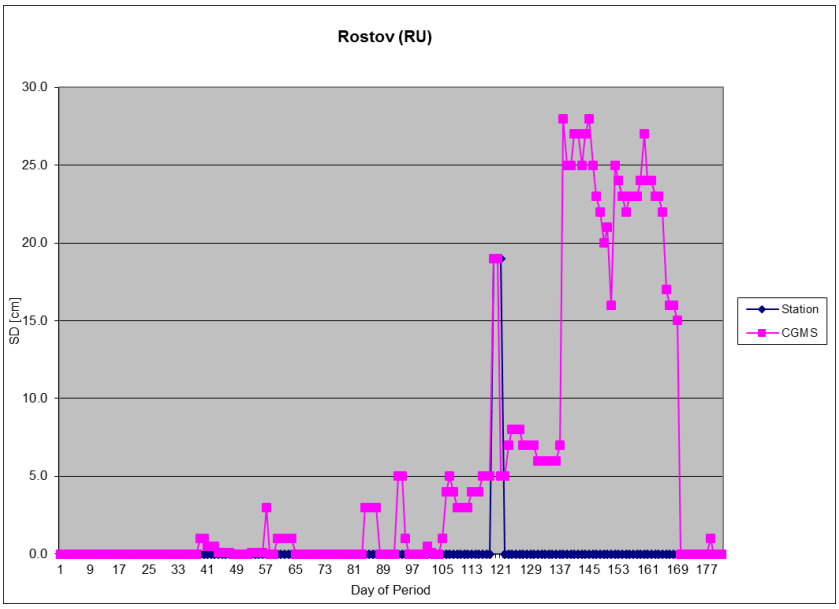

Fig. 13 -Interpolated snow depth [cm] of CGMS completes the time series for the grid cell at the absence of snow data at the nearest station. Example for Rostov (RU) for period from October 1, 2011 until March 31. (Station – measured, CGMS – CGMS Europe interpolated data).

Comparison of measured values versus snow depth derived from ECMWF SWE at constant snow density

The snow depth was calculated from the SWE by a simple constant multiplication factor (4.0), which is in accordance with the recommendation of ECMWF (2001). This approach theoretically assumes a constant average snow density of 250 kg/m^3 (ECMWF, 2001), which is reliable for usual settled snow cover (Table 1). The temporal change of snow density (e.g. aging of snow-cover) was not taken into consideration during this experiment.

Though there are considerable differences (mostly underestimation) between observed and ECMWF-simulated values of these two parameters, the temporal evolution and the duration of snow cover

(starting and end dates) are quite realistic and in close relationship between the measured and calculated values (Figs. 14 and 15). The reason behind the underestimation of snow depth is very likely the overestimated snow density.

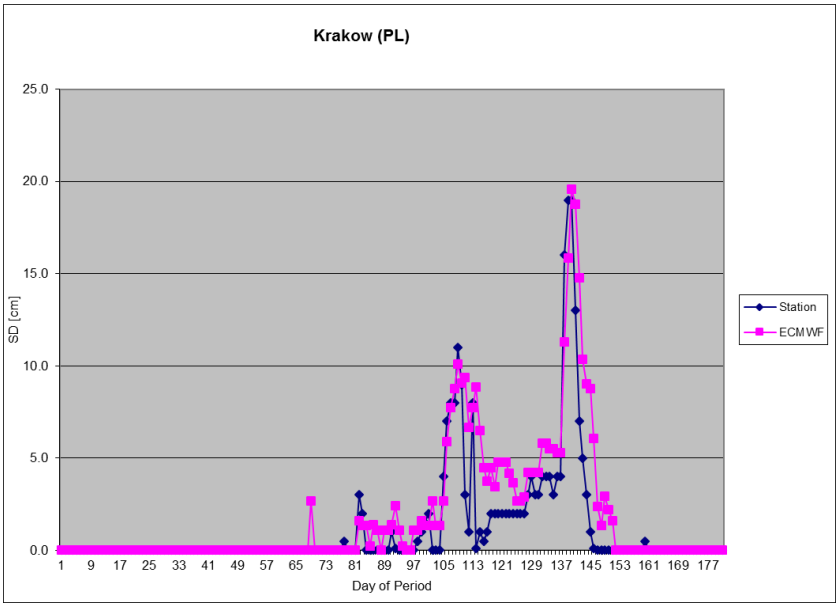

Fig. 14 - Example of realistic snow depth [cm] estimation by the help of ECMWF SWE and constant snow density parameters for Krakow (PL) for period from October 1, 2011 until March 31. (Station – measured, ECMWF – calculated snow depth using ECMWF SWE data and fixed snow density).

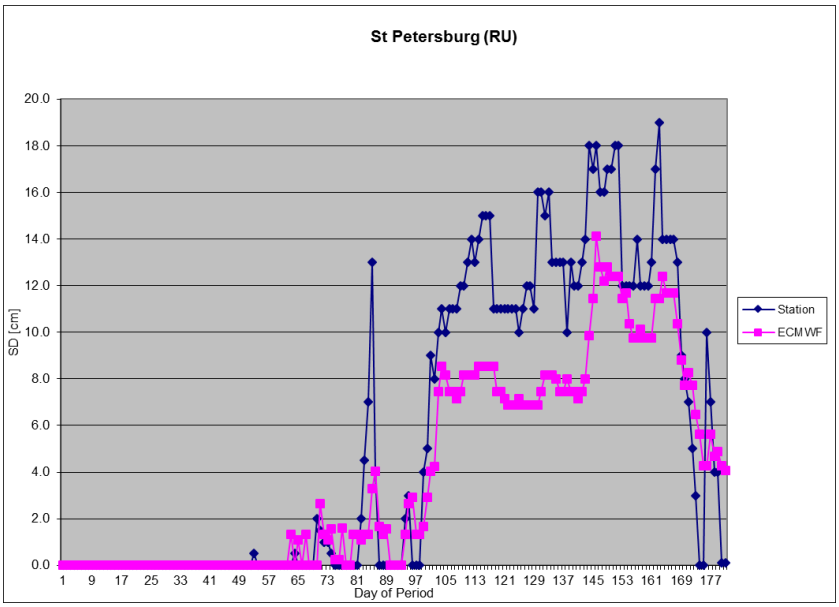

Fig. 15 - Example of underestimated snow depth for St. Petersburg (RU) for period from October 1, 2011 until March 31. (Station – measured snow depth, ECMWF – calculated snow depth using ECMWF SWE data and fixed snow density).

Comparison of measured snow depth versus snow depth derived from ECMWF snow water equivalent and ECMWF snow density

The best results were obtained with the combination of the modelled SWE and S_DEN data. The measured and calculated snow depths are very similar (Fig. 16). The improvement of snow depth estimates is obviously visible when comparing the new non-constant and the previous fixed snow density parameters (Figs. 14 and 15). The combined method of data assimilation and Land Surface Model simulation provides better agreement with the observations. However, the S_DEN parameter has significant instability especially for thinner snow cover (Fig. 17 and 18).

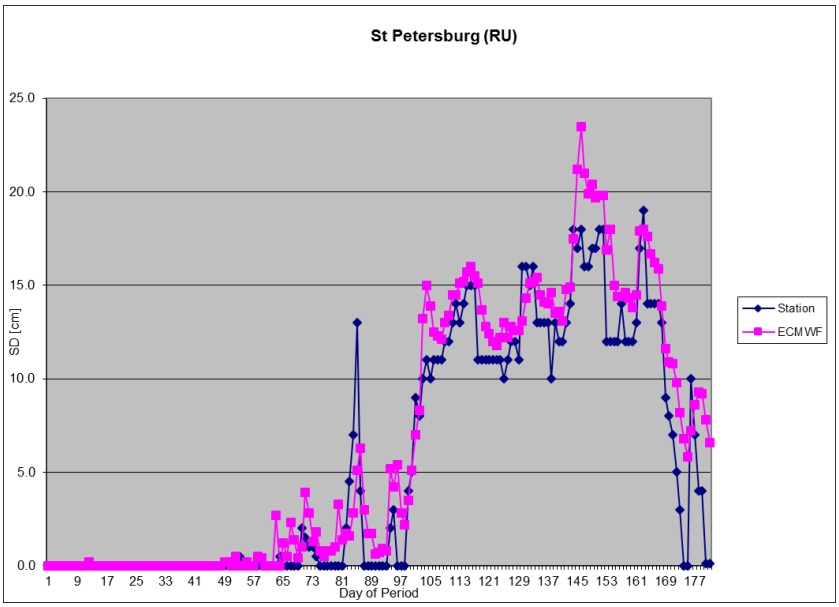

Fig. 16 Example of realistic snow depth [cm] estimation for St Petersburg (RU) for period from October 1, 2011 until March 31. (Station – measured snow depth, ECMWF – calculated snow depth using ECMWF SWE and non-constant snow density).

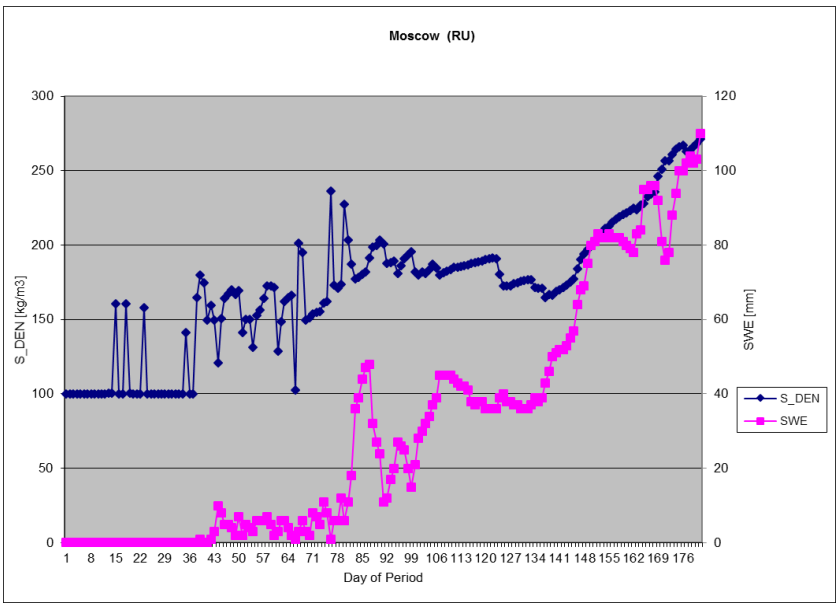

Fig. 17 - Example of temporal course and variability of snow density for Moscow (RU) for period from October 1, 2011 until March 31. (S_DEN – ECMWF snow density [kg/m^3], SWE – ECMWF SWE [mm]).

Furthermore, the inter-diurnal variability of snow density is high especially in autumn and early winter (Fig 17 and 18). This fluctuation is decreasing with the increase of SWE and depth of snow cover. The temporal evolution of snow density shows an increasing trend; this is in agreement with the aging of snow which becomes more compact.

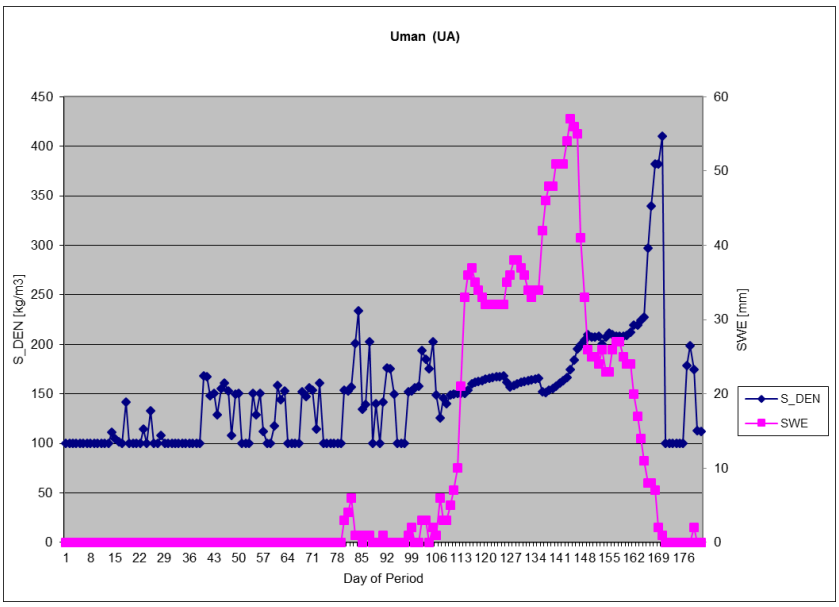

Fig. 18 - Example of temporal course and variability of snow density for Uman (UA) weather station for period from October 1, 2011 until March 31. (S_DEN – ECMWF snow density [kg/m³], SWE – ECMWF SWE [mm]).

Analysis of shallow snow cover data

In order to evaluate the use of snow products for winter frost kill simulations, a simple analysis was performed to compare the efficiency of SnowMaus, ECMWF SWE-based and snow density-based snow depth products. Frost kill in winter is negligible, if thick snow cover (SD>12 cm) provides sufficient protection against severe frost, but even shallower snow cover (SD=3-6 cm) can increase the minimum temperatures at crown depth relative to minimum air temperatures by more than 10°C (Wiersma et al., 2006). In the WOFOST model 15 cm deep snow fully protect the winter cereals (Annex 1). The same holds for the winter frost kill model used at JRC-MARS (Lazar et al., 2005). For this exercise, we selected all measurements from 20 stations having snow depth between 0 and 20 cm (0 cm < SD < 20 cm) and the related three snow products. The size of the investigated data sample was equal to 823.

The results indicate that the SnowMaus model performs weakly in the estimation of shallow snow depth. With the actual parameters, the model overestimates snow depth (Fig. 19). The determination coefficient (r^2) is only 0.37. This low correspondence can be caused by deficiencies in the simulation of the melting phase. This implies that the SnowMaus model is less useful and accurate in spring-time. The Root Mean Square Error (RMSE) is considerably high (29.8cm). Large deviations make questionable the use of this model in the workflow of ARGI4CAST in current form and without significant improvements.

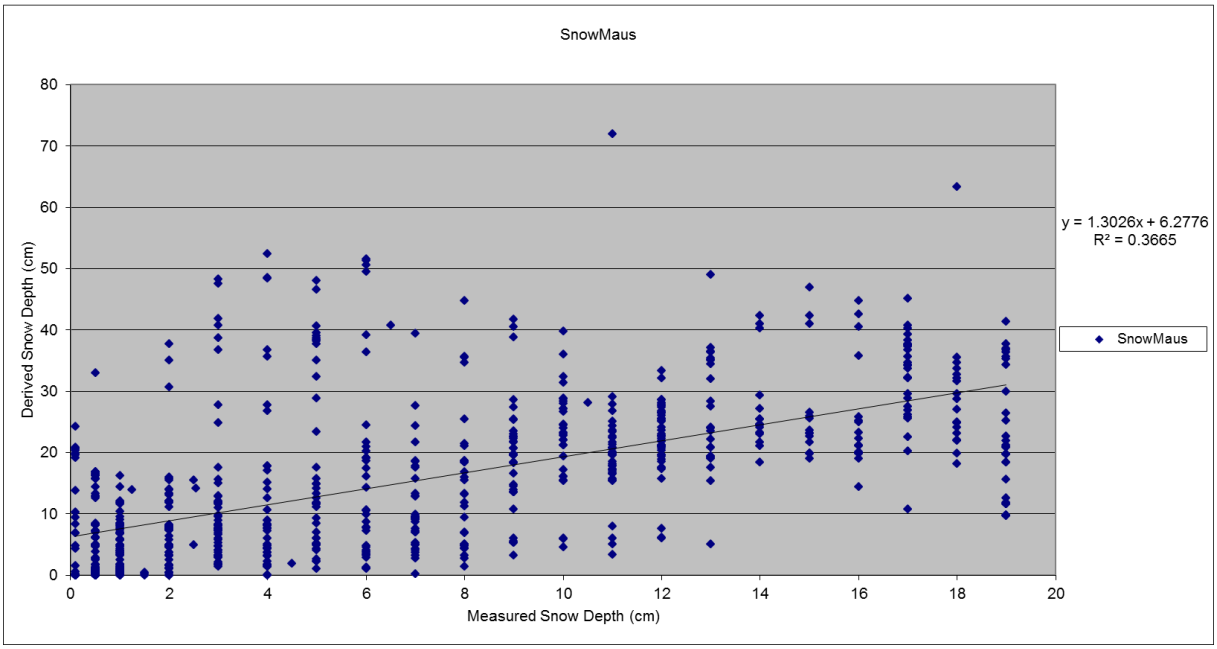

Fig. 19 - Comparison of measured (X-axis) and SnowMaus model simulated (Y-axis) snow depth with the regression line and equation of trend line.

The comparison of the measured snow depth and the snow depth derived from ECMWF SWE with fixed snow density based data shows a better correlation. The determination coefficient (r^2) reaches 0.63, while the RMSE is on an acceptable level (3.7 cm). Unfortunately, the snow depth is considerably underestimated by nearly 40%. This method seems to be applicable, but it would require recalibration taking into consideration the different geographical and climatological conditions (similarly to the determination of the constants during the calculation of global radiation in CGMS scheme).

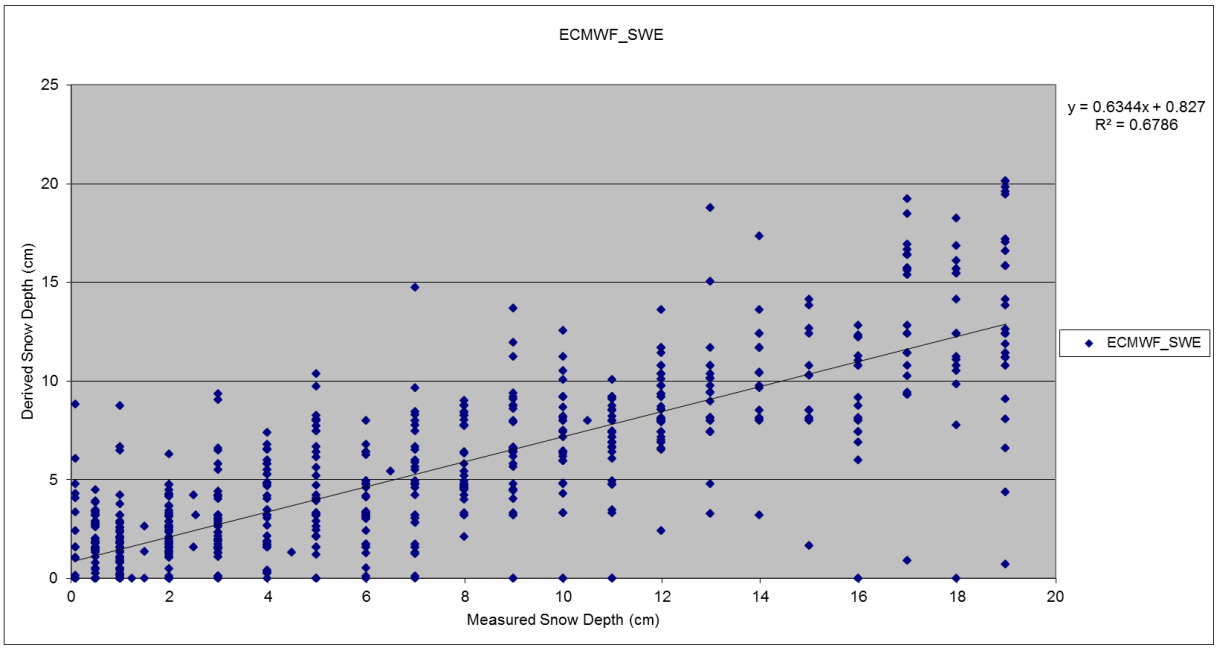

Fig. 20 - Comparison of measured (X-axis) and ECMWF SWE based (Y-axis) snow depth with the regression line and equation of trend line.

The most consistent snow depth comes from the combination of ECMWF SWE and ECMWF S_DEN data. The correlation coefficient is 0.87 (r^2=0.76). The RMSE was the lowest in this case, with a value of 3.0cm. The calculated snow depth was only slightly underestimated (by 10%).

Additionally, favourable conditions for the frost kill simulations have a low number of events when the snow cover depth is underestimated (decreased probability of false winter kill damage forecast). Considering the easy acquisition of the ECMWF input data and the accuracy of this method, the ECMWF-based snow product seems to be the most appropriate for winter kill simulation at JRC-AGRI4CAST. Further advantage is the most likely further development of this method at ECMWF and the involvement of the WMO GTS independent snow measuring networks as well as the planned usage of the newest remote sensing based products.

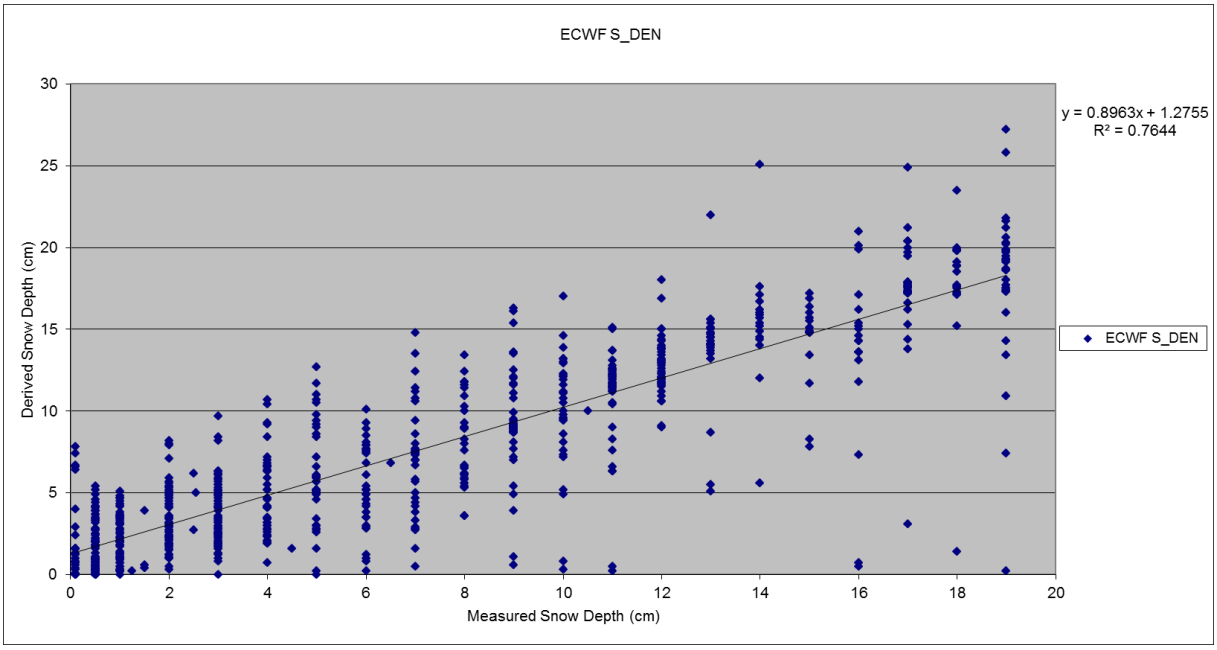

Fig. 21 - Comparison of measured (X-axis) and ECMWF SWE and S_DEN based (Y-axis) snow depth with the regression line and equation of trend line.

References

Aase, J. K., Siddoway, F.H., 1979: Crown – depth soil temperatures and winter protection for winter wheat survival. Soil Sci. Soc. Am. J. 43, 1229-1233.

Anderson E., 2006: Snow Accumulation and Ablation Model – SNOW-17. http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/part2/_pdf/22snow17.pdf, accessed on 22-08-2014.

Armstrong, R., Steffen, K., Monteduro, M., Sessa, R., 2009: Assessment of the status of the development of the standards for the terrestrial essential climate variables: Snow cover, FAO/GTOS ECV Report T5.

Cressman G, 1959: An operational objective analysis system. Monthly Weather Review Vol. 87, pp. 367–374

Cuffey K. M., Paterson W.S. B., 2010: The Physics of Glaciers, Fourth Edition, Elsevier, Amsterdam, p. 12.

de Rosnay P., Muñoz Sabater J., Albergel C., Isaksen L. and Balsamo G., 2011: ECMWF Land Surface Data Assimilation System Activities, SRNWP Expert Team Meeting, 5 Sep. 2011, ECMWF, Reading, UK, http://www.ecmwf.int/newsevents/meetings/workshops/2011/SRNWP/8-derosnay.pdf

de Rosnay P., Balsamo G., Albergel C., Muñoz-Sabater J., Isaksen L., 2012: Initialisation of land surface variables for numerical weather prediction. Surveys in Geophysics, 1-15.

de Rosnay P., 2013: ECMWF snow data assimilation: Use of snow cover products and In situ snow depth data for NWP, GCW Snow Watch Workshop, Toronto, 28-30 January 2013, http://www.wmo.int/pages/prog/www/OSY/Meetings/GCW-PS1/Doc5.6_ECMWF_assimilation.pdf, accessed 30-09-2013

Dutra E., G. Balsamo, P. Viterbo, P. Miranda, A. Beljaars, C. Schär, K. Elder, 2010: An Improved Snow Scheme for the ECMWF Land Surface Model: Description and Offline Validation. J. Hydrometeor, 11, 899–916.

ECMWF 2001: http://www.ecmwf.int/newsevents/training/rcourse_notes/PARAMETRIZATION/SURFACE_ASSIMILATION/Surface_assimilation8.html#649026, accessed 26-07-2013

ECMWF, 2010: http://www.ecmwf.int/staff/gianpaolo_balsamo/DOC/Snow_rd_memo_1.pdf, accessed on 26-07-2013

Gusta, L.V., Fowler D.B., 1976: Effects of temperatures on de-hardening and re-hardening of winter cereals. Can. J. Plant Sci. 56, p. 625-636

Lazar C., Micale F., Genovese G., 2005: Simulation of Frost Resistance of Winter Wheat in Europe between 1975 and 2005; www.agrometeorologia.it/documenti/Aiam2005/62.pdf

MOCCCASIN, 2013: http://www.mocccasin.eu/home accessed on 21-12-2013

NASA, 2013: Daily North American Snow Cover, http://modis-snow-ice.gsfc.nasa.gov/, accessed 30-09-2013

NOAA. 2014: US National Ice Centre Interactive Multisensor Snow and Ice Mapping System (IMS) archive, http://www.natice.noaa.gov/pub/ims/ims_gif/ARCHIVE/EuAsia/2012/ , accessed on 22-08-2014

Pullen S., Jones C., Rooney G., 2011: Using satellite-derived snow cover data to implement a snow analysis in the met office NWP model. J Applied Meteorology Vol. 50, pp. 958–973.

Ritchie, J.T., 1991. Wheat phasic development. p. 31-54. In Hanks and Ritchie (ed.) 1991: "Modeling plant and soil systems. Agron. Monogr. 31", ASA, CSSSA, SSSA, Madison, WI.

Sturm, M., Holmgren, J., Liston, G. E., 1995. A seasonal snow cover classification system for local to global applications. Journal of Climate, 8(5), 1261-1283.

Takala M, Luojus K, Pulliainen J, Derksen C, Lemmetyinen J, Kärnä JP, Koskinen J, Bojkov B, 2011: Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing Environment Vol 115, pp. 3517–3529.

Wiersma, J. J., Durgan, B. R., Hollingsworth, C., MacRae, I. V., Rehm, G., 2006. Winter wheat in Minnesota. University of Minnesota Extension Service.

Annex 1.

The actual frost kill calculation method

The current frost kill model of JRC-MARS is based on the method developed for winter wheat crop by J.T. Ritchie (1991). The used time step of the model is daily. The main input meteorological data are: maximum temperature, minimum temperature and snow depth. The model simulates the hardening index of winter crops and thus provides an estimate of the low-temperature tolerance of cereals, taking into account plant physiology. During the hardening process of crops the cellular starch is transformed into glucose resulting lower freezing point of the cellular liquids to survive more severe frosts. The fully hardened winter wheat is considered to tolerate –18°C. Temperatures lower than –20°C can be harmful for the crops with no insulation effects of a sufficient snow cover (>15 cm).

The hardening and de-hardening concept is used to describe the change of the low-temperature tolerance of winter wheat. This sub-model uses the results of Gusta and Fowler (1976). Hardening is assumed to occur in two stages:

- First, it occurs when mean crown temperature is between -1 and +8°C. Ten days in this range completes the first stage of hardening.
- The second stage of hardening starts when the mean crown temperature is less than 0°C. Twelve days are needed to arrive at a full hardened plant.

De-hardening is assumed to occur when maximum crown (tillering node) temperature is higher than 10°C during the first stage of hardening. The de-hardening increment is assumed to be half of de-hardening rate in second stage.

Crown (tillering node) temperature is assumed to be equal to the soil temperature measured at 3cm depth, and it is estimated on the basis of an empirical sub-model developed by Aase and Siddoway (1979). Main factors that influence damages are crown temperature, snow depth, and hardening status of the winter wheat. Snow depth has an important influence on plant hardening and survival when air temperature is lower than -10°C. If mean crown temperature decreases below a given threshold (kill crown temperature), an increasing fraction of a plant population dies; it reaches 95% of entire population, if mean crown temperature is at least 7 degrees colder than kill crown temperature. Kill crown temperature depends linearly on the hardening level (expressed by the hardening index) reached by the crop (Lazar et al., 2005).

The values of kill crown temperature introduced in the model are based on the analysis of winter wheat varieties grown in cold regions of Canada. Varieties of winter wheat with lesser cold tolerance could have higher kill crown temperatures. The calculated winter kill damage index should be considered as mean potential winter kill risk that could impact plant population in the field.

Annex 2

SnowMAUS model in C#

Implementation of the SnowMAUS model in BIOMA platform in C# for estimating snow depth and snow water equivalent using standard daily agrometeorological weather variables.

Based on: M. Trnka et al. 2010. Simple snow cover model for agrometeorological applications, Agricultural and Forest Meteorology, Volume 150, Issues 7–8, 15, Pages 1115-1127, ISSN 0168-1923, 10.1016/j.agrformet.2010.04.012.

Antonio Zucchini, European Commission, JRC, IES, MARS-Agri4Cast, Ispra 2014

```
internal double SnowMaus_(double Snow_, double SnowBefore_, double Tmax_, double Tmin_, double Rain_, double MausOutputSnowWaterEquivalent_, double MausInputSnowWaterEquivalent_, double MausTminPartialRainLowThreshold_, double MausTminTotalRainLowThreshold_, double MausTminMeltLowThreshold_, double MausTmaxMeltLowThreshold_, double MausRainMeltRate_, double MausSublimationLowThreshold_, double MausSublimation_)
{
    double RetVal_ = 0.0;
    double SnowAcc_ = 0.0;
    double SnowMelt_ = 0.0;
    int SnowAccPresence_ = 1;

    RetVal_ = SnowBefore_ * 10 / MausInputSnowWaterEquivalent_;

    if (Tmin_ = MausTminTotalRainLowThreshold_)
        SnowAcc_ = Rain_;
    else if (Tmin_ = MausTminTotalRainLowThreshold_ && Tmin_  MausTminPartialRainLowThreshold_)
        SnowAcc_ = (1 - (Tmin_ - MausTminTotalRainLowThreshold_) / Math.Abs(MausTminPartialRainLowThreshold_ - MausTminTotalRainLowThreshold_)) * Rain_;
    if (SnowAcc_ = 0)
    {
        SnowAccPresence_ = 0;
        SnowAcc_ = 0;
```

```
    }
    if (Tmin_ == MausTminMeltLowThreshold_ && Tmax_ == MausTmaxMeltLowThreshold_)
        SnowMelt_ = (Tmin_ + Math.Abs(MausTminMeltLowThreshold_)) * MausRainMeltRate_;

    if (RetVal_ = MausSublimationLowThreshold_)
        RetVal_ = RetVal_ + SnowAcc_ - SnowMelt_;
    else
        RetVal_ = RetVal_ + SnowAcc_ - SnowMelt_ -  (1 - SnowAccPresence_) * MausSublimation_;

    RetVal_ = RetVal_ * MausOutputSnowWaterEquivalent_ / 10;

    if (RetVal_  0)
        RetVal_ = 0;

    return RetVal_;
}
```

List of used parameters used in the SnowMaus model:

VarInfo name="MausTminPartialRainLowThreshold"

Description= Value of Tmin below which part of rain is assumed to be snow

DefaultValue=0

Type=double

Units=Celsius degrees

VarInfo name="MausTminTotalRainLowThreshold"

Description= Value of Tmin below which all rain is assumed to be snow

DefaultValue=-6

Type=double

Units=Celsius degrees

VarInfo name="MausTminMeltLowThreshold"

Description= Value of Tmin above which melting of snow is possible

DefaultValue=-12

Type=double

Units=Celsius degrees

VarInfo name="MausTmaxMeltLowThreshold"

Description= Value of Tmax below which no melting is possible on the day if Tmin is below freezing point

DefaultValue=5

Type=double

Units=Celsius degrees

VarInfo name="MausRainMeltRate"

Description= Melting Rate in mm of snow water equivalent for every Celsius degree above MausTminMeltLowThreshold

DefaultValue=0.42

Type=double

Units="mm/C*Day

VarInfo name="MausSublimationLowThreshold"

Description= Value of Snow water equivalent above which sublimation occurs if we don't have snow accumulation in same day

DefaultValue=20

Type=double

Units=mm

VarInfo name="MausSublimation"

Description= amount of snow water equivalent that sublimes every day when conditions are fulfilled

DefaultValue=1

Type=double

Units=mm

VarInfo name="MausInputSnowWaterEquivalent"

Description= Factor of Snow Water Equivalence Input

DefaultValue=4

Type=double

Units=-

VarInfo name="MausOutputSnowWaterEquivalent"

Description= Factor of Snow Water Equivalence Output

DefaultValue=4

Type=double

Units=-

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