Simulated versus Satellite Retrieval Distribution Patterns of the Snow Water Equivalent over Southeast Europe

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Abstract**—** *Snow is a very important component of the climate system which controls surface energy and water balances. Its high albedo, low thermal conductivity and properties of surface water storage impact regional to global climate. The various properties characterizing snow are highly variable and so have to be determined as dynamically active components of climate. However, on large spatial scales the properties of snow are not easily quantified either from numerical modelling or observations. Since neither observations (ground measurements or satellite retrievals) nor models alone are capable of providing enough adequate information about the time space variability of snow properties, it becomes necessary to combine their information. In the presented study the obtained with the regional climate model RegCM snow water equivalent (SWE) on monthly basis over Southeast Europe for a time window of 14 consecutive winters is compared with the Globsnow satellite product. The concordance between both datasets is evaluated with number of statistical scores. The result reveals the principal agreement between the two products, but however, with very significant discrepancies, mainly overestimations, for some years and gridcells.*

Keywords**— *Snow water equivalent, Satellite observation, RegCM simulation, Globsnow product, Datasets comparison.***

I. INTRODUCTION

The snow is a very important component of the climate system which controls surface energy and water balances and is the largest transient feature of the land surface Yang et al., 2001). It has an effect on atmospheric circulation through changes to the surface albedo, thermal conductivity, heat capacity and aerodynamic roughness as has been documented in numerous observational and modelling studies (e.g., Barnet et al., 1989 Gong et al., 2003). According Cliford et al., (2010), the snow properties of surface water storage control the availability of water in many ecosystems and to a sixth of the world's population. Therefore it is vital that snow is properly represented in geophysical models if we want to understand and make predictions of weather, climate, the carbon cycle, flooding and drought.

The various properties characterizing snow are highly variable and so have to be determined as dynamically active components of climate. These include the snow depth (hs), SWE, density, and snow cover area (SCA). The SWE is a measure of the amount of water contained in snow pack and is the product of snow depth and snow density. Unfortunately, from the four snow metrics listed above, only extent (i.e., SCA) is easily monitored using satellites. SCA, however, is only an indirect measure of the world's snow water resources (e.g., Brown, 2000 Brown et al. 2000). To understand global snow water trends in the necessary depth, the most fundamental metric to assess is SWE, with hs a close second. However, on large spatial scales the properties of snow are not easily quantified either from modelling or observations. For example, station based snow measurements often lack spatial representativeness, especially in regions where the topography, vegetation and overlaying atmosphere produce considerable heterogeneity of the snow-pack distribution (Liston, 2004).

Of the two fundamental parameters, depth is quicker and easier to measure than SWE. No detailed estimates of the total number of depth and SWE measurements made worldwide is available, but what is available suggests that considerably more depths are collected than SWE measurements. So, for example, following the directives of the World Meteorological Organization (WMO), hs is measured in every station of the network of the Bulgarian National Institute of Meteorology and Hydrology at the Bulgarian Academy of Sciences (NIMH-BAS) every day, at 06 UTC and SWE - usually only five times monthly. It is clear that data-sets with such time gaps are highly insufficient for any comprehensive snow climatology. This fact is strengthened by the already mentioned spatial heterogeneity of the snow cover parameters. Satellite Earth observation (SEO) and RCM provides spatially and temporally consistent data regularly; especially as many snow-affected areas are covered with sparse ground-based measurement networks. Despite the weaknesses of both methods, data from these information sources should be combined with conventional data in optimal way in order to produce comprehensive representation of the snow-pack distribution and its long-term dynamics. Hence, due to these weaknesses, which will be adressed further, not RCM-, nor SEO-products can be treated solely as 'ultimate true', every evaluation of the model performance (i.e. “model verification”), respectively the satellite data quality, based only upon the comparison with the other, would be incorrect. It is possible and necessary, however, to asses the concordance between them over certain area for climatologically long enough (i.e. more the decade) period.

The presented work is part of common effort in NIMH-BAS elaborate more reliable picture of snow- pack distribution and its long-term dynamics over Bulgaria and the surrounding territories, involving all available information. Thus, subject of previous paper of Chervenkov et al. (2015) was the comparison of RCM output for SWE with measurements and, therefore, the presented study can be treated as possible continuation.

Main aim is to compare the gridded digital maps of SWE, resulting from the Globsnow SEO-product, which, as will be shown further, are practically only one reasonable possibility, with the output of the well-known in the climatological community regional climate model RegCM for 14 consecutive winters in the period 2000-2014 for the region of Southeast Europe, searching, in particular, systematic disagreement.

The paper is organized as follows: The considered two information sources and the corresponding datasets are described briefly in Section 1. Explanation of the methodology of the performed comparisons is placed in Section 2. Core of the paper is Section 3, where the results are presented and commented. The conclusions and concise summary and the are briefly stated in Section 4.

II. USED DATA

2.1 SEO SWE Product Globsnow

The SWE is measured by passive microwave (MW) radiometers carried by near-polar orbiting platforms on routinely basis since 1988. All objects emit MWs, although the soil under the snow-pack emits stronger MW-signal and these microwaves are scattered and attenuated by the snow as they travel upwards. The attenuation depend on the wavelength and the snow-pack properties, in particular the amount of snow (SWE) grain size, snow density, presence of ice lenses and the amount of liquid water. The shorter the wavelength the greater the scattering for a given set of snow-pack properties, thus the difference between the signals at two wavelengths is related to the amount of snow and this is the basic of the measurement principle. Although it has been theoretically derived and tested over certain areas this approach is known to suffer from a number of issues, as dependence from the snow grain size, liquid water amount and vegetation cover as well as saturation in deeper snow covers (SWE>120 mm). Not at least, shallow snow-packs cause little scattering and can be missed by microwave sensors. These obstructive issues are inherent source of errors and biases and, strictly speaking, implemented techniques can only minimize this effect. Additionally, satellite retrieval estimates require inversion algorithms to relate raw signals recorded at the satellite to physical properties of the land surface and these inverted estimates can introduce further deviations.

Several SEO SWE products for the Northern hemisphere are available nowadays. As far as their description is far beyond the scope of the presented work, only the considered one will be discussed briefly here. The reader, however, can find in Hancock et al. (2013) and in the references therein explanatory description of most of these products, as well as in depth intercomparison between their performances.

SEO SWE product Globsnow, noted further as Globsnow, is main outcome of the European Space Agency (ESA) Data User Element (DUE) GlobSnow-2 project (http://www.globsnow.info) with participants from 10 institutions.

The key objective of the project was the further development of methodologies for producing long-term records of snow cover information at the global scale intended for climate research purposes. The efforts were focused on developing methodologies for the retrieval of SCA and SWE information based on satellite data. The work involved acquisition of the long-term satellite data records and development of suitable algorithms and software for producing snow cover information at the global scale spanning decades. Globsnow relays on considerable support from ancillary information from surface observations, performed in network of established stations, located mainly over Fennoscandia (Metsämäki et al. 2015). The sophisticated iterational Globsnow procedure includes emission inversion calculations used as first guess field, which are corrected with ground measurements of the snow depth and grain size via original assimilation technique (see Takala et al. 2015 for detailed description).

Strong reasons has motivated the authors to choose Globsnow: First, the utilization of the state-of-the-art procedures for the processing of the satellite retrieval ensures, at least theoretically, better final outcome in comparison with older counterparts. Second, and most important, many studies (see, for instance, Hancock et al., 2013) demonstrate the overall better performance of Globsnow. Not at at least is the unrestricted and unlimited access of validated SWE data-sets (daily, weekly and monthly aggregated) and especially their time extend (more than 35 years), which is relevant for climatological intercomparison studies as the presented here. As certain drawback of this informational source can be pointed the absence of data for mountainous regions, which, at least from hydrological point of view, are important.

2.2 RCM simulations

RCMs have been developed and extensively applied in the recent decades for dynamically downscaling coarse resolution information from different sources, such as global circulation models (GCMs) and reanalysis, for different purposes including past climate simulations, as in the presented study and future climate projection. This widely used and productive approach is applied here. The main simulation tool is the freely available version 4 of the Regional climate model RegCM of the International Center of Theoretical Physics (ICTP) in Italy (www.ictp.it). RegCM4 is a 3-dimensional, sigma-coordinate, primitive equation RCM with dynamical core based (version 2 and later) on the hydrostatic version of the NCAR-PSU Mesoscale Model 5 (MM5) (Grell et al. 1994). The radiative transfer package is taken from the Community Climate Model v. 3 (CCM3) (Kiel et al.1996) The large-scale cloud and precipitation computations are performed by Subgrid Explicit Moisture Scheme (SUBEX, Pal et al., 2000) and the land surface physics are according to the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al., 1993). The adopted convective scheme for the RCM simulations in the present study is the Grell scheme (Grell, 1993) with the Arakawa and Schubert (Arakawa and Schubert 1974) closure assumption. The reanalysis datasets ERA-Interim of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011) are used for the initial and boundary conditions.

The model domain is centered over Bulgaria and consists of 72×77 20 km×20 km gridcells. The simulation period is from 1th November till 31th March (hereafter: winter) for 14 consecutive years between 2000 and 2014. Model output is the gridded distribution of the SWE on 6-hourly basis (i.e. at 00, 06, 12 and 18 UTC), which are post-processed to the monthly averages.

III. METHODOLOGY AND PERFORMED MODEL CALCULATIONS

Aim of the study, as already mentioned, is compare the gridded output of the considered data sources for the target area and period, rather to perform long-term assessment of the snow cover. Thus and for sake of brevity a detailed description of the snow climatology should be omitted. As usual in many climatological studies, January is accepted as representative for the winter. Additionally, according Kjuchukova (1974), the climate mean snow depth reaches maximum in the plains of Bulgaria at the end of January and due to this reasons all presented comparisons are performed for this month.

The Globsnow SWE is presented on Fig. 1 and the simulated with the RegCM values on Fig. 2.

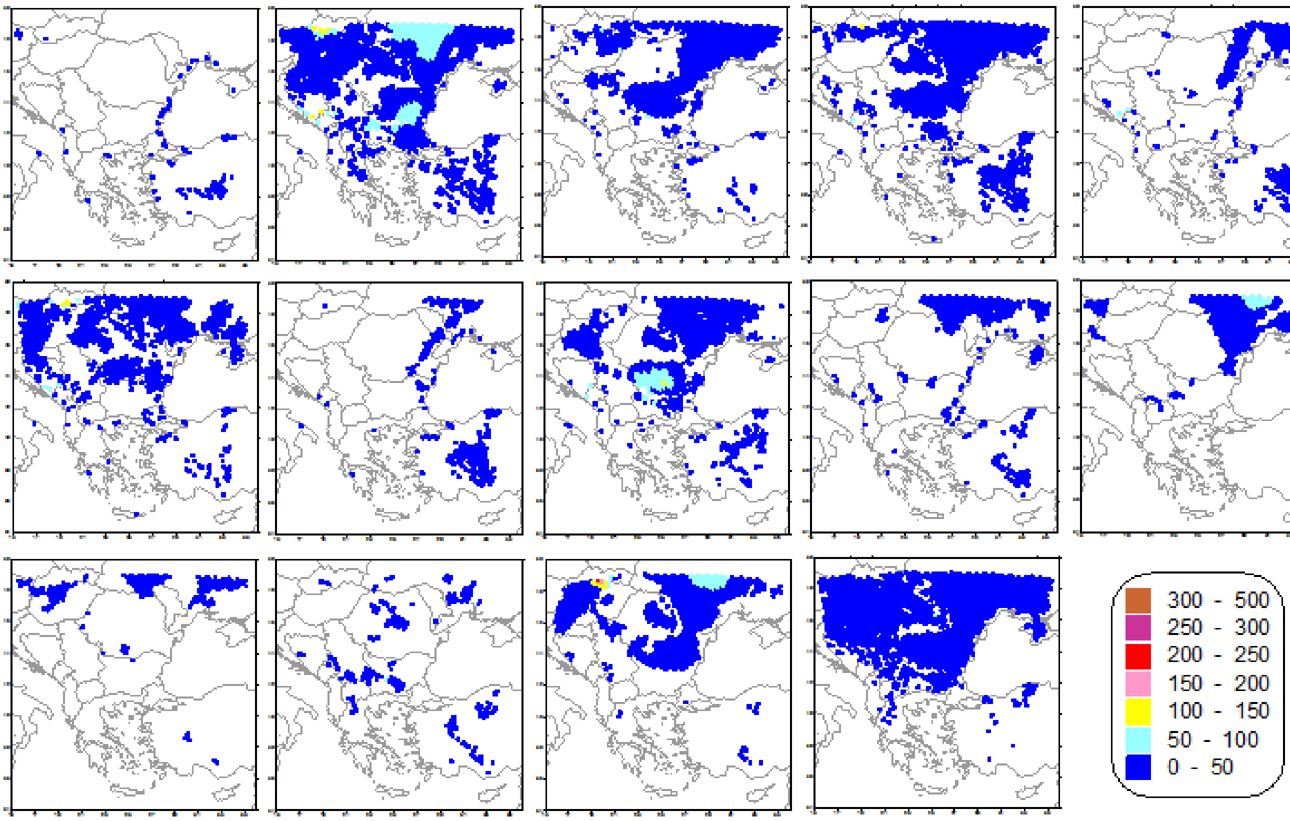

Figure 1. Monthly aggregated Globsnow SWE (unit: kg.m-2) for January for the period 2001 – 2014. January 2001 is in the UL corner, the order is in rows.

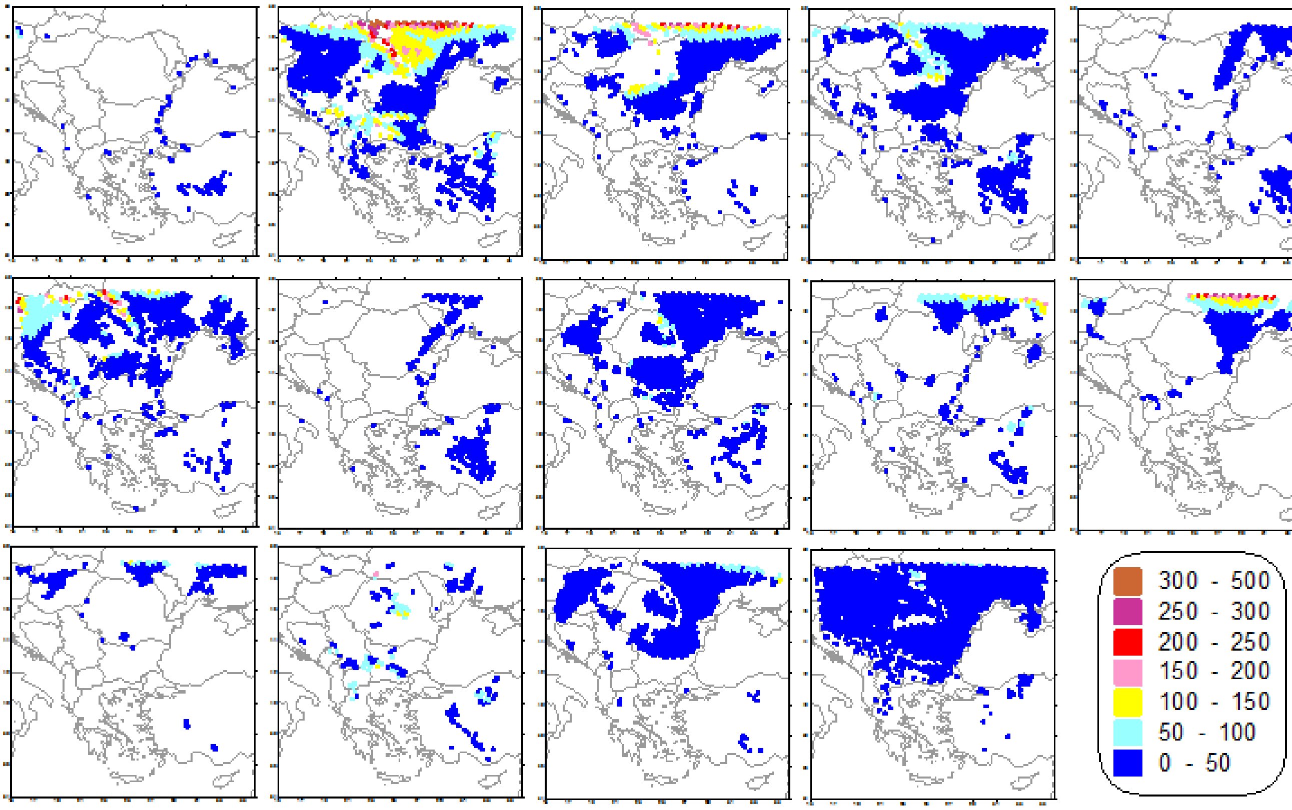

Figure 2. Same as Figure 1, but for the RegCM

The comparison with the monthly aggregated Globsnow values is performed pixel-by-pixel using the inverse distance weighted (IDW) interpolation method. The comparison is impossible if the SWE value in given Globsnow pixel is below 0.001 mm (according the product description, -2, -1 and 0.001 are flags for mountains, water basins and fractional snow cover correspondingly) or the Globhsnow value, respectively the Globsnow one in some pixel are undefined. As far as the model domain is semi-mountainous, the exclusion of these pixels limits significantly the number of the possible comparisons.

Traditionally the degree of agreement of the observed values O_i and their modelled correspondents M_i, is estimated with set of frequently used statistical quantities, including the root mean square error (RMSE), the correlation coefficient (also termed the Pearson correlation coefficient, r), the index of agreement (IA) and the mean bias (BIAS). Explicit formulas for the first two will not be given due to their popularity, and the last two are equal accordingly to:

$$IA = 1 - \frac{\sum_{i=1}^{N}(O_i - M_i)^2}{\sum_{i=1}^{N}\left(\left|M_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2} \tag{1}$$

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i) \tag{2}$$

The summation is along the number of comparisons N and the overlines notes space-averaging. Additionally, the pattern of the normalized mean bias (NMB), which is quantitative metrics of the departure of the modelled results to the measurement in every pixel with geographical coordinates φ, λ is obtained, according to

$$NMB_{\varphi,\lambda} = \frac{O_{\varphi,\lambda} - M_{\varphi,\lambda}}{O_{\varphi,\lambda}} \cdot 100\% \tag{3}$$

IV. RESULTS

The values of the computed statistical indexes are shown in Table 1.

TABLE 1
VALUES OF THE STATISTICAL INDICES OF THE COMPARISON GLOBSNOW/REGCM YEAR-BY-YEAR. THE SECOND COLUMN ("PAIRS NUMBER") CONTAINS THE LENGTH OF EACH DATASET (I.E. NUMBER OF POSSIBLE GLOBSNOW/REGCM COMPARISON PAIRS). THE LAST ROW IS FOR THE UNITED DATASET.

year	pairs number	RMSE (kg.m^{-2})	r (corr.coeff.)	IA	BIAS (kg.m^{-2})
2001	78	10.46	0.75	0.57	1.76
2002	1180	59.52	0.57	0.47	28.99
2003	636	51.76	0.06	0.15	24.80
2004	886	22.85	0.39	0.45	10.59
2005	279	5.48	0.45	0.58	-0.74
2006	750	38.74	0.48	0.43	17.71
2007	215	5.35	0.29	0.45	1.68
2008	700	20.94	0.25	0.46	2.93
2009	305	42.34	0.35	0.24	25.69
2010	332	54.76	0.64	0.48	34.96
2011	160	21.61	0.48	0.44	11.38
2012	161	40.31	0.01	0.17	26.68
2013	603	22.94	0.37	0.57	-6.20
2014	1219	9.26	0.52	0.36	0.62
TOTAL	7504	36.69	0.47	0.49	13.00

As can be seen, depending from the winter, the number of the performed comparisons varies greatly – from up to 200 for years with overall thin snow cover, like 2001, 2011 and 2012 to more than 1100 in opposite case (the years 2002 and 2014). The statistical scores vary also greatly, but, as general, no remarkable linkage between the number of the comparisons and any pattern of the change of these indices can be determined.

The distribution of the NMB is presented on Figure 3.

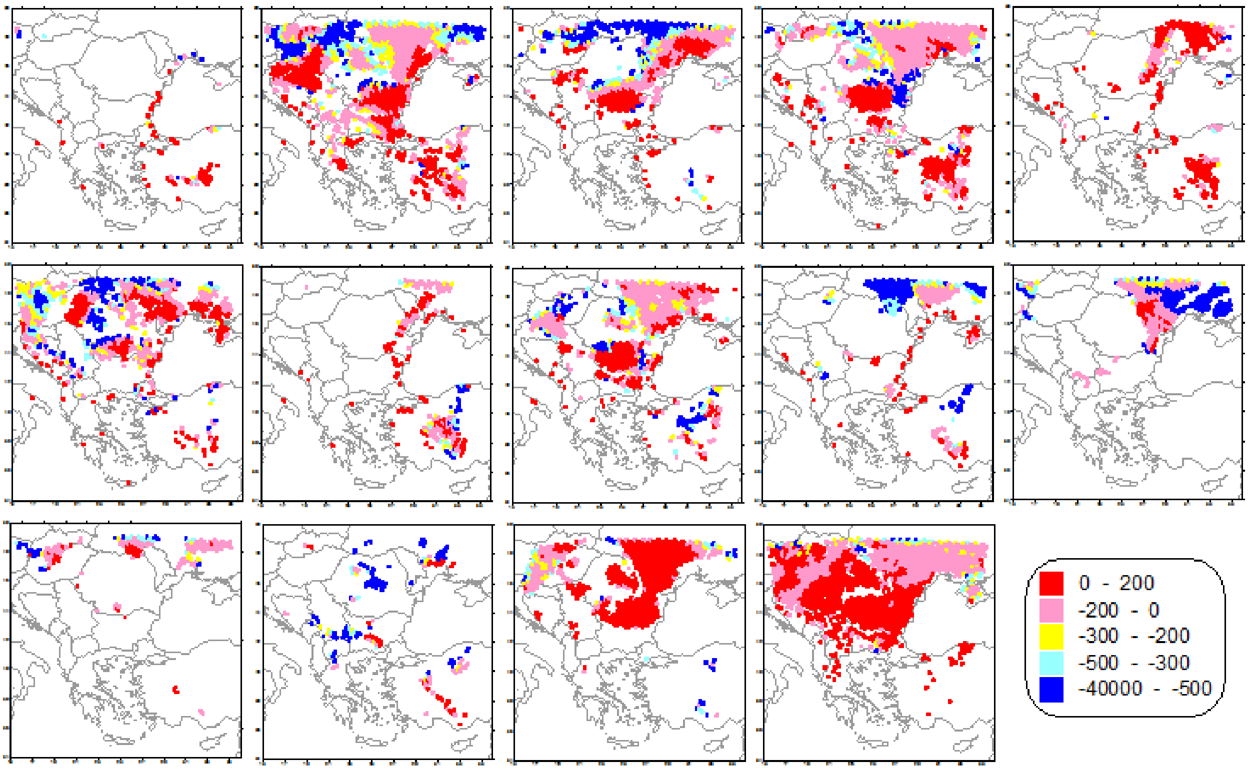

Figure 3. Distribution of the NMB (in %) for the same period in the same order as the previous two figures

The scatter plot diagrams for two winters, 2008 and 2014, when snow cover is relatively deep, are shown on Figure 4. Additionally, the united (i.e. for all 14 months January) dataset is depicted on the same figure. Hence the SWE varies naturally up to 3 orders, the log-log axes ensures more compact representation.

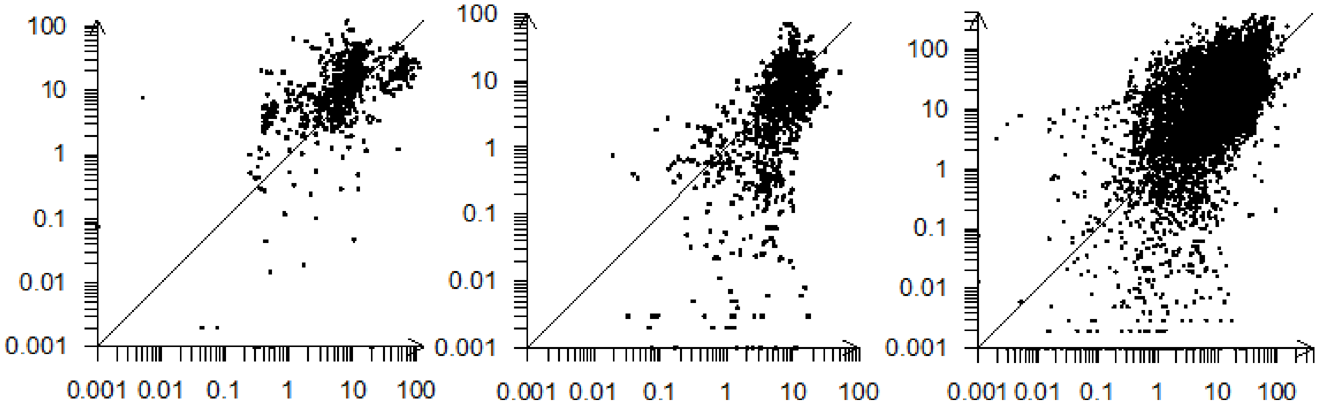

Figure 4. Scatter plot diagrams for January 2008 (on left), January 2014 (in the middle) and for the united (i.e. for all 14 years) dataset. The GlobSnow values are along the abscissa, the units are kg.m^{-2}.

The comparison can be extended further, in particular involving more advanced statistical methods, but the performed analysis, preliminary indeed, already reveals some basic features, which are summarized as follows:

In certain years and/or pixels of comparison the differences between the observed and the modelled values of the SWE are significant and most drastic are the discrepancies in direction overestimation (NMB<<0), i.e. the model values are in orders greater then the observed ones.

The analyzed information do not suggest the presence of sub domains, where these differences seems to be systematic. Nevertheless however, over the central part of the domain (Bulgaria) NMB is most often in the interval -200% - 200%.

The scatter plot diagram for the united dataset shows best commensurability in the interval of values SWE 10-100 mm, which is relevant, keeping in mind that the typical monthly average values over the plains in the domain is roughly around 50 mm. Hence these areas, which are with prevailing share in the domain’s topography, plays the most important role in the regional agriculture and food supply, this fact is very relevant.

V. CONCLUSION

Providing spatially and temporally continuous distribution of the snow-pack pattern, the Globsnow SWE product is suitable tool for quantitative assessment of the snow cover features. Despite its listed drawbacks, the Globsnow digital maps are preferable for comparison with RCM output then the point wise ground measurements, which, at least in the domain are scarce, irregular and delivers data with temporal gaps. So, in Bulgaria, only a couple of stations provides time series of measurements on daily basis, with acceptable length in the period under consideration. Comparison with of these data with RegCM4 model output, presented in Chervenkov et al., (2015), reveals that the biases over the whole time span are acceptable, but, however, with large discrepancies in the day-by-day comparisons.

The overall judgment of the obtained results is hampered by the lack of information about the evaluation of the capabilities of Globsnow in other regions of the hemisphere, where the snow-pack conditions and dynamics are different from those in the northern part of Eurasia. The comparison of RCM RCA4 output with Globsnow for the territory of Sweden (see Strandberg et al., 2014), although performed by other means and described concisely, reveals better concordance. This fact suggest that the product's performance is not equal everywhere.

More generally, the efforts for synergistic treatment of the data from all available informational sources have to be continued with increased activity. Thus, the COST action ES1404 (http://www.harmosnow.eu/index.php?page=Structure) for harmonization of the snow monitoring is significant step ahead in the right direction.

The model RegCM is constantly developed and, respectively, its simulation capabilities are steadily increasing. Further numerical experiments have to performed, in particular comparisons with other data sources, among which the gridded digital maps of assimilated data from objective analysis and/or reanalysis are most reliable hence it is impossible to obtain meteorologically consistent snow cover patters without the means of the physical and mathematical simulation.

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