Using reanalyses for studying past Eurasian snow cover and its relationship with circulation variability

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ABSTRACT

In order to investigate the relationships between the climate variability and the state of snow cover in Northern Eurasia, we used two different sources of simulations to reconstruct the historical snowpack conditions. The first one is based on a stand-alone simulation with the detailed snowpack model Crocus. Forcing data were extracted from ERA-interim reanalyses. Without assimilating any local snow-related observation, the simulated snow depth, snow water equivalent (SWE) and density have been successfully compared with local observations from more than 1000 monitoring sites. The simulations show a very small bias as well as high correlations. In terms of SWE, the overall performance of the simulations is very similar to the accuracy of the satellite gridded snow product GlobSnow which, in contrast, assimilates local snow depth observations.

The second approach directly uses the snow cover from the meteorological reanalysis 20CR which covers the whole past century. A detailed comparison with more than 1000000 daily in-situ snow depth observations shows that the simulated snow cover in October and November exhibits a very high and steady performance throughout the XXth. Century. 20CR performance for detecting the presence of snow on the ground is even higher than the performance of the NOAA satellite-based snow cover product. This snow reconstruction was used to investigate the relationship between the onset of snow cover over Northern Eurasia in Fall and the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) conditions which occurred the following Winter. It shows that the high correlation which is observed for the last decades has not been steady over the whole Century.

1 Introduction

Northern Hemisphere snow extent is characterized by a high interannual variability, providing a potential predictive value for seasonal forecasting. Many studies have explored systematically the potential source of predictability carried by snow cover extent. Some of them suggest that Siberian snow cover extent during Fall is linked with the subsequent Arctic Oscillation (AO) phase in winter (Cohen and Jones, 2011). Most of these studies use satellite-based snow extent observations, which limit the investigation to the period after the 1970's. In order to investigate the steadiness over the whole XXth. century of the correlation observed during the last decades, it is necessary to reconstruct past snow conditions. Numerous in-situ snow depth exist, especially those from the synoptic network of the Former Soviet Union (FSU) (Armstrong, 2001), but they are unevenly distributed. Furthermore, the availability of the records at individual stations vary in time. This makes it impossible to produce an historical daily snow depth gridded field from in-situ observations which would be sufficiently reliable and steady over time.

Hence, snowpack modelling may be the unique alternative way to reconstruct past snow conditions. The present paper addresses key aspects of different modelling approaches which have been discussed in details in Brun et al. (2013) and Peings et al. (2013).

2 Reconstruction of daily detailed snowpack characteristics using ERA-interim meteorological forcings

2.1 Observations and models

Detailed snowpack models have been developed and used for several decades. They simulate key features of the snowpack, such as its layering and its density vertical profile. When run over open fields with locally observed meteorological forcings, they prove themselves quite efficient in simulating a realistic state of the local snowpack (Brun et al., 1992; Etchevers et al., 2004). However, their performance is much better over open fields than over forested areas. Up to a recent time, detailed snow models have been rarely run with the meteorological forcings produced by large-scale reanalyses, probably because reanalyses were suspected to exhibit too large biases in snowfalls or in downwards radiation for driving such kind of snow models which are very sensitive to any bias.

In order to investigate such an approach, we used different sources of meteorological forcings to run the Crocus physically-based snowpack model (Brun et al., 1992; Vionnet et al., 2012). Crocus is coupled with the multi-layer soil model ISBA-DF within the externalized land-surface model SURFEX (Decharme et al., 2011; Masson et al., 2012). Key simulated characteristics of the snowpack (depth, snow water equivalent (SWE), density, duration, onset and vanishing dates of continuous ground coverage) were compared with two different in-situ observations data sets:

- the Historical Soviet Daily Snow Depth (HSDSD) data set which includes quality-controlled daily snow depth observations from more than 250 synoptic stations over the period 1979-1993;
- the Former Soviet Union Hydrological Snow Surveys (FSUHSS) data sets (Krenke, 2004). It includes snow density, depth and SWE observations, which were collected 3 times per month, along transects. More than 1000 stations provided observations during the considered period.

The meteorological forcings which are used by Crocus (2m air temperature and humidity, 10 m wind velocity, precipitation rate, downwards long-wave and short-wave radiation, pressure) are extracted from ERA-Interim (Dee et al., 2011) and from the Princeton University Global Forcing data set (PGF) (Sheffield et al., 2006). A major difference between PGF and ERA-Interim comes from the fact that PGF uses the monthly gridded precipitation product from the Climate Research Unit (CRU), which is based on in-situ observations. In contrast, ERA-interim does not use any precipitation and radiation observations. Hence, its precipitation, long-wave and short-wave downwards radiations are those forecasted by the meteorological model during the analysis process.

Crocus was run at all stations where observations are totally or partially available during the 1979-1993 period. In order to take into account the difference in elevation between the actual altitude of the stations and the elevation of the corresponding grid cells in ERA-interim and PGF, the forcings conditions are corrected according to the method developed by Cosgrove et al. (2003). The very same configuration of the snow and soil models is used at all stations.

2.2 Simulation results

Many important results were achieved from this study which are presented in details in Brun et al. (2013). The most important ones are summarized below.

Crocus performs much better with ERA-interim forcings than with PGF. It provides daily simulations of many characteristics of the snowpack (onset and vanishing dates, depth, SWE, density) which exhibit very small biases and high correlations when compared to local observations. This result was

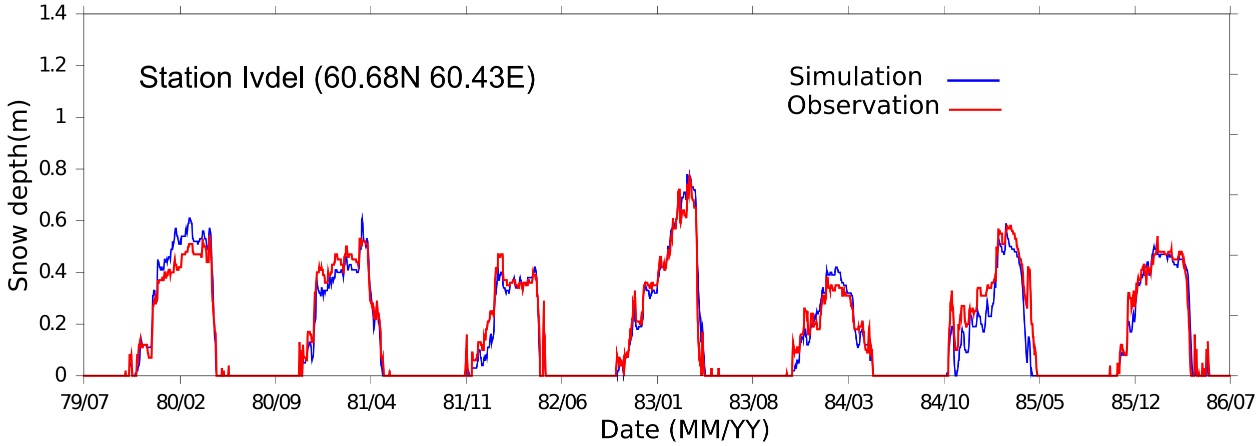

Figure 1: Comparison between the observed daily snow depth at Ivdel station (60.7 N ; 60.4 E) (red) and the simulations performed by Crocus using ERA-Interim forcings (blue).

not expected and it proves that winter precipitations are particularly well simulated in state-of-the-art meteorological models.

The simulations perform as well as the SWE GlobSnow product (Takala et al., 2011), which is based on in-situ snow depth observations and micro-wave satellite observations (see Table 1). This result is of primary importance since it makes it possible to reconstruct historical characteristics of the snowpack prior to the satellite era, provided reliable reanalyses are available.

Table 1: Comparison of bias and RMSe in snow water equivalent over northern Eurasia between GlobSnow retrievals (Luojus et al., 2011) and ISBA-Crocus simulations from 1979 to 1993.

All observations	GlobSnow	ISBA-Crocus
number of obervations	137,379	109,189
bias(kg m^{-2})	-4.8	0.9
RMSe(kg m^{-2})	44.9	44.6

Many stations are surprisingly well simulated at the daily scale, though no calibrations are applied to pass from the resolved spatial scale of ERA interim (typically 80 km) to the local scale of the stations.

Figure 1 illustrates such a performance for Ivdel station from 1979 to 1986. Most events affecting the snow depth are well simulated, including blowing snow events which induce compaction and sublimation. This leads to an almost perfect reconstruction of the seasonal and interannual variability. Many stations behave similarly and more than half of the 265 stations exhibit an absolute bias in the melting-out date less than 6 days. However, there are a few stations which are very poorly simulated, especially at locations where prevailing strong winds systematically blow the snow away.

A systematic comparison was made between the simulated density and the observations. Once again, the simulations driven with ERA-interim are significantly better than those with PGF forcings. Density is unbiased with ERA-interim, with a very realistic evolution throughout the winter season, while density is systematically overestimated with PGF. This is mainly due to 2 factors:

- better wind velocities in ERA-interim, which control the density of fresh snow and the occurrence of blowing snow events;

- a much better chronology of precipitation events in ERA-interim. PGF snowfalls are rarer but more intense, leading to a rapid compaction before high temperature gradients turn the surface snow layers into depth hoar, which is an efficient inhibitor of compaction.

The ability to simulate a reliable seasonal and regional variability of snowpack densities is a critical point for the simulation of the thermal regime of the underlying soils. Indeed, for a given snow mass, the thermal resistance of a snowpack approximately varies as the inverse of the density at the power 3. Hence the thermal resistance may vary over more than one order of magnitude for a same amount of snow. Snowpacks with a very low density, as simulated by Crocus over eastern Siberia (see Figure 3 in Brun et al. (2013)), dramatically reduce the freezing of the soils. Therefore it made it possible to simulate the near-surface soil temperature just from ERA-interim forcings and ISBA-DF/Crocus with a performance never achieved before.

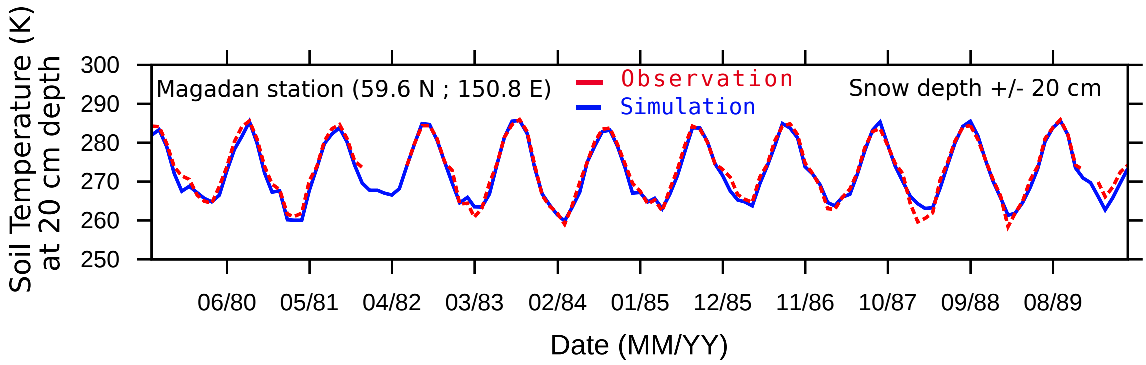

Figure 2: Comparison between the observed monthly soil temperature at 20cm depth at Magadan station (59.6 N 150.8 E) (dotted red) and the simulations performed by ISBA-DF coupled with Crocus using ERA-Interim forcings (blue).

This is illustrated in Figure 2. Similar results are achieved at most stations, as shown in Figure 10 in Brun et al. (2013). There are a few stations exhibiting an overestimation of the simulated soil temperature, which generally correspond to stations where snow is blown away by strong winds.

3 Representation of snow cover in 20CR

A similar study was attempted with 20CR meteorological forcings instead of ERA-interim forcings. 20CR is a recent ensemble atmospheric reanalysis (using a climatology of sea surface temperature and sea ice as ocean boundary conditions), extending from 1871 to 2010 (Compo et al., 2011). In contrast to other reanalyses, 20CR assimilates only surface pressure observations. Hence, it does not include an analysis of surface conditions, either from observations of the surface state or from atmospheric observations in the boundary layer. Hence, the snow cover in 20CR freely forms and evolves in interaction with the atmosphere during the ensemble of meteorological forecasts which the assimilation system is based on.

3.1 Snow cover in Autumn

In a first stage, we performed a detailed evaluation of 20CR snow cover over Northern Eurasia during October and November. The 20CR snow cover field was extracted from the ensemble average, turning it into a binary snow cover field, named SC-20CR, using a threshold value of 50%. This field has been compared to 2 data sets:

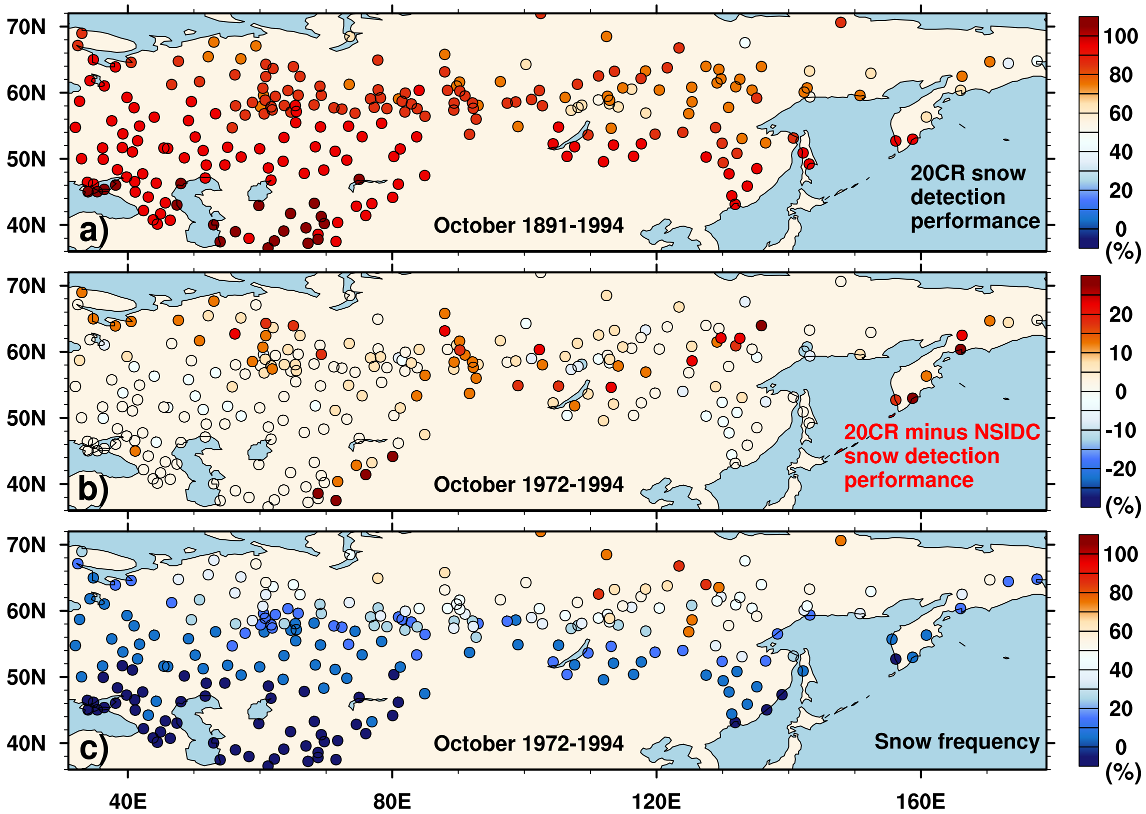

Figure 3: 20CR snow cover detection performance: (a) percentage of October days with snow/no snow in both 20CR snow cover and HSDSD data (threshold 5 cm) over 1881–1994. (b) Difference in % between the 20CR and NSIDC snow detection performance over 1972–1994. (c) Observed snow frequency in % of October days over 1972–1994, defined as the ratio of HSDSD data higher than 5 cm. Adapted from Peings et al. (2013)

- the Northern Hemisphere weekly snow cover extent Version 3 product (Armstrong and Brodzik, 2005), available at the National Snow and Ice Data Center (NSIDC). This data set was used for the 1972–2006 period and interpolated on the 20CR horizontal grid. We named it SC-NSIDC;

- the HSDSD data set as in section 2.2. Using a threshold of 5 cm, daily snow depths at synoptic stations were turned into a binary index, describing the presence or the absence of snow on the ground.

A monthly index describing the performance of 20CR in the detection of the presence of snow on the ground was defined. For a given station, it is the rate of daily observations in agreement with SC-20CR. A similar performance index was defined for SC-NSIDC. Figure 3, adapted from Peings et al. (2013), compares the skill of SC-20CR with the one of SC-NSIDC in October for the period 1891-1994. The total number of observations amounts to more than 400000. Most stations exhibit a performance higher than 0.8 (top panel). The middle panel compares the detection performance of SC-20CR with SC-NSIDC over the common dates during the period 1972-1994 (more than 20000 observations). SC-20CR clearly outperforms SC-NSIDC. The largest differences are located over the transition area where snow covers the ground during half of October on average (see snow frequency in the bottom panel of Figure 3). It is a very encouraging result for 20CR snow cover, since it is quite challenging to simulate early snowfalls and their stay on the ground at a period of the year when the temperature varies around the freezing point.

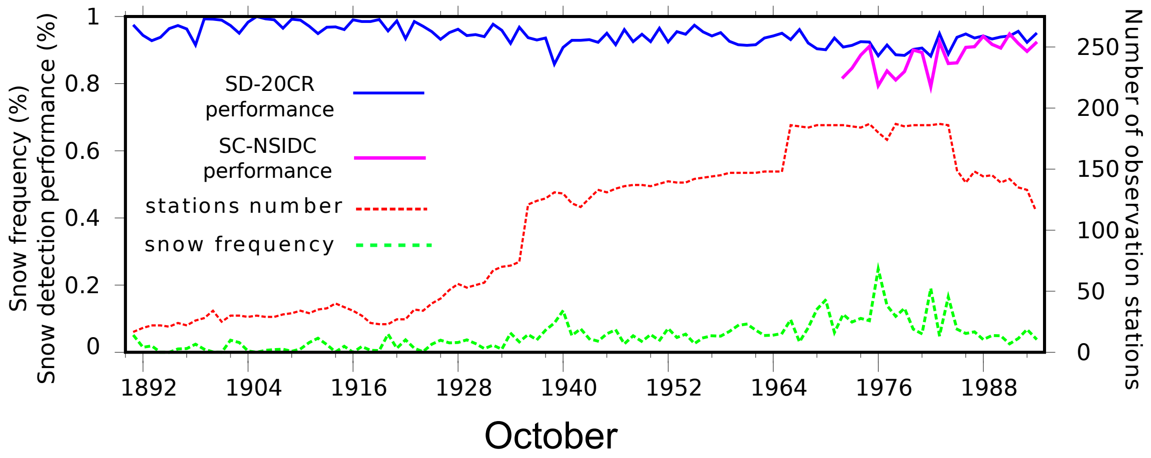

Figure 4: Time evolution of the snow detection performance for 20CR and NSIDC in October averaged over the available HSDSD stations. The monthly snow frequency averaged over available stations is indicated. The snow detection and frequency are expressed in % on the left axis and the number of HSDSD stations is indicated on the right axis. Adapted from Peings et al. (2013)

While assimilating only surface pressure observations, 20CR targets the best possible consistency over time. Considering the 35-60 °N/40-180 °E domain used by Cohen and Jones (2011) to establish a Snow Advance Index (SAI), we evaluated the interannual variability of the detection performance of SC-20CR in October and November from 1891 to 1994 (see Figure 4 for October. November exhibits similar results). The performance is surprisingly very high throughout the whole historical period. More amazing is the fact that it is always better than its SC-NSIDC counterpart over the common period.

3.2 Steadiness of the relationship between early snow conditions and the Arctic Oscillation during the following winter

The impressive and steady performance of 20CR in representing the advance of the snow cover over Northern Eurasia in Autumn made it possible to investigate the steadiness of the correlation between the SAI and the AO, which was established by Cohen and Jones (2011) over the satellite era. Figure 5 shows that the high correlations exist only from the last 3 decades. Peings et al. (2013) invoke the phase of the QBO as a possible inhibitor of the influence of an early snow cover on the circulation anomaly during the following winter.

3.3 Evidence of snow overestimation in 20CR during mid-winter and spring

Building up on the good performance of 20CR in representing the snow cover in October and November, we extracted from 20CR the meteorological conditions necessary to Crocus for the simulation of the snowpack, in a similar way as with ERA-interim in section 2.1. The comparison with in-situ observations shows a growing overestimation of the snow amount along the course of the snow season, which leads to a delay of one to several weeks in the vanishing date of the snow cover. It seems that it comes from weaknesses in the too simple snow scheme used by the NOAH land surface model (Niu et al., 2011) implemented in 20CR. The main characteristics of these weaknesses are shown at a representative station in Figure 6:

- a quasi-saturation of vapour pressure over snow covered grid points which inhibits the sublimation of the snow by Crocus during blowing-snow events;

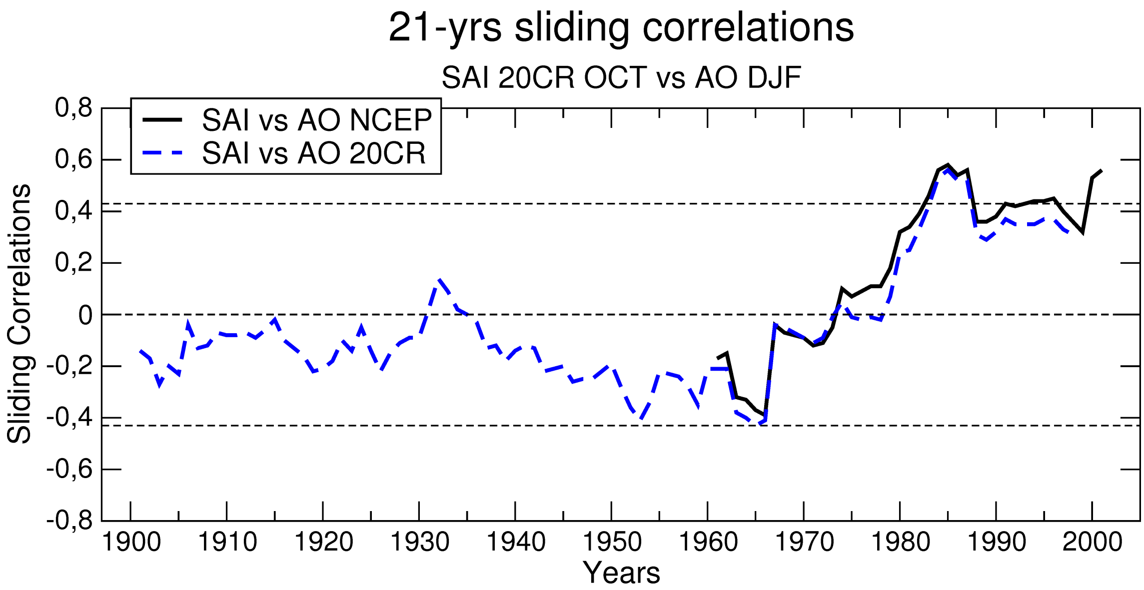

Figure 5: Time evolution of the 21-year sliding correlation between the SAI derived from 20CR snow cover and the AO index derived from 20CR (dashed blue line) and the AO index derived from the NCEP reanalysis (solid black line). Adapted from Peings et al. (2013)

- too cold temperatures during the snow melting seasons which limit the melting rate.

We verified that the above-mentioned biases in the atmospheric boundary-layer temperature and humidity propagate upwards in the lower troposphere, which amplifies their negative impact on the capacity of Crocus to simulate realistic snowpack characteristics.

4 Conclusion

A reconstruction of daily and local snowpack characteristics over Northern Eurasia was performed with a detailed snowpack model using ERA-interim forcing conditions. When compared with in-situ observations over open fields, the simulations exhibit high correlations and insignificant biases in snow depth, density, SWE as well as in the snowpack onset and vanishing dates. The good performance of this approach proves that state-of-the art meteorological models haw now reached a performance level in the forecast of precipitation, radiation, temperature, wind velocity and humidity which is sufficient for the control of snowpack daily dynamics. This is true at least for the cold season over mid-latitude and pan-Arctic regions.This is true only at the spatial scale of global models (i.e. 50 to 100 km). The study was limited to Northern Eurasia, but there are no reasons to expect poorer results over northern America.

Though these results are limited to open field conditions, this study is a major step towards a future historical reconstruction of the daily detailed snowpack characteristics over regions where such observations are not available. A key point comes from the fact that is does not use any prescribed information on the local climatology or physiography. The simulations do not use any assimilation of observed precipitation or snow depth. Hence their performance does not depend on the availability of past snow observations, avoiding time inconsistencies. In-situ snow depth observations are just used by ERA-interim to update its own snow depth but this information is never forwarded to Crocus.

A similar approach with the 20CR reanalysis was attempted. 20CR proved itself quite performing in the representation of snow cover during the early snow season and throughout the period extending from

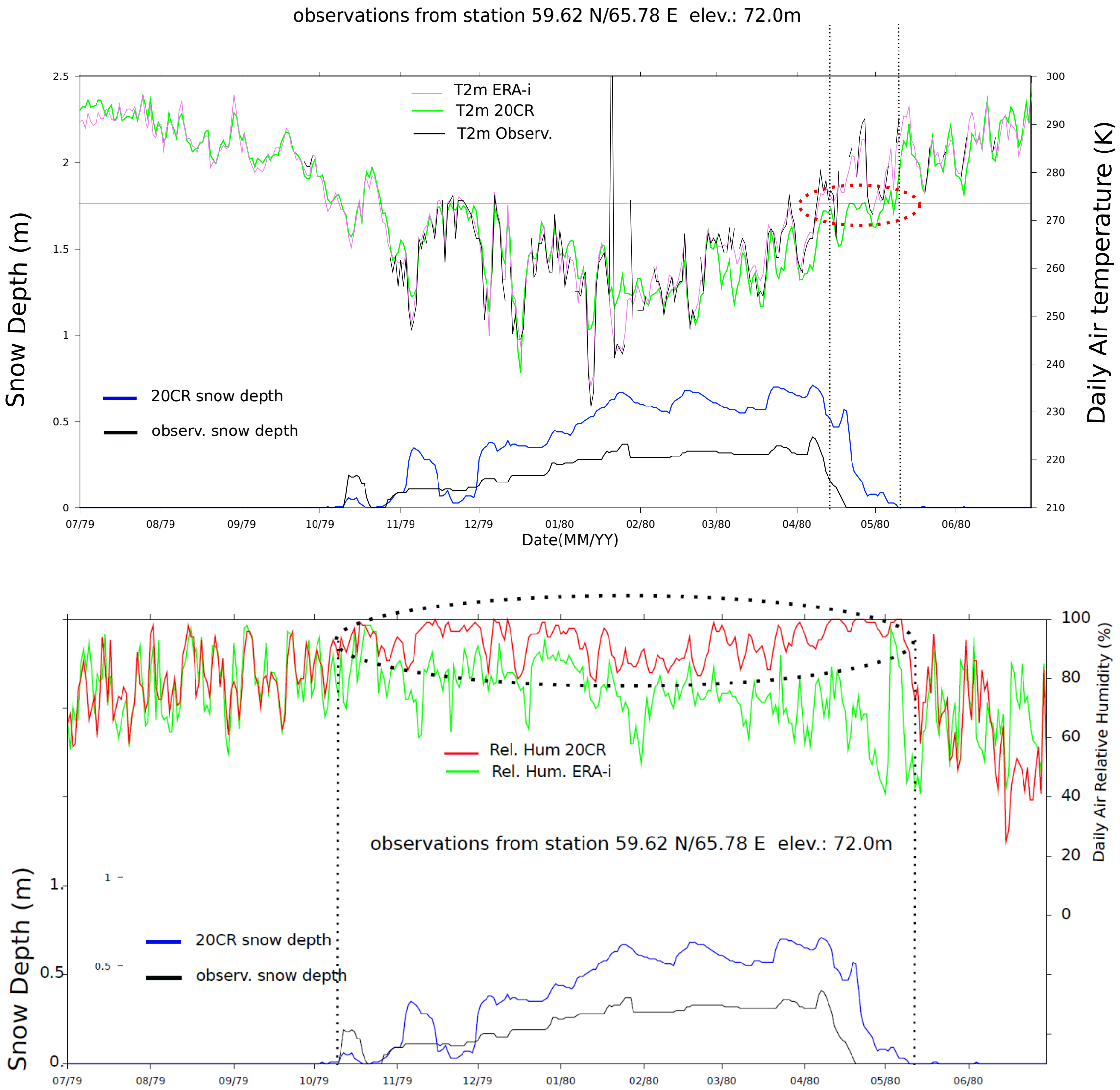

Figure 6: Top panel : Illustration of the under-estimation of daily air temperature in 20CR (green) during the snow melting period (see dotted red ellipse). ERA-interim temperature is in pink and the observation in black. Bottom panel: over estimation of 20CR daily relative humidity (red) in presesence of snow on the ground. ERA-interim humidity is in green. In both panels 20CR snow depth is in blue, the observed snow depth is in black.

1891 to 2010. Its ability to detect the presence of snow on the ground was even better than one of the available satellite products. However, the presence of snow on the ground in 20CR involves a quasi-saturation of the relative humidity in the boundary layer as well as in the low troposphere. During the melting period, 20CR air temperature is underestimated. We suspect weaknesses in 20CR snow model which is amplified by interactions with the atmosphere.

Both studies emphasize the importance of implementing snowpack models of sufficient complexity in meteorological and climate models, as well as the importance of properly representing the energy and mass exchanges between the snow cover and the atmosphere. It is particularly critical in polar regions for the prediction of snow cover depletion in the context of climate change as well as for its potential retro-actions with the atmospheric variability.

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