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The Cryosphere Discussions

A regional climate model hindcast for Siberia – assessing the added value of snow water equivalent using ESA GlobSnow and reanalyses

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Abstract

This study analyzes the added value of a regional climate model hindcast of CCLM compared to global reanalyses in providing a reconstruction of recent past snow water equivalent (SWE) for Siberia. Consistent regional climate data in time and space is necessary due to lack of station data in that region. We focus on SWE since it represents an important snow cover parameter in a region where snow has the potential to feed back to the climate of the whole Northern Hemisphere. The simulation was performed in a 50 km grid spacing for the period 1948 to 2010 using NCEP Reanalysis 1 as boundary forcing. Daily observational reference data for the period of 1987–2010 was obtained by the satellite derived SWE product of ESA DUE GlobSnow that enables a large scale assessment. The analyses includes comparisons of the distribution of snow cover extent, example time series of monthly SWE for January and April, regional characteristics of long-term monthly mean, standard deviation and temporal correlation averaged over subregions. SWE of CCLM is compared against the SWE information of NCEP-R1 itself and three more reanalyses (NCEP-R2, NCEP-CFSR, ERA-Interim). We demonstrate a significant added value of the CCLM hindcast during snow accumulation period shown for January for many subregions compared to SWE of NCEP-R1. NCEP-R1 mostly underestimates SWE during whole snow season. CCLM overestimates SWE compared to the satellite-derived product during April – a month representing the beginning of snow melt in southern regions. We illustrate that SWE of the regional hindcast is more consistent in time than ERA-Interim and NCEP-R2 and thus add realistic detail.

1 Introduction

Terrestrial snow cover is a key component of the cryosphere and by modifying the surface energy and water balance of the whole climate system (Alexander et al., 2010; Cook et al., 2008). This extensive, most rapidly and seasonally changing cryospheric variable (ACIA, 2005) plays a crucial part in shaping the land surface during the prolonged Siberian cold season (Bulygina et al., 2009). The higher albedo of snow-covered compared to snow-free surfaces leads to an increased reflectance of solar radiation and a near-surface cooling (Stieglitz et al., 2003; Vavrus, 2007). Additionally, the low thermal conductivity of snow makes it a good insulator that limits the heat exchange between soil and atmosphere. Changes in snow depth, extent, timing, duration and density have profound implications for soil temperatures and thus permafrost thermal state (Shkolnik et al., 2010; Stieglitz et al., 2003; Zhang et al., 2005), ecology and biogeochemical cycles (Sturm et al., 2005). Moreover, snow cover plays an important role within the hydrological cycle controlling evaporation, water storage, soil moisture, river discharge and thus freshwater transport to the Arctic Ocean (Groisman and Amber, 2009; Troy et al., 2012; Yang et al., 2003). Numerous studies indicate that Siberian snow cover has the potential to influence the large scale atmospheric circulation. As stated by Cohen and Fletcher (2007) increasing snow cover induces diabatic cooling and strengthens the Siberian High pressure system resulting in upward propagation of planetary waves and thus favour meridional flow (Allen and Zender, 2011; Cohen et al., 2012). Evidence that Eurasian snow cover may feed back to Arctic- and North-Atlantic Oscillation was mentioned by Alexeev et al. (2012). Despite its important implications, Arctic snow cover has received little attention in previous assessments as, e.g. ACIA (2005), IPCC AR4 (Solomon et al., 2007). Therefore, a review of recent work was published within the SWIPA-report by Callaghan et al. (2011). In our analysis we focus on snow water equivalent (SWE) as an important parameter within the hydrological cycle determining snowmelt runoff and hence Arctic freshwater supply. Furthermore, snow depth and SWE anomalies play an important role within the snow-climate relationship but have been less investigated than snow extent due to the lack of reliable observational data (Ge and Gong, 2008). Also Bulygina et al. (2011) mentioned that the analysis of spatio-temporal variations of snow cover characteristics particular changes of SWE for the whole Russia was hampered because of limited data availability. The availability of consistent, homogeneous in-situ snow observations in Siberia is restricted

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due to a sparse meteorological network and incompleteness of data records (Brown et al., 2003; Khan et al., 2008). After the break down of the Soviet Union many stations were closed and the station density in Siberia was reduced about half of the size in the 1980s (Serreze et al., 2003). Brown et al. (2003) developed a gridded SWE dataset over North America from historical snow depth observations but this effort could not be extended for Eurasia because of insufficient in situ snow data (Brown and Mote, 2009).

A possibility to retrieve large scale SWE data was introduced by space borne passive microwave radiometer having the advantage of wide swath, all-weather monitoring capabilities day and night and being insensitive to cloud cover (Brown et al., 2010; Foster et al., 2005; Derksen et al., 2012). Brightness temperature derived from different channels of passive microwave sensors onboard satellites makes it possible to provide daily information on SWE, snow depth and thus snow mass for the full spatial coverage under dry snow conditions for a time period back to 1978 (Derksen et al., 2012; Foster et al., 2005; Pulliainen, 2006). The National Snow and Ice Data Center has produced a global snow depth/SWE data set derived from passive microwave data (Armstrong and Brodzik, 2001). However, stand-alone passive microwave SWE retrieval algorithms are highly uncertain which limits the use of these datasets for model validation (Clifford, 2010; Takala et al., 2011). Snow properties affecting microwave emission and scatter are, e.g. changes in snow grain size and melt water which can raise the microwave brightness temperature and makes the extraction of SWE information difficult. Additional vegetation cover, e.g. densely forested areas such as the boreal forest in Siberia, can impact the accuracy of the SWE estimates and lead to underestimations (Foster et al., 2005). A well known problem of the SWE retrievals is the tendency to systematically underestimate deep snow due to changes in microwave behaviour of snowpack (Foster et al., 2005; Pulliainen, 2006; Takala et al., 2011). To overcome these problems a new dataset of SWE for the Northern Hemisphere was produced by the GlobSnow consortium of the European Space Agency (ESA) applying an algorithm assimilating synoptic station data of snow depth together with space-borne passive microwave radiometer data (Pulliainen, 2006; Takala et al., 2009).

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A further possibility to get a three-dimensional global dataset of various parameters and hence SWE, that are continuous in time, were provided by reanalyses (e.g. Kalnay et al., 1996; Uppala et al., 2005). Using a fixed assimilation scheme past observations were incorporated into an atmospheric numerical weather prediction model (Bromwich et al., 2007). A general problem of reanalyses are some temporal inconsistencies due to historical changes in the observing system (e.g. since the 1970s when satellite data became available), and discrepancies due to different assimilation schemes (Bengtsson et al., 2004). The snow information directly from existing reanalyses can differ considerably. Khan et al. (2008) compared SWE of three reanalyses (ERA-40, NCEP-R1 and JRA-25) over Russian watersheds showing large discrepancies. This is partly related to erroneous snow cover analysis in NCEP-R1 (Kanamitsu et al., 2002). Additional, the long-term products are still in a coarse resolution. This may lead to incorrect representation of snow cover distribution and local-scale variability being strongly dependent on altitude, terrain and vegetation (King et al., 2008).

A method to derive detailed regional, spatially continuous and temporally consistent climate information is the dynamical downscaling of global data applying a regional climate model (RCM). Large-scale atmospheric fields are taken as forcing and boundary condition over a limited area to perform high-resolution regional climate simulations (Giorgi, 1990; Giorgi and Mearns, 1999). The atmospheric forcing is derived either from global model data or reanalyses. Most RCM studies showed a horizontal resolution between 50 and 10 km (Giorgi et al., 2001). A detailed overview of abilities and limitations of RCMs was given by Rummukainen (2010). There are several efforts in applying RCMs over Siberia. Mostly they consider a pan-arctic domain including northern parts of Siberia (e.g. Rinke et al., 2010). Within the SHEBA (Surface Heat Budget of the Arctic Ocean) project an ensemble was evaluated to quantify the scatter amongst a number of RCMs (ARCSyM, COAMPS, CRCM, HIRHAM, RegCM, PolarMM5, and REMO) and to assess the reliability of their Arctic simulations (Rinke et al., 2006). The Polar Weather Research and Forecasting (Polar WRF) model (e.g. Hines and Bromwich 2008) was used to provide a high resolution (10 km) Arctic System Reanalysis for

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2000–2011. Shkolnik et al. (2010) used the MGO regional climate model for snow cover and permafrost studies in Siberia. One main application of RCMs, besides process and sensitivity studies is to perform long-term simulations on the regional scale, either for future climate conditions or to reconstruct recent past climate (Feser et al., 2001; Sotillo et al., 2005; Weisse et al., 2009). The climate hindcast simulation can complement existing observation data and provide consistent and homogeneous information of various parameters in a higher spatial and temporal resolution than global reanalyses can provide. This motivates the need to perform a climate hindcast of the period 1948–2010 for Siberia using the regional climate model CCLM (COSMO model in CLimate Mode) in a region where in situ data of SWE is particularly sparse. Due to the higher spatial resolution, RCMs allow a more detailed representation of regional aspects, e.g. land-sea contrast, local orography, land-cover and small-scale atmospheric features. It is expected that this leads to a better description of regional and even local climate and hence snow characteristics than presented by the coarsely resolved global data. However, the question arises whether the dynamically downscaled data of reanalysis can really improve the representation of recent past snow conditions for Siberia and thus add value to global data. A large number of studies validated the RCM output and demonstrated that RCMs can realistically simulate climate in comparison to observations (e.g. Früh et al., 2010). But mostly they did no explicitly show whether the skill of the RCM is improved compared to the global forcing data (Prömmel et al., 2010). However, to assess the ability in improving climate statistics relative to the driving data is an important issue within regional climate model validation (Di Luca et al., 2012). There exists no added value of RCMs per se – it depends on the physical parameterizations, experimental setup, analyzed variable and location, mentioned in the review about the added value of RCMs by Feser et al. (2011). The higher resolution does not result automatically in more realistic detail since many variables are spatially quite homogeneous and are already well described in coarser reanalyses. So far only a few added value assessments of RCMs exist. Mostly they concentrate on temperature, precipitation, sea level pressure, wind or mesoscale atmospheric circulation systems. More realistic detail compared to driving reanalyses could be achieved at regional scales, e.g. in case of temperature with complex orography (Prömmel et al., 2010), orographical induced wind systems (Winterfeldt et al., 2010) or North Atlantic polar lows and East Asian typhoons (Feser and von Storch, 2008; Zahn and von Storch, 2008). The specific objective of this study is to assess the added value of the conducted regional climate model hindcast for Siberia in terms of SWE compared to the global forcing data and further reanalyses products. This is of special interest due to sparse meteorological station data and large discrepancies between different datasets in that region (Clifford, 2010; Khan et al., 2008). Furthermore, SWE is useful for assessing the skill and added value of a regional climate model, since both the precipitation and temperature regime needs to be correctly described (Foster et al., 1996). An accurate simulation of SWE is crucial in terms of hydrological processes and snow cover extent plays an important role for the surface energy balance via the albedo. We want to address the question if CCLM can really produce SWE and snow cover extent with more realistic detail than provided by reanalyses due to its own model physics and finer resolution in space and time. So far no added value study was conducted for a hindcast simulation of CCLM over Siberia in terms of SWE. The model output and driving reanalysis data are compared against ESA GlobSnow as reference data and NCEP-R2, NCEP-CFSR and ERA-Interim as additional reanalyses datasets. We decided to use a satellite derived SWE dataset as observational reference in order to assess the added value on a large scale. ESA Globsnow was chosen since it shows an improved accuracy of SWE compared to typical stand-alone passive microwave algorithm (Takala et al., 2011) and additionally includes the uncertainty of the SWE estimate per grid cell.

Section 2 gives an overview of the regional climate model CCLM and the hindcast simulation as well as reanalyses and satellite-derived SWE product of ESA DUE GlobSnow used for comparison. A description of methods for the data analysis follows in Sect. 3 and results are shown in Sect. 4. A conclusion and discussion is provided in the last section.

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2 Data and methods

2.1 RCM data

To perform the climate hindcast simulation we apply the nonhydrostatic regional climate model CCLM (COSMO-CLM: http://www.clm-community.eu, Rockel et al., 2008). CCLM is the climate version of the numerical weather prediction model COSMO (Steppeler et al., 2003), originally developed by the Deutscher Wetterdienst (DWD). Since the standard model setup was optimized for simulations over Europe its application over Siberia implies some changes in the configuration, e.g. the reduction of the minimal heat diffusion coefficient to better reproduce winter temperatures during the high pressure system of the Siberian High. Different physical parameterizations represent sub-grid scale processes, e.g. the Tiedtke convection scheme (Tiedtke, 1989), radiation scheme (Ritter and Geleyn, 1992) and a multi-layer soil and vegetation model as land-surface scheme after Jacobsen and Heise (1982). Thermal and hydrological processes of the ground are calculated using the heat conduction and Richards's equation. In order to take vertical temperature changes of Siberian permafrost soils better into account, we add soil layers from the standard 13 m up to a total soil depth of 92 m. Due to the strong importance of snow cover in Siberia we additionally apply a multi-layer snow model. Several aspects of cryospheric processes are considered in the CCLM, e.g. of melting of falling snow, freezing of rain, freezing of water in the interception reservoir, melting of snow in the snow reservoir, freezing and thawing of water, ice in the soil layers. For the hindcast simulation we choose two snow layers (a higher number of layers did not improve the results in our case) each described by its own temperature, water content, depth and porosity according to the snow density. Snow layer thickness changes may vary at any time step due to changes of snow density in case of phase changes, water percolation into underlying layer or for the uppermost layer due to fresh snow. The lower boundary condition of the soil model is prescribed by the climatological mean temperature of the lowest soil layer since the heat conduction equation is solved for the entire column consisting of snow and soil layers.

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A time dependent snow-albedo is used and gravitational compaction and compaction of snow due to metamorphism are described as well. Spectral nudging is applied to prevent the regional model from deviating from the prescribed large-scale state within the whole simulation domain (von Storch et al., 2000). The horizontal resolution is of 0.44° (approximately 50 km) in rotated coordinates with 40 atmospheric vertical layers. Figure 1 presents the entire model domain of the CCLM hindcast simulation on lon/lat grid. It covers a region in Siberia, spanning from the Laptev Sea and Kara Sea to Northern Mongolia and from the West Siberian Lowland to the border of Sea of Okhotsk. As global forcing for the initialization and the regional boundaries we use NCEP Reanalysis 1 (NCEP-R1) of the National Centers for Environmental Prediction (Kalnay et al., 1996) since it provides the longest temporal data coverage (from 1948 to present) among the reanalysis products. The regional hindcast of CCLM constitute thus a dataset of 1948 onwards and provides an hourly output of main variables.

2.2 Reference data

2.2.1 Reanalyses

To study the added value of the CCLM we compare the reconstructed SWE against four reanalyses. Three provided by the National Centers for Environmental Prediction (NCEP): NCEP-R1 (Kalnay et al., 1996; Kistler et al., 2001), which is used as forcing data, the updated NCEP/DOE or R2 (Kanamitsu et al., 2002), the newest generation – climate forecast system reanalysis (CFSR) (Saha et al., 2010) and ERA-Interim produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011). NCEP-R1, is available in a grid spacing of 1.875° × 1.875° (~ 210 km) and daily SWE is provided on T62 Gaussian grid output in a 6 hourly interval. A 3-D-variational scheme is used as spectral statistical interpolation and various observations e.g. upper air rawinsonde observations of temperature, horizontal wind, and specific humidity; operational Television Infrared Observation Satellite (TIROS), Operational Vertical Sounder (TOVS), vertical temperature soundings from NOAA are assimilated

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(Kalnay et al., 1996; Kistler et al., 2001). Snow cover is based only on a weekly Northern Hemisphere snow cover analysis without snow depth. Therefore, maximum snow depth was set to 100 mm in an empirical formulation (liquid water equivalent) and no prediction of the snow accumulation by the model was used. Further errors in the snow cover analysis has been detected, e.g. the repeated use of the 1973 data for the period 1974–1994, wrong snowmelt term that let to an overestimation in the conversion of snow to water by a factor of 1000 and erroneous moisture diffusion leading to wrong snowfall in winter over valleys in high latitudes ("spectral snow" problem) (Kistler et al., 2001). We use the SWE data of NCEP-R1 for comparison despite the mentioned problems. Since this dataset is used as forcing data we want to highlight the ability to add realistic detail via the technique of dynamical downscaling using CCLM. Above mentioned errors were eliminated in the NCEP-DOE or R2 reanalysis, an updated version of NCEP-R1, covering the time period of 1979 to present. Additional, different snow budget diagnostics were introduced (Kanamitsu et al., 2002). The procedure to compute snow depth was handled differently than in R1. The model predicted snow depth was not ignored anymore. In case of correspondence with snow cover observations (weekly Northern Hemisphere analysis of snow cover based on satellite imagery) the model snow depth was used. Otherwise, the modelled snow depth was adjusted to the analysis. This was done by either deleting snow or by adding snow applying the same empirical formulation as in R1. Using this scheme has the advantage in accumulating deep snowpacks (Kanamitsu et al., 2002). Furthermore, we use a third generation reanalysis product – the climate forecast system reanalysis (CFSR), which is available from 1979 to present (Saha et al., 2010). This latest reanalysis of NCEP offer a coupled atmosphere-ocean-land surface-sea ice system having a spatial resolution of $\sim$ 38 km (T382) and 64 vertical levels for the atmosphere. Additional new features are among others the assimilation of satellite radiances and the integration of observed green house gases, aerosols and solar variations. To produce daily analyses of snow depth over land data of the Air Force Weather Agency's SNODEP model (Kopp and Kiess, 1996) and the NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS)

(Helfrich et al., 2007) were used. Since February 1997 both analyses of SNODEP and IMS were used in combination for the Northern Hemisphere. For the comparison of SWE we also choose ERA-Interim as latest version of the ECMWF forecast system that is available for 1979–2010 and covers many years of the GlobSnow product. Besides the higher horizontal resolution of ~80 km (T255), it includes improvements as, e.g. an 4-D variational assimilation system, variational bias correction of satellite radiances, new humidity analysis and improved model physics compared to the former ERA-40 reanalysis (Dee et al., 2011). It is expected that all these changes provide a better quality and more homogeneous analysis than presented in the ERA-40 forecast. After the analysis of the basic upper-air atmospheric fields the analysis of near-surface parameters, soil moisture, soil temperature and snow followed in a second step. Estimates of snow depth, snow water equivalent, and snow density provided by the forecast model were then adjusted to the interpolated station observations of snow depth and snow cover data from satellites (Drusch et al., 2004). Some problems were documented with respect to the analyzed snow and data processing. Errors occurred in the Cressman-based interpolation scheme inducing snow free patterns in periods where only sparse observations were available. Since July 2003 the ERA-Interim snow analysis has been constrained with the satellite-derived NOAA/NESDIS daily IMS snow-cover dataset for the Northern Hemisphere. Shortcomings in the pre-processing of this dataset were addressed which led to wrong locations of the data itself as well as the land-sea mask and the orography. As stated by Dee et al. (2011) this problem has caused errors in the snow analysis form July 2003 onwards until February 2010.

2.2.2 ESA GlobSnow

The GlobSnow product, which is mainly produced by the Finnish Meteorological Institute and Environment Canada, is based on an assimilation scheme using satellite passive microwave radiometer data and synoptic station data of snow depth (Pulliainen, 2006) in combination with a time-series melt-detection algorithm (Takala et al., 2009). The combination of these two algorithms enabled to provide information of SWE

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and of the extent of snow cover. A detailed description of these methods was published by Pulliainen (2006) and Takala et al. (2009). SWE estimates together with the error estimate and the information of snow extent were produced in a resolution of 25 × 25 km grid cells in a Lambert's equal-area azimuthal – projection for the Northern Hemisphere land surface. Mountainous regions were masked out due to poor algorithm performance in complex terrain (Takala et al., 2011). The passive microwave data included radiometer information of SSMR for 1979–1987, SSM/I for 1987–2002 and AMSR-E for the period 2003–2009. Additional weather station measurements of snow depth, which were collected by ECMWF, were used. The Helsinki University of Technology (HUT) semi-empirical snow emission model was used for interpreting the passive microwave radiometer data and calculating the SWE estimates. In a first step estimates of snow depth were provided given by the inversion of two frequencies using the emission model. Then the estimates were calibrated with the station-based snow depth measurements. Additionally, an estimate of effective grain size was produced using Kriging interpolation of radiometer and in situ measurement data. Together with a snow density value for each grid cell SWE was derived. In case of wet snow no radiation data can be used due to saturated brightness temperature values – then only station data was interpolated. The produced SWE estimate and the snow depth map from weather stations were combined in a spatial assimilation approach to get the final SWE estimate. To determine the onset of snow-melt season using the available radiometer the time-series melt detection approach described by Takala et al. (2009) was used. A validation study of the GlobSnow SWE retrievals had been performed for the years of 1980–2010 (Takala et al., 2011). The SWE estimates were compared for Eurasia against INTAS-SCCONE snow course observations from a network across the former Soviet Union and Russia (Kitaev et al., 2002). This study demonstrated RMSE values of 30–40 mm when SWE below 150 mm were considered. The uncertainty of SWE estimates increased to RMSE to 45 mm for Eurasia when the complete dataset was assessed. Takala et al. (2011) compared also the performance of the SWE assimilation technique against the SWE retrievals of NSIDC global monthly SWE climatology

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(Armstrong et al., 2007) obtained by a stand-alone passive microwave algorithm. They found a clear improvement in RMSE and bias error. In this study it is also mentioned that further improvement is needed due to better account for land cover and forest properties and the effect of lakes. We use ESA GlobSnow for assessing the skill and added value of CCLM for Siberia due to the more sophisticated approach to retrieve SWE from passive microwave satellite data than given in stand-alone algorithms. An important point in selecting this product was also the availability of an error-estimate and the advantage being a gridded dataset for whole Northern Hemisphere compared to single point station measurements.

2.3 Methods

For the assessment of added value we use ESA GlobSnow data as reference. In order to assure reasonable comparison with model data we use the daily L3A-product (v1.2) as one of the available products where no postprocessing was applied (e.g. 7-day sliding time window aggregation). This daily product of GlobSnow has the disadvantage that it contains several missing days and in certain months, e.g. May, June and September, the data availability is reduced to single days. This is due to the fact that for some dates the assimilation algorithm was not able to produce good SWE output. Reasons for erroneous retrievals are, e.g. missing data of weather stations or unusable satellite data. Especially in late spring and early autumn problems in the retrieval of SWE occur due to difficulties in using radiometer data when thin snow layer or wet snow is predominant. Therefore, no standard seasons are considered – the analysis is restricted to single months. We choose January and April representing months of snow accumulation and the beginning of melting period for southern regions where enough daily data over the long-term period of 1987–2010 is available. Unfortunately, no fall season representing the beginning of snow accumulation can be considered due to data shortage of daily data of GlobSnow over the considered years. Additional missing values occur over mountainous regions and water bodies. From daily SWE data monthly mean values are calculated. All missing values that occur in GlobSnow are excluded from all datasets before the monthly mean value of each dataset is calculated. In this study we decide to use the daily data from 1987 until 2010. 1987 was the year when the Special Sensor Microwave/Imager (SSM/I) started to operate and daily data was available. Using SSM/I ascending and descending data it is possible with daily data to cover all land areas north of ~20° N. The SWE product of GlobSnow includes also the information of snow cover extent where 0 mm denote snow-free areas and > 0.001 mm means areas with full snow cover (Snow Extent 100 %). In a first step the frequency of snow cover of April averaged over 1987–2010 is evaluated masking all daily datasets according this criterion and average over the full time record. Regional averaged analysis of SWE data is carried out decomposing the model domain in seven subdomains representing Arctic (northwards of the Arctic Circle), subarctic regions and those for the mid-latitudes. The subregions are named Arctic-West (AW), Arctic-East (AE), Mid-West (MW), Mid-Mid (MM), Mid-East (ME), South-West (SW) and South-East (SE) and are shown in Fig. 1. The GlobSnow SWE data is originally available in EASE-Grid projection and the SWE of CCLM is interpolated into the geographical coordinate system in 0.44° spatial resolution. The reanalyses data is kept on their original projection and spatial resolution and masks are used for selecting the single regions. Multi-year monthly means, standard deviation and temporal correlation are calculated for all the months where more than 20 yr of SWE of GlobSnow for the time period 1987–2010 are available. Time series presented here exclude the monthly mean if GlobSnow has more than 3 missing values. The uncertainty range of GlobSnow is calculated as standard deviation of the error estimates. Basically, 2 ways of data analyses are conducted: on the one hand spatial patterns of snow cover frequency for April averaged over 1979–2010 are examined for all considered datasets. On the other hand we consider area averages of subregions to evaluate the regional variations of all the different datasets for monthly, multi-year monthly and multi-year monthly standard deviation of SWE in January and April. In order determine a direct measure of association to GlobSnow the temporal correlation of monthly SWE is calculated using the Kendall rank correlation coefficient. We choose this non-parametric correlation as the monthly SWE of January

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and April does not follow the normal distribution. The statistical significance of the correlation coefficient is defined at the 95 % level. No temporal correlation of monthly SWE for April or January among the years is evident checking the autocorrelation function of observational dataset.

3 Results and discussion

3.1 Spatial patterns of snow cover frequency

The ability of reproducing large-scale distribution of snow extent over Siberian land areas by CCLM and reanalyses is critical concerning the surface albedo and thus the amount of energy available to turbulent and radiant energy exchange. Of special concern is the representation of onset and melt of snow during transition season of fall and spring. Since for the fall season the data coverage of GlobSnow was not sufficient throughout the years we can only consider the spring period represented here by April. In Fig. 2 the frequency of snow cover extent of April averaged over 1987–2010 is illustrated for the whole model domain for CCLM and reanalyses compared to GlobSnow. In some areas, e.g. Sayan Mountains in the south west, GlobSnow product does not deliver data which makes the evaluation for these regions difficult. This is a big disadvantage for this study since the potential of a RCM providing an added value is especially expected in areas with strong orography. The borderline of regions with days of 80–100 % and 60–80 % snow covered during April for 1987–2010 are well captured by CCLM in comparison to GlobSnow except for regions west of Lake Baikal. In that region the snow cover is less frequent in GlobSnow. Despite the missing data GlobSnow reveals a more heterogeneous structure of landgridboxes being more than 80 % snow covered in the southernmost parts than CCLM presents. The spatial pattern of CCLM is similar to NCEP-R1. In contrast to NCEP-R1 and NCEP-R2, CCLM offer more regional details of snow cover frequency. This is obvious, e.g. in the Lake Baikal Region. CCLM, NCEP-R1 and NCEP-R2 underestimate the frequency of snow

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cover in South Siberia especially in northern parts of Mongolia south of Lake Baikal. Thus the snow retreat takes place earlier than presented by GlobSnow. Reanalyses of CFSR and ERA-Interim with a higher spatial resolution than NCEP1 and NCEP2 overestimate the snow cover frequency during April, snow cover persists longer in lower latitudes averaged over all years. The melting occurs later since still 80–100 % of the days are snow covered at around 52° N given by CFSR and ERA-Interim, whereas in GlobSnow only 40–80 % of days are snow covered at the same latitude. A special feature of NCEP-R1 and NCEP-R2 becomes obvious for coastal regions of Siberia where the frequency of snow cover in April is lower than presented by Globsnow with more than 80 % snow covered. Here CCLM can show an added value being in the same range of frequency of snow covered gridboxes as GlobSnow.

3.2 Regional characteristics of monthly mean SWE and temporal correlation

In order to analyze the added value in representing characteristic monthly SWE during snow accumulation and melting period we compare the long-term means of January and April given by CCLM, GlobSnow and reanalyses averaged over 1987–2010 for each subregion. Figure 3a illustrates that all data sets show more SWE than presented by NCEP-R1 for all subregions except the southern domains. No latitudinal variation occurs in NCEP-R1 for January and only marginal in April in southern regions. GlobSnow as reference, show in contrary a north-south gradient from arctic to the southern subregions with less SWE of arctic regions than in the middle domains and decreasing values southward. In January the higher values of AW compared to AE which can be seen in all data sets except NCEP-R1 match with climate conditions during winter in Siberia. From November to March Siberia is dominated by the Siberian high pressure system centered southwest of Lake Baikal (Przybylak, 2003). The relatively infrequent eastward propagating cyclones with moist air masses from the Atlantic occur mainly in the northern regions. The decreasing moisture source explain the decline in snow and SWE eastwards of AW and MW. MW presents the highest value of SWE which is evident in GlobSnow, ERA-Interim and CCLM. This region is located in the West-Siberian

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Lowlands where the Central-Siberian Highlands act as barrier and favour orographically induced solid and fluid precipitation. In the direct dataset comparison it is evident that CCLM reproduces well SWE for January compared to GlobSnow whereas NCEP-R1 is clearly outside the uncertainty range given by GlobSnow, except for SW and SE. The poor performance of NCEP-R1 is related to erroneous snow analysis, which was already documented by Kanamitsu et al. (2002) and further mentioned in the study by Khan et al. (2008). But this shows the added value of CCLM compared to NCEP-R1 for January and the benefit in using a RCM to generate more realistic SWE than the driving reanalysis provide. NCEP-R2 is in better agreement to GlobSnow than NCEP-R1 except for SE. ERA-Interim reproduces the regional SWE distribution of satellite-derived SWE but tends to overestimate SWE. Largest discrepancies occur for the Region MM where ERA-Interim is outside the uncertainty range of GlobSnow. Except for AW the CCLM hindcast is in closer agreement to GlobSnow than ERA-Interim. NCEP-CFSR shows the regional variations of SWE but underestimates SWE for all subregions being even outside the uncertainty range for the middle Siberian regions. Therefore, we conclude that CCLM for January even provide an added value compared to ERA-Interim and CFSR. In April CCLM overestimates SWE in all subregions compared to GlobSnow data. CCLM is even outside the uncertainty range of GlobSnow for the subregions AW, MW, MM and ME showing higher values than ERA-Interim. In this month, ERA-Interim is for AW, MW and SW clearly in better agreement to the satellite-derived SWE data, even though SWE is overestimated as well. This overestimation is especially pronounced in the regions MM and ME. NCEP-R1 shows again almost no regional variations of SWE and is outside the error-range of GlobSnow except for the regions SW and SE being close to the values presented by GlobSnow. During these months in most regions southward the Arctic Circle snowmelt period begins indicated by decreasing SWE values of GlobSnow. For all subregions NCEP-R2 is in good agreement to GlobSnow and within the uncertainty range. For the regions MW, MM and ME almost no variations are evident. Again, CFSR has, besides NCEP-R1, lowest SWE for all subregions and falls apart the error-estimate of GlobSnow for MW, MM. Additionally, only

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small regional variations are obvious. The overestimation during melting of snow pack which is here the case in southern regions, is a common feature of climate models. Also state-of-the-art global climate models overestimate snow mass of the Northern Hemisphere (Clifford, 2010; Raeisaenen, 2008; Roesch, 2006). The overestimation by CCLM might be partly related to the absence of subgrid snow cover heterogeneities in CCLM leading to a snow cover that not gradually ablates (Liston, 2004). Even though CCLM produces much more SWE for several regions than GlobSnow, an added value can be seen in terms of the regional variations which are more realistically described in CCLM than in NCEP-R1. Nevertheless, it highlights also shortcomings in snow cover simulations, especially during melting seasons, which needs to be addressed in future work. In order to determine a measure of association for provided SWE between CCLM, reanalyses and GlobSnow we calculate the temporal correlation of monthly mean SWE using the Kendall rank correlation coefficient. Statistically significant coefficients at the 95 % level of confidence are marked with crosses in Fig. 3b. CCLM shows in January for all subregions significant highest correlations with a maximum of around 0.8 in ME. Except for SW and SE ERA-Interim shows higher correlations than CCLM. We find lower correlations of NCEP-CFSR for all subregions. For NCEP-R1 even negative correlations of around −0.2 in MM are evident. In April CCLM shows for all subregions statistically significant correlations between 0.4 and 0.7 (SE). Except for AW and MW higher correlations are given by ERA-Interim, NCEP-R2 and CFSR. Interesting to see is that even though CCLM overestimates the multi-year mean SWE for April for MW, MM, ME, and SW it shows higher rank correlation coefficient than ERA-Interim due to better agreement in ranks with GlobSnow. Despite the low long-term mean April SWE of NCEP-R1 in some regions as MW, MM, ME and SE correlations between 0.4 and almost 0.6 are reached although they are not significant.

3.3 Interannual variability of SWE

In the previous section it was evident for the multi-year monthly means that CCLM is in good agreement to the remote sensing derived SWE during the cold season but

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overestimates SWE in April. To assess the added value of CCLM in terms of interannual variations of these characteristic months Fig. 3c provides the multi-year monthly standard deviation. In NCEP-R1 almost no interannual variations take place for January and April. The deviation of the long-term monthly mean in January is around 8–15 mm in case of GlobSnow. A good agreement to GlobSnow is given by CCLM which tends to sligthly overestimate the standard deviation, especially for the region MW. CCLM capture well the regional characteristics of long-term monthly standard deviation in April compared to GlobSnow with an overall slight overestimation, especially in AE, ME and SW. In terms of the two considered months (January and April) CCLM provides more realistic detail, and thus an added value to NCEP-R1 and even NCEP-R2. NCEP-R2 shows the highest discrepancy to GlobSnow, especially pronounced for ME in April. High standard deviations are also evident for NCEP-CFSR in January for the region MW and in April for ERA-Interim in the region MM. In order to explain the long-term monthly standard deviations, Fig. 4 and 5 presents the time series of monthly mean SWE. Here we can see that the strong deviations in January and April of NCEP-R2 for all subregions are caused by the sudden change of SWE from 1999 or 2000 onwards with lower SWE in the following years. A pronounced sudden jump is also obvious for ERA-Interim in 2003 for MM which causes the high standard deviation in that region. Before, ERA-Interim reveals a pronounced overestimation and less interannual variations than presented by GlobSnow and CCLM in all regions until 2001. After 2003 ERA-Interim gets closer to the satellite-derived SWE data for the regions AW, AE, MA. This temporal inconsistency is very pronounced in MM and SE. An explanation of this sudden change might be the geolocation errors that have affected the ERA-Interim snow analyses from July 2003 onwards, as mentioned by Dee et al. (2011). Strong deviations also occur in January in NCEP-CFSR for the regions MW and MM where sudden changes of monthly SWE around the year 2000 are evident. In general NCEP-CFSR provides besides NCEP-R1 lowest SWE throughout the years for January and April in all subregions. CCLM tends to overestimate SWE in AW in most of the considered years whereas in ME and SE SWE is underestimated by CCLM compared to

GlobSnow. In general CCLM follows the temporal evolution of SWE within the given uncertainty range of GlobSnow. High discrepancies are shown by the NCEP-R1 SWE in comparison to all other datasets. Almost no variation takes place throughout all the years having values around 30 mm per months. Except for the south-west region where the SWE values from GlobSnow show the same range NCEP-R1 is clear outside the observed SWE uncertainty range. Due to the erroneous snow processing of NCEP-R1, as stated in (Kanamitsu et al., 2002), the SWE for the whole considered Siberian region can be regarded as unrealistic. This shows a clear added value of CCLM during cold season compared to GlobSnow as reference data. The approach of dynamical downscaling of NCEP-R1 reanalysis using CCLM can add realistic details in terms of SWE due to its own model physics of 1987–2010 and even compared to ERA-Interim for 2003–2010, NCEP-R2 and NCEP-CFSR. This clear added value cannot be seen April. In contrast to January the CCLM-simulated SWE for April shows an overestimation for all considered subregions. In most of the years CCLM is even outside the uncertainty range of GlobSnow except for the South-East region. Here ERA-Interim agrees better with GlobSnow whereas in certain subregions the sudden change in the presented time series is again visible after 2003 leading to higher SWE values than estimated by GlobSnow. Even though CCLM overestimates SWE this overestimation is consistent with time. In contrast to ERA-Interim and NCEP-R2, that show temporal inconsistencies in their SWE estimates.

4 Summary and conclusions

This study demonstrates the potential and limitation of the regional climate model hindcast of CCLM for Siberia to provide a gridded dataset of recent past SWE with more realistic detail than global reanalyses can present. As reference data we choose a satellite derived SWE product of ESA GlobSnow in order to assess the added value of the regional climate model hindcast in a large scale. In terms of the spatial distribution of the frequency of snow cover during April CCLM is in good agreement to GlobSnow presenting especially in the coastal areas more days with snow cover than NCEP-R1 and NCEP-R2. In terms of the southernmost extent with more than 80 % of snow cover ERA-Interim and NCEP-CFSR show highest discrepancies to GlobSnow. CCLM indicates a great added value of SWE compared to NCEP-R1 since the reanalysis does not represent any of the regional and temporal variations of SWE for the considered subregions except for southern parts. The poor performance of NCEP-R1 is no new finding – the snow processing errors are already well documented. But it shows that the technique of dynamical downscaling here of NCEP-R1 can provide more realistic detail of SWE using the forcing fields (e.g. pressure, wind) than the reanalysis itself can present for SWE. The RCM makes it possible due to the own model physics, e.g. snow parameterization and finer resolved regional features as orography and land cover. It is evident for the whole SWE field even for mean values. We conclude from these results that an added value of CCLM compared to global reanalyses is strongly dependant on the considered variable and the used physical parameterizations. Additional we illustrate that SWE of the regional hindcast is more consistent in time than ERA-Interim presenting a sudden jump in 2003 that gets obvious in certain subregions. A temporal inconsistency is also evident in NCEP-R2 around 1999–2001 that explains the highest multi-year monthly standard deviation among the considered datasets. The regional climate model hindcast driven with coarse NCEP-R1 can even compete with the newest generation of NCEP reanalysis (CFSR) at 38 km resolution that underestimates SWE in many subregions. Especially in the period of snow accumulation the CCLM hindcast is in better agreement to GlobSnow. However, as clearly shown by the SWE overestimation of CCLM in April, there is still some model deficiency obvious which needs to be addressed in order to justify the RCM application even in snow dominated cold regions as Siberia. It should be stressed that the results are dependant on the quality of the reference data ESA GlobSnow which itself needs further improvement in the algorithm (Takala et al., 2011). Nevertheless, the intercomparison of the datasets in terms of SWE suggests that CCLM output is useful to study regional changes in SWE in the data sparse region of Siberia with more regional and realistic detail and temporal consistency than many reanalyses present.

Appendix A

Nomenclature

CCLM	COSMO model in CLimate Mode
SWE	Snow water equivalent
NCEP-R2	NCEP Reanalysis 2/DOE
NCEP-CFSR	NCEP Reanalysis CFSR
SWIPA	Snow, Water, Ice and Permafrost in the Arctic
JRA-25	Japanese 25-yr ReAnalysis
RCM	Regional Climate Model
MGO	Main Geophysical Observatory
NCEP	National Centers for Environmental Prediction
ECMWF	European Centre for Medium-Range Weather Forecasts
NOAA	National Oceanic and Atmospheric Administration
CFSR	Climate Forecast System Reanalysis
IMS	Ice Mapping System
SSMR	Scanning Multichannel Microwave Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer – EOS
INTAS-SCCONE	International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union – Snow Cover Changes Over Northern Eurasia
RMSE	Root Mean Square Error
SSM/I	Special Sensor Microwave/Imager

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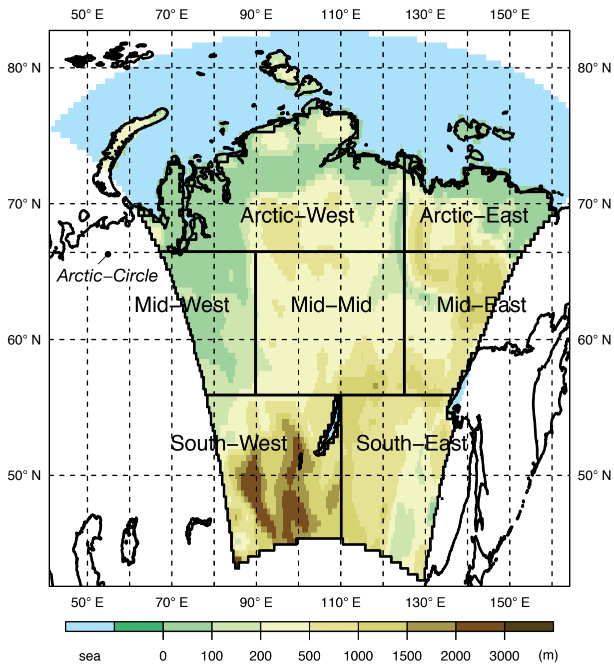

Fig. 1. Orography (m) of model domain of CCLM (coloured area) for Siberia and considered subregions on lon/lat grid.

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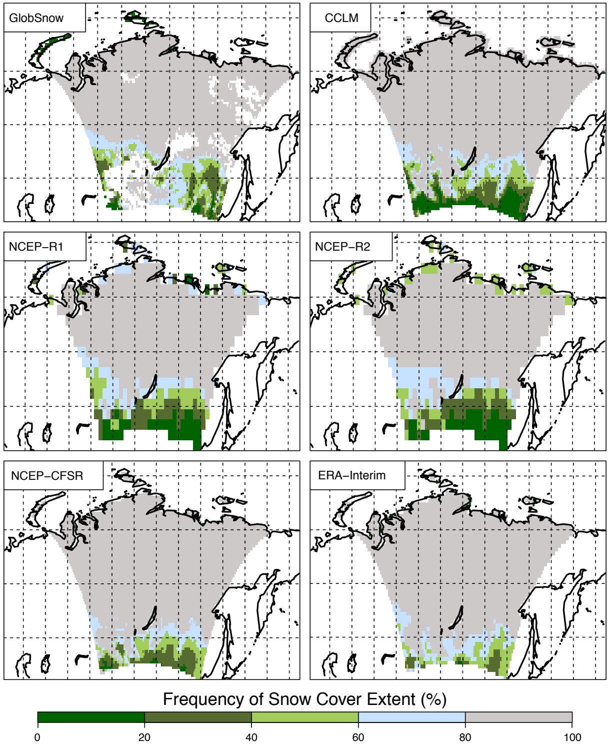

Fig. 2. Frequency of snow coverage over land points of model domain during April between 1987–2010, presented by all considered data sets. White boxes within the model domain indicate missing values.

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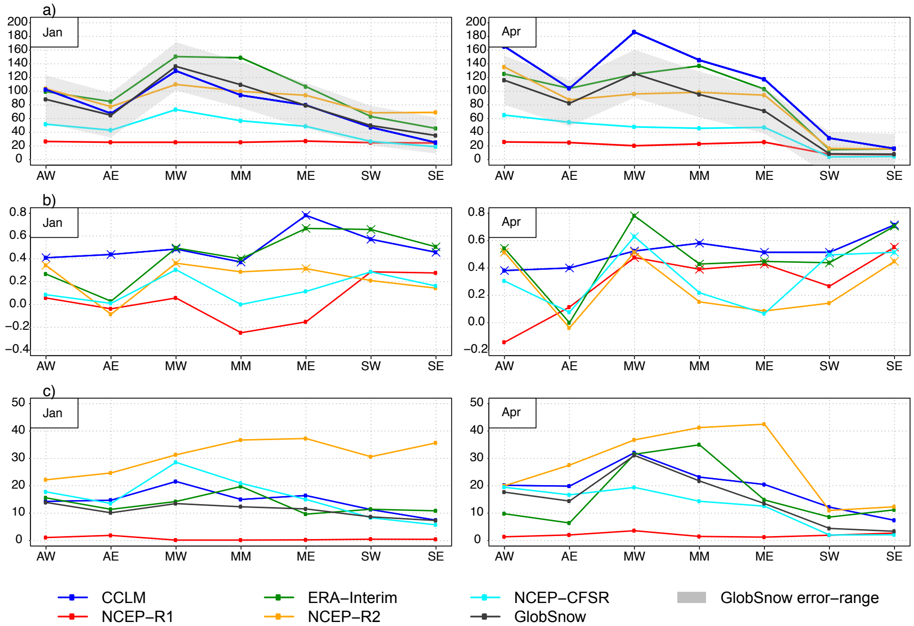

Fig. 3. (a) Regional variations of multi-year (1987–2010) monthly mean of SWE (mm) for January and April for CCLM, NCEP-R1, NCEP-R2, NCEP-CFSR, ERA-Interim and GlobSnow; **(b)** temporal correlation of monthly mean of SWE (1987–2010), statistical significant coefficients defined at the 95 % level are marked with crosses; **(c)** multi-year monthly standard deviation of SWE for 1987–2010. The gray shaded area represents the error-range of GlobSnow.

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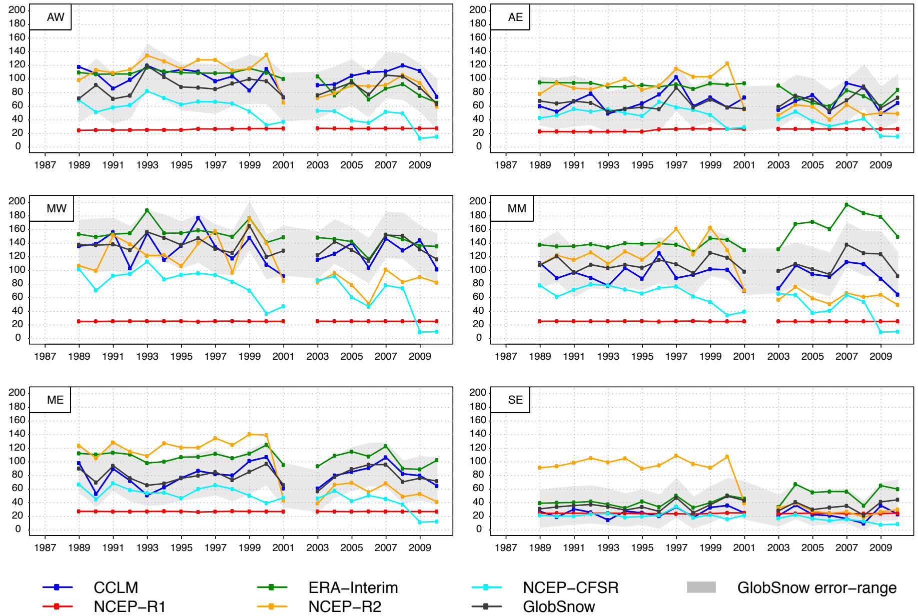

Fig. 4. Time series mean January SWE (mm) (1987–2010) for all considered datasets for different subregions. The gray shaded area represents the error-range of GlobSnow. Data gaps occur where GlobSnow provides SWE with more than 3 missing days per month. These months are excluded in all data sets.

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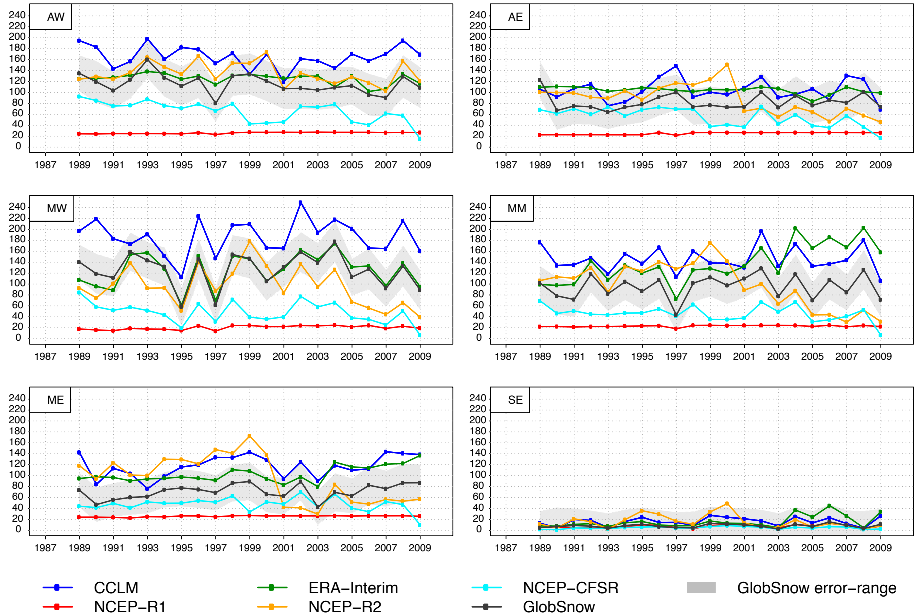

Fig. 5. As Fig. 4 – mean April values are shown.