Snow Cover Characteristics over the Main Russian River Basins as Represented by Reanalyses and Measured Data

V. KHAN

Hydrometeorological Research Centre of the Russian Federation, Moscow, Russia

L. HOLKO

Institute of Hydrology, Slovak Academy of Sciences, Liptovsky Mikulas, Slovakia

K. RUBINSTEIN

Hydrometeorological Research Centre of the Russian Federation, Moscow, Russia

M. BREILING

Technical University Vienna, Vienna, Austria

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ABSTRACT

Snow water equivalents (SWE) produced by the National Centers for Environmental Prediction–U.S. Department of Energy (NCEP–DOE) and 40-yr European Centre for Medium-Range Weather Forecasts (ERA-40) reanalyses and snow depths (SD) produced by the 25-yr Japanese "JRA-25" reanalysis over the main Russian river basins for 1979–2000 were examined against measured data. The analysis included comparisons of mean basin values and correlation of anomalies, as well as seasonal and interannual variabilities and trends. ERA-40 generally provided better estimates of mean SWE values for river basins than did the NCEP–DOE reanalysis. Mean SD values from the JRA-25 reanalysis were systematically underestimated. The best correlations among the anomalies were given by ERA-40, followed by JRA-25. All reanalyses reproduced seasonal variability well, although the differences in absolute values varied substantially. The highest differences were typically connected with the snowmelt period (April and May). Interannual variability confirmed the errors of ERA-40 and JRA-25 in 1992–94 and 1979–83, respectively. Otherwise, the reproduction of the interannual variability of SWE and SD was reasonable. Strong biases in SD data from JRA-25 that decrease with time induce artificial positive trends. Significant underestimations of SWE data by ERA-40 for 1991–94 influenced the values of the trends. NCEP–DOE reasonably represented the trend found in measured data. In general, the highest discrepancies between measured and reanalysis data were found for the northern European and eastern Asian rivers (Pechora, Lena, and Amur). The assessment of the quality of SWE and SD reanalysis data can help potential users in the selection of a particular reanalysis as being appropriate to the purpose of their studies.

1. Introduction

Snow is a very important component for the predictability of weather and climate and for the hydrological cycle. Modeling and empirical studies of the effect of snow cover revealed the influence of snow cover on atmospheric circulation patterns (e.g., Clark et al. 1999; Clark and Serreze 2000). Despite significant efforts (e.g., Groisman et al. 1994; Fallot et al. 1997; Cohen and Entekhabi 1999; Hall and Qu 2006), the understanding of the influence of snow cover on the environmental system through its direct and indirect feedbacks is not complete.

Hydrodynamical models are useful tools for the examination of impacts and physical mechanisms of snow as a surface forcing and a part of the hydrological cycle. Yet the lack of reliable data on snow cover character-

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Corresponding author address: Dr. V. Khan, Hydrometeorological Research Centre of the Russian Federation, Bol. Predtechensky 9–13, Moscow 123242, Russia.
E-mail: khan@mecom.ru

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istics complicates the validation of snow cover simulations at regional and global scales, and limits improvements of the models for numerical weather prediction and climate change investigations. Several recent studies analyzed snow cover extent simulated by hydrodynamical models using satellite data for validation (e.g., Frei and Robinson 1998; Frei and Gong 2005). Other important reviews on the evaluation of snow simulation in numerical models were presented, for example, by Foster et al. (1996) and Frei et al. (2005). However, to the best of our knowledge there was no work devoted to the use of reanalysis in the evaluation of snow simulation.

Brown et al. (2003) developed regional gridded monthly snow-depth (SD) and snow water equivalent (SWE) data for 1979–96 with good spatial resolution. This dataset was derived by blending output fields of a snowpack model and observed snow data. They compared SWE estimates over North America with independent observational data and demonstrated good agreement over midlatitude regions of North America. Frei et al. (2005) complemented the dataset developed by Brown et al. (2003) with National Oceanic and Atmospheric Administration (NOAA) weekly satellite-derived snow extent observations and gridded precipitation and air temperature data, using it to evaluate the performance of 18 atmospheric general circulation models in snowmass and SWE simulations over North America. Roesch (2006) compared and validated the SWE of state-of-the-art coupled climate models against an SWE dataset transformed from the global snow-depth climatological dataset of the U.S. Air Force Enviromental Technical Application Center using the empirically estimated density of snow from Verseghy (1991). Roesch (2006) reported a positive SWE bias of most Intergovernmental Panel on Climate Change "A4" models in the spring period resulting from heavy snowfall during the winter and spring seasons.

Gridded SWE and SD data similar to those prepared by Brown et al. (2003) for North America do not exist for northern Eurasia. Brown et al. (2003) stated that the preparation of gridded SD and SWE data could not have been extended to northern Eurasia because of insufficient in situ snow data. The number of stations providing measured snow data from northern Eurasia even decreased in the 1990s. Thus, the only information on SWE and SD over longer periods available for northern Eurasia is provided by reanalysis. Reanalysis is a new method that has recently completely changed the traditional approach to climatology (Kalnay et al. 1996). A state-of-the-art data assimilation system is used to reprocess all past environmental observations, combining them with short forecasts to derive the best estimate of the state and evolution of the environment. In the last decade, several lead meteorological centers have made their reanalyses available. For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) provides reanalyses that cover periods of 15 and 40 yr, [i.e., ERA-15 (Gibson et al. 1997) and ERA-40 (Uppala et al. 2005), respectively]. Other reanalyses are provided by the U.S.-based National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996; Kistler et al. 2001), the U.S. Department of Energy (NCEP–DOE; Kanamitsu et al. 2002), the U.S.-based National Aeronautics and Space Administration Goddard Earth Observing Systems (GEOS1 and GEOS2; Schubert et al. 1993), and the Japan Meteorological Administration and Central Research Institute of Electric Power Industry (JRA-25; Onogi et al. 2007). Reanalyses are used by a large number of scientists and not only in the fields of climatology and atmospheric studies. Evaluation of the information provided by reanalyses (e.g., on snow characteristics) may therefore be useful for various users.

North-flowing Russian rivers are responsible for the bulk of freshwater supplied to the Arctic Ocean. The regime of freshwater inflow is an important component of coastal ocean dynamics. Recent studies demonstrated an increase of northern river runoff, especially in winter and spring seasons (e.g., Serreze et al. 2003; Yang et al. 2003, 2004). However, the reasons for these changes are under discussion. The variability of snow mass could be an important factor for explaining the reported changes in river runoff. However, the state of the meteorological network in northern Eurasia sharply deteriorated after the disintegration of the Soviet Union. In vast areas, especially in the north of Asian Russia, snow cover monitoring has been irregular since 1990. Several studies (e.g., Yatagai 2003; Schär et al. 2004) proposed to overcome the problem of sparse network observations by using outputs from modern state-of-the-art atmospheric assimilation systems. Schär et al. (2004) created a statistical forecast model to predict summer river discharges in central Asia. The model was based on winter and spring precipitation estimates from the ERA-15 reanalysis. Results of the study demonstrated the applicability of ERA-15 precipitation and snow data. The authors showed that in central Asia, the assimilated precipitation estimates from ERA-15 had higher quality than did rain gauge–based precipitation analyses. Reanalysis could again be useful to provide supplementary data in case of decreasing density of ground meteorological stations.

It is known that the outputs of different reanalyses can differ considerably at some locations (e.g., Serreze and Hurst 2000; Li et al. 2005). The objective of this paper is to analyze the value of three reanalysis datasets in a study of snow cover characteristics (SWE by ERA-40 and NCEP–DOE; SD by JRA-25) in northern Eurasia. The analysis was conducted for the large river basins in Russia (Fig. 1; Table 1) for the period 1979–2000. The results could help in the selection of a particular reanalysis for specific applications (e.g., validation of snow cover simulations at larger scales, improvement of the models for numerical weather prediction and climate change investigations, or explanation of changes in hydrological regime at decreasing number of meteorological stations).

2. Datasets

a. Reanalyses

We used snow characteristics from three reanalyses. SWE data from the first reanalysis, the ERA-40, cover the period from 1957 to 2002. The ERA-40 model uses T159 spherical harmonic resolution and 60 vertical levels. The forecast system contains a modern version of the model physics, including a recent land surface scheme, and a 3D variational assimilation system with a 6-h analysis cycle (Uppala et al. 2005). Snow-depth analysis at ECMWF relies on in situ observations, short-range forecasts of the Integrated Forecast System, and snow climatological information. Final SWE is estimated from the analyzed snow depth and the corresponding snow density simulated by the model (Drusch et al. 2004). Time series of global-mean snow mass exhibit low values from 1992 to 1994 because of an computer coding error introduced into the snow analysis. The analysis up to 1997 also suffers, though to a lesser extent, from a miscoding by ECMWF of Canadian snow-depth observations that moved some observation dates to later within the same month (http://www.ecmwf.int/research/era/). The spatial resolution of the ERA-40 SWE available in this study was 2.5° (Fig. 1).

The second reanalysis used contained SWE data from the NCEP–DOE reanalysis (1979–2004). The NCEP–DOE reanalysis is the updated and human-error-fixed version of the NCEP–NCAR reanalysis (Kanamitsu et al. 2002). The model used in this reanalysis has a T62 spectral resolution (Fig. 1) and 28 sigma vertical levels. The analysis scheme is a three-dimensional variational scheme (Kalnay et al. 1996; Kistler et al. 2001). The correction of human processing errors and updating the forecast model and data assimilation system have resulted in significant improvements of some output fields in the NCEP–DOE reanalysis (Kanamitsu et al. 2002). In particular, the error in the snow cover analysis of the previous version of the NCEP–NCAR reanalysis (repeated use of the 1973 data for the entire 1974–94 period) was fixed. The so-called spectral snow problem caused by a simplification of the diffusion equation was resolved. An error in the expression of the snowmelt term in the model, in which the conversion of snow to water was overestimated by a factor of 1000 the NCEP–NCAR reanalysis, was corrected. SWE in NCEP–DOE does not include any information from surface measurements. Only a weekly Northern Hemisphere analysis of snow cover based on satellite imagery was available for ingestion. If the modeled SWE value is not consistent with input snow cover analysis, the modeled snow is adjusted to the snow cover analysis by either removing the model snow or by adding snow using an empirical formulation (Kanamitsu et al. 2002).

The third reanalysis, the JRA-25 reanalysis developed by the Japan Meteorological Agency in association with the Central Research Institute of Electric Power Industry (http://jra.kishou.go.jp/index_en.html), contains SD data and covers the period from 1979 to 2004. The global forecast model used for JRA-25 has the resolution of spectral T106 (Fig. 1) with 40 vertical layers, and the data assimilation scheme is a three-dimensional variational system with a land surface assimilation system (Onogi et al. 2007). Most of the observational snow data used in the reanalysis came from snow-depth data from surface synoptic observations (SYNOP). The reanalysis also used new observational datasets that were not used in other reanalyses: the Special Sensor Microwave Imager (SSM/I) snow coverage since July 1987 and newly digitized Chinese SD data from monthly reports on Chinese ground meteorological conditions (since January 1979). NOAA weekly snow coverage data were used prior to July 1987, before which time no SSM/I data were available. Snow-depth analysis in JRA-25 was performed once per day on a T106 Gaussian grid using a 2D optimal interpolation scheme. Snow-depth forecast from the JMA Global Spectral Model is used as a first guess (background). An observation error of snow-depth data was specified depending on the snow coverage rate (Onogi et al. 2007). Some of the available snow data were not used in the SD analysis during certain periods (e.g., the Siberian data between January 1979 and August 1983) because of technical problems. Onogi et al. (2007) also reported that the decreased frequency of snow reports from the territory of the former Soviet Union during 1984–90 caused the SD to increase suddenly (every 10 days) in the reanalysis during the snowfall season in autumn.

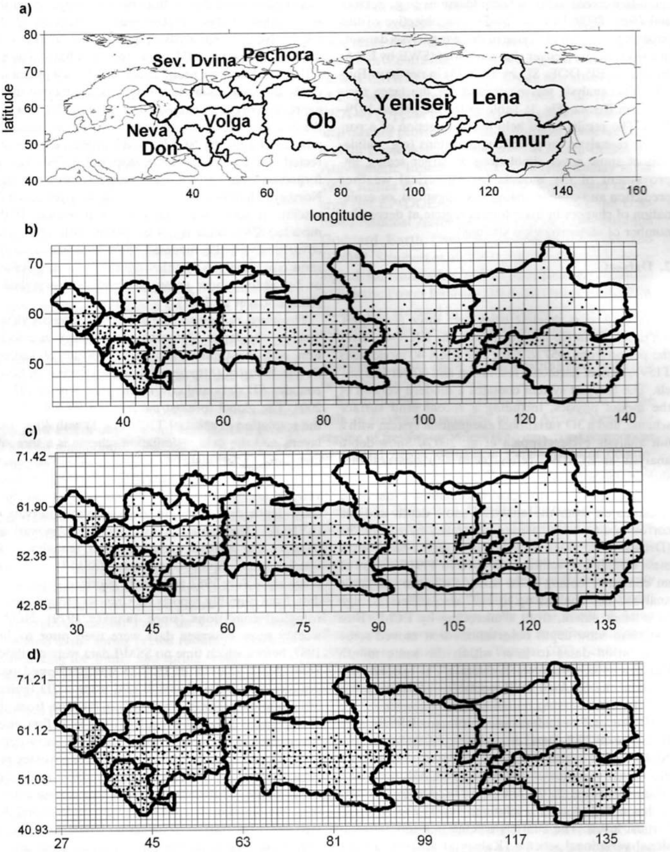

FIG. 1. (a) The studied river basins, the spatial resolution of gridded SWE from (b) ERA-40 and (c) NCEP–DOE, and (d) the spatial resolution of SD from JRA-25. The dots in (b)–(d) represent locations of stations providing measured SWE (mm) and SD (cm) data.

TABLE 1. Basic characteristics of studied river basins, mean SWE as given by measurements and ERA-40 and NCEP–DOE reanalyses, and mean SD as given by measurements and JRA-25 reanalysis (1979–2000).

River basin	River length (km)	Basin area (km^2)	Mean annual discharge (m^3 s^{-1})	SWE measurements (mm)	SWE ERA-40 (mm)	SWE NCEP–DOE (mm)	SD measurements (mm)	SD JRA-25 (mm)
Volga	3690	1 380 000	8000	82	77	88	30	24
Don	1950	425 000	935	42	35	69	14	10
Neva	74	282 000	2600	70	73	76	27	21
Pechora	1809	322 000	4100	133	105	105	53	37
Severnaya Dvina	744	357 075	3530	106	100	88	44	33
Ob	5410 (to Irtysh)	2 972 497	12 500	81	73	82	32	25
Yenisei	5500	2 580 000	19 600	68	75	89	29	21
Lena	4400	2 500 000	17 000	67	80	104	32	24
Amur	4444	1 855 000	8600	46	57	85	23	14

b. Measured data

Selected snow characteristics from the database of the former Soviet Union Hydrological Snow Surveys were used as validation data. Snow surveys were carried out every 5 or 10 days during the snow cover season using a portable snow measuring rod and a snow weighting balance. The transect snow-depth data are the spatial average of 100–200 individual measuring points. The transect snow water equivalent is the spatial average of 20 individual measuring points. Snow surveys were carried out in the vicinity of meteorological stations at a typical forested and/or open site, but not closer than 500 m from buildings, roads, or other structures. The length of a snow course was 2 km in an open area, 1 km in a sparsely forested area, and 500 m in a dense forest. Original hard copies of monthly reports of snow surveys are kept by the Russian Institute of Hydrometeorological Information–World Data Center at Obninsk, Russia. They comprise data from more than 1300 sites since 1966. The data were digitized at Obninsk (until 1996) and at the Institute of Geography, Russian Academy of Sciences (1996–2000; Krenke 1998). The development of this dataset was funded by the NOAA Environmental Services, Data, and Information Management program through the NOAA National Environmental Satellite, Data, and Information Service National Geophysical Data Center.

Because of gaps in observations, not all of the stations could be used in our study. We have thus selected only stations within the studied river basins (Fig. 1) that have at least 67% of observations during the winter seasons of 1979–2000. This way the total number of stations was reduced to a maximum of 690. The spatial distribution of stations over the main Russian river basins is not uniform. The European part of Russia is covered considerably better than is northern Asia (Fig. 1).

3. Approach

The value of reanalyses in the study of snow cover characteristics was determined by a comparison of measured SWE data with those of the ERA-40 and NCEP–DOE reanalyses and a comparison of measured SD data with those of the JRA-25 reanalysis. The comparison was made for the period of 1979–2000. The data were analyzed from various aspects. First, mean SWE and SD values for the whole period of 1979–2000 and each river basin were calculated. Then, mean values and the spatial distribution of correlation coefficients of anomalies between measured and reanalysis data were determined and seasonal and interannual variabilities of both measured and reanalysis data were examined. The analysis was completed by a comparison of the results of trend analysis.

Corresponding values of snow water equivalents and snow depths from the reanalyses were compared with measured data. The reanalysis grid nodes with coordinates closest to the coordinates of the in situ data were selected for the comparative analysis. In this way was each measured value compared with a value from reanalysis. It means that sometimes the same value from a reanalysis was compared with several measured values. This approach did not influence the results of the analysis of mean river basin values of measured data, but it could have influenced values of the correlation coefficients because of using more data in calculation.

Mean values of measured and reanalysis snow characteristics for the river basins were calculated as an arithmetic mean of the measurements at stations (and corresponding values from reanalysis nodes) situated in particular river basins. This way, all of the measured data in a river basin were used. Such an approach was used to avoid the uncertainty connected with calculation of weighted means (i.e., selection of "the most appropriate weighting technique"). Correlation coefficients between the anomalies from reanalysis and measured snow characteristics were calculated for monthly data. The anomaly (i.e., the difference of the value in a particular month and the long-term mean value for the same month) was used instead of direct data to remove the effect of seasonality.

The values of correlation coefficients were classified in three categories: 1) values of less than 0.2 were classified as an unsatisfactory agreement, 2) values from 0.2 to 0.5 represented an uncertain agreement, and 3) values higher than 0.5 were classified as a satisfactory agreement. Seasonal and interannual variabilities and trends in snow characteristics were evaluated for the main river basins. Trends were calculated as the slopes of linear regression lines.

4. Results and discussion

a. Mean values and correlation coefficients for river basins

Mean values of SWE and SD for the river basins are shown in Table 1. Except for the Ob River basin, ERA-40 always provided better results than did NCEP–DOE. Mean values of SWE from ERA-40 in particular river basins represented from 79% (Pechora) to 125% (Amur) of the measured mean SWE in the same basins. With the exception of the Pechora River basin, mean SWE values from ERA-40 were comparable with measurements, although the differences were greater for the Lena and Amur River basins. Both reanalyses provided good results for Neva, Volga, and Ob. The NCEP–DOE data provided mostly overestimated mean values. They did not provide good results for Don, Amur, and Lena. Mean values of SWE from NCEP–DOE represented from 79% (Pechora) to 186% (Amur) of the measured mean SWE in the same basins.

TABLE 2. Correlation coefficients between anomalies from measured and reanalysis snow data (SWE for ERA-40 and NCEP–DOE and SD for JRA-25).

River basin	ERA-40	NCEP–DOE	JRA-25
Volga	0.54	0.30	0.62
Don	0.53	0.14	0.63
Neva	0.65	0.43	0.61
Pechora	0.51	0.39	0.65
Severnaya Dvina	0.57	0.38	0.66
Ob	0.47	0.15	0.50
Yenisei	0.39	0.23	0.41
Lena	0.34	0.23	0.46
Amur	0.35	0.18	0.34

The differences between mean measured and reanalysis data for SD from JRA-25 were generally greater than those for SWE (from ERA-40 and NCEP–DOE). For the European rivers (with the exception of the Pechora) they were smaller than for the Asian rivers. The SD values from JRA-25 systematically underestimated measured values of SD. Mean values of SD from JRA-25 in particular river basins represented from 62% (Amur) to 80% (Volga) of the measured mean SD in the same basins.

It is clear from Fig. 1 that measured data are not equally distributed over river basins, especially in northern Europe and Siberia. Mean SWE/SD values therefore do not represent true characteristics for the river basins in northern Europe and Siberia territory.

Mean correlation coefficients between anomalies from measured and reanalysis data had higher values for ERA-40 than for the NCEP–DOE reanalysis. The largest values belonged to JRA-25 (Table 2). Correlation coefficients for the European rivers were higher than for the Asian rivers.

The percentages of the best correlations between anomalies from reanalyses and measurements (i.e., having correlation coefficients higher than 0.5) were 48% for ERA-40 and 39% for JRA-25 (Table 3). In the case of NCEP–DOE only 17% of stations were in the highest rank.

Analysis of the spatial distribution of the correlation coefficients (Fig. 2) showed that the ERA-40 reanalysis compared well to measurements in the European part of Russia (river basins of Volga, Don, Severnaya

TABLE 3. Numbers and percentages of stations corresponding to three classes of the correlation coefficients between measured and reanalysis data (SWE for ERA-40 and NCEP–DOE and SD for JRA-25).

	ERA-40		NCEP–DOE		JRA-25	
Correlation coef	% of stations	No. of stations	% of stations	No. of stations	% of stations	No. of stations
<0.2	15%	105	42%	294	31%	213
0.2–0.5	37%	250	41%	283	30%	207
>0.5	48%	335	17%	113	39%	270

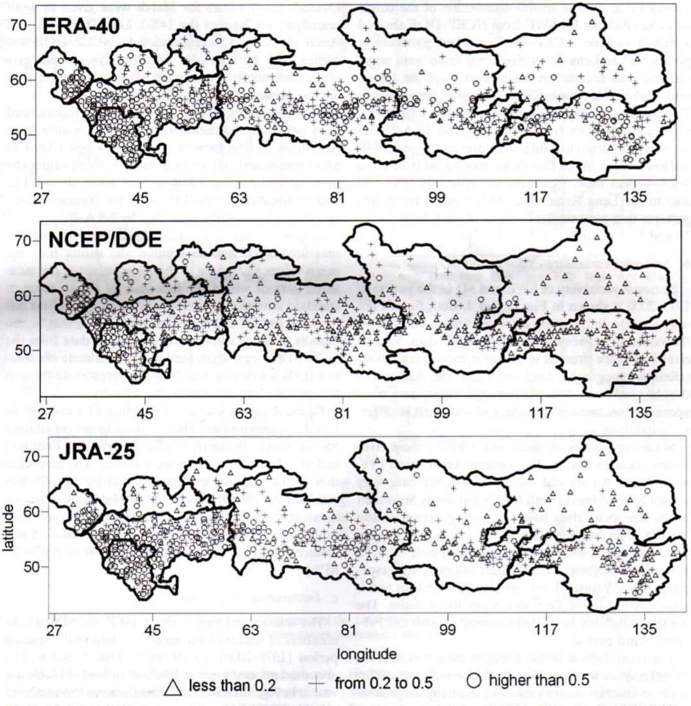

FIG. 2. Spatial distribution of correlation coefficients between measured and reanalysis data (SWE for ERA-40 and NCEP–DOE; SD for JRA-25).

Dvina, Pechora, and Neva). There were no stations with correlation coefficients from the lowest rank in these river basins. A "mixed picture" was found for the basins of the Asian rivers Ob, Yenisei, and Lena. Low values of correlation coefficients were found for middle reaches of Ob and low and middle reaches of Lena. ERA-40 and measured anomaly data compared reasonably well also in the Amur river basin in the sense that there were almost no correlation coefficients from the lowest rank there. However, relative to other river basins the mean correlation coefficient for Amur was lower (Table 2). The spatial distribution of the correlation coefficients for SWE from NCEP–DOE showed a mixed picture. NCEP–DOE worked particularly poorly for the Lena River basin, but there were many stations with correlation coefficients from the lowest rank also in the Amur, Ob, and Yenisei River basins. The spatial distribution of the correlation coefficients between anomalies from measured and JRA-25 SD showed more stations with correlation coefficients from the lowest rank in the European river basins than when ERA-40 was used. Correlation coefficients were low also in the Lena River basin. Other Asian rivers had patterns that were similar to those of SWE from ERA-40 and NCEP–DOE.

b. Seasonal variability of SWE and SD

Seasonal variability of SWE and SD in the period of 1979–2000 is shown in Figs. 3 and 4. Both figures not only give the information on mean values, but also on the variation of measured and reanalysis data. Studied river basins are situated in different natural conditions (climate, topography, land use, etc.). The figures can thus be used to see how the reanalyses reproduce snow accumulation, snow maximum, and snowmelt in different conditions.

Maximum values of measured SWE in most river basins occur in March. The eastern Asian rivers (Yenisei, Lena, Amur) and the Pechora River have very similar SWE values in both March and April. Snowmelt in the European river basins (except Pechora) and in the Ob River basin starts in April. Yenisei, Lena, and Amur exhibit a more pronounced snowmelt later, in May. The variability of measured values is high especially in the Yenisei, Lena, and Ob River basins and is relatively low in the Don and Amur River basins. The highest variability is typically connected with the February–April period.

The reproduction of the seasonal evolution of SWE by reanalyses was generally fair, although the differences in absolute values varied substantially. In general, the worst results were obtained for the eastern Asian rivers (Yenisei, Lena, Amur), for which the reanalyses mostly strongly overestimated measured values (by up to 200%). The reanalyses, especially the NCEP–DOE, typically overestimated SWE at the beginning of the season. However, ERA-40 provided good SWE values for the beginning of the season for most European rivers.

Maximum SWE from reanalyses, especially from ERA-40, were generally acceptable in most river basins. Underestimated maxima were given by NCEP–DOE for the northern European rivers Pechora and Severnaya Dvina (by 22% and 26%, respectively). Overestimated values for March were given by both reanalyses for Yenisei (by 14%), Lena (by 34%), and Amur (by 61%). Overestimation by NCEP–DOE was higher than by ERA-40. The reanalyses sometimes placed the month of maximum SWE to be earlier than did the measured data (Volga, Don, Neva).

Both reanalyses indicated a much more pronounced snowmelt than did measured data. SWE values from reanalyses in months with strong snowmelt (April or May) significantly underestimated measured values (by up to 60% in April and 80% in May, respectively). The underestimation by NCEP–DOE for Yenisei, Lena, and Amur was smaller than that by ERA-40.

In general, ERA-40 satisfactorily reproduced the measured SWE data in autumn and winter [i.e., the mean values were close to the mean values of the measured data or within the half interval (mean value ± standard deviation of measured data)]. The largest differences were found for March and April, that is, the months in which snowmelt occurs. SWE data from the NCEP–DOE reanalysis tend to underestimate observational SWE in spring months and overestimate them in late autumn and in early winter months.

Figure 4 shows seasonal variability of snow depths based on measured and JRA-25 data. In almost all river basins, maximum snow depths occurred in February and March and both values were similar. The reproduction of the seasonal evolution of SD by JRA-25 was satisfactory. The differences in absolute values among measurements and reanalysis are generally greater than in the case of SWE. Snow depth from the JRA-25 was underestimated in all months and river basins (by 20%–85%).

c. Interannual variability

The interannual variability of SWE and SD and the numbers of stations with measured data in the studied period (1979–2000) are shown in Figs. 5 and 6. The above-mentioned error in ERA-40 in 1992–94 is clearly visible in Fig. 5. This error also influenced the results of trend analysis. Otherwise the reanalysis reproduced the interannual variability of SWE reasonably well. Bigger

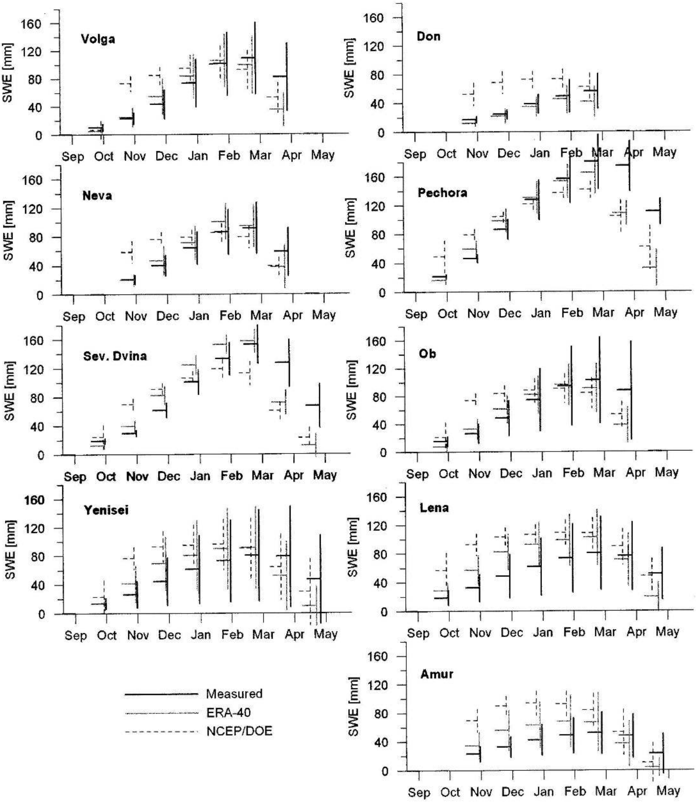

FIG. 3. Seasonal variability of SWE given by measured data and the ERA-40 and NCEP–DOE reanalyses (1979–2000); the symbols show mean values plus/minus 1 std dev.

differences between absolute values given by both reanalysis and measured data were found in the northern European and eastern Asian rivers. The NCEP–DOE reanalysis mostly overestimated SWE for the entire period from 1979 to 2000, but the pattern of variability was reproduced well. The exception was found for the Pechora and Severnaya Dvina, where NCEP–DOE mostly underestimated measured values until 1994.

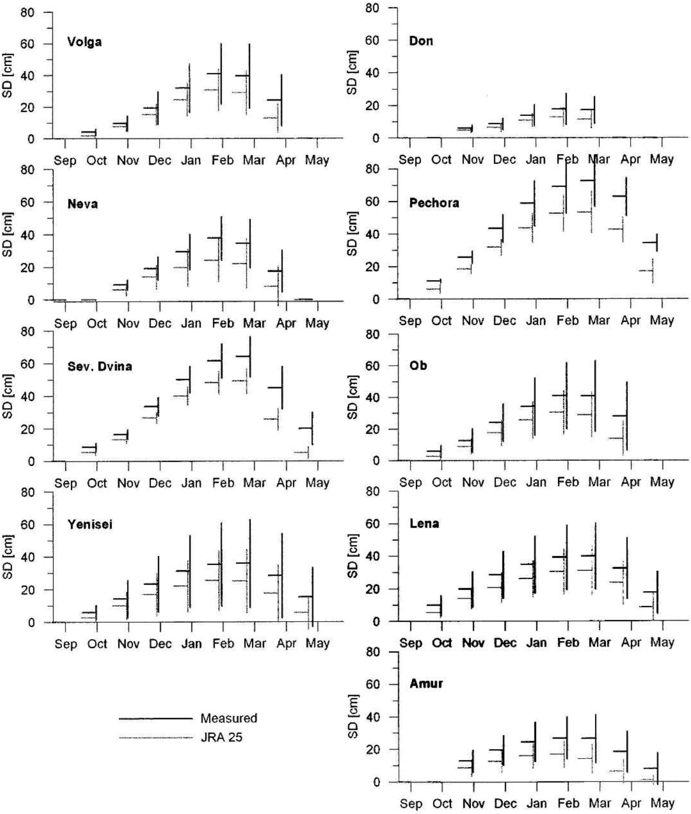

FIG. 4. Seasonal variability of SD given by measured data and JRA-25 (1979–2000); the symbols show mean values plus/minus 1 std dev.

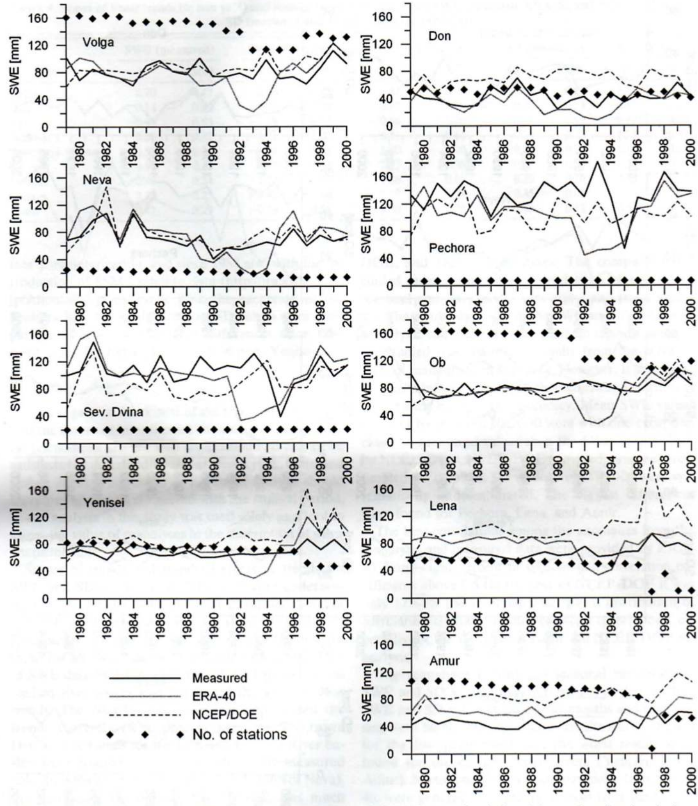

FIG. 5. Interannual variability of SWE according to measured data and reanalyses, and variation of the number of stations in the studied period.

ERA-40 overestimated the SWE values in the Lena and Amur River basins.

Interannual variability of snow depth as given by measurements and JRA-25 is shown in Fig. 6. Severe underestimation of measured data was observed for the period 1979–83 in all analyzed basins. Starting from 1984, the course of measured and reanalysis values improved, especially for Volga, Don, and Neva. The

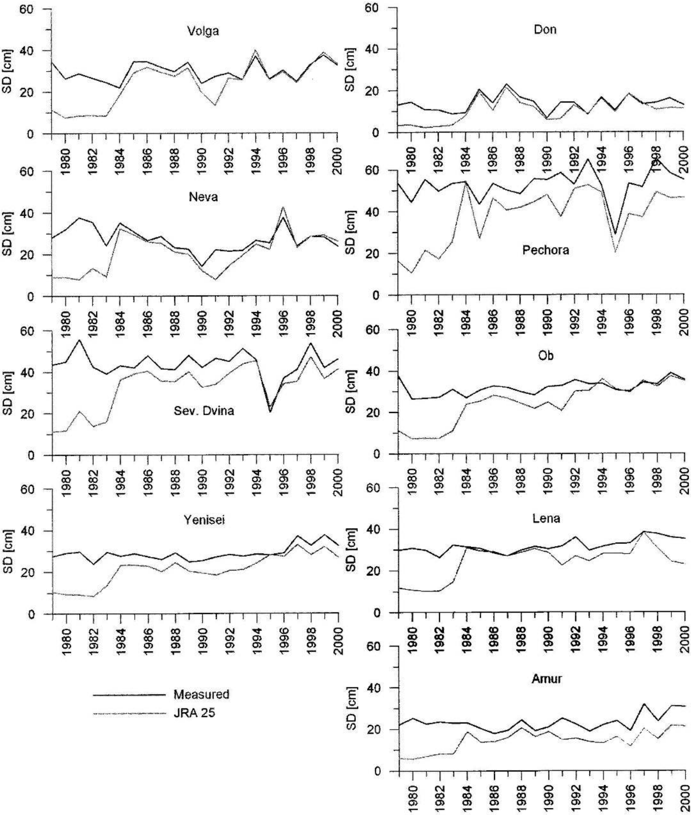

FIG. 6. Interannual variability of SD according to measured data and JRA-25.

exception is 1991, when the reanalysis data seem to be systematically underestimated in all basins. According to Onogi et al. (2007), the snow depth in Siberia is underestimated before 1983 because part of the snow data was not assimilated because of technical problems. It can also be hypothesized that significant improvement of snow-depth estimation since 1984 might also be associated with changes in the land sur-

TABLE 4. Slopes of linear trends (b; mm yr^{-1}) and standard errors of b [$S(b)$] for SWE (measured, ERA-40, and NCEP–DOE) and SD (measured and JRA-25) data for 1979–2000.

	SWE (measured)		SWE (ERA-40)		SWE (NCEP–DOE)		SD (measured)		SD (JRA-25)	
Basin	b	$S(b)$	b	$S(b)$	b	$S(b)$	b	$S(b)$	b	$S(b)$
Volga	0.20	0.47	0.06	0.82	1.37	0.36	0.15	0.15	1.15	0.24
Don	0.14	0.40	−0.06	0.50	0.12	0.42	0.08	0.14	0.42	0.17
Neva	−0.93	0.53	−1.39	0.98	−0.50	0.70	−0.31	0.19	0.77	0.27
Pechora	0.09	0.87	−0.45	1.00	0.11	0.66	0.24	0.25	1.23	0.37
Severnaya Dvina	−0.58	0.74	−1.54	1.08	1.00	0.70	−0.14	0.24	1.16	0.28
Ob	0.55	0.31	0.67	0.68	1.63	0.38	0.29	0.10	1.33	0.16
Yenisei	0.48	0.24	1.02	0.73	1.86	0.65	0.29	0.10	0.95	0.13
Lena	0.75	0.25	−0.42	0.58	2.38	0.74	0.35	0.08	0.75	0.21
Amur	0.41	0.29	−0.38	0.58	1.30	0.35	0.25	0.12	0.53	0.12

face parameterization, and since 1987 also with the introduction of SSM/I satellite data (http://jra.kishou.go.jp/AboutJRA25_en.html). With the exception of the Pechora River, even the absolute SD values were comparable after 1992–94. Bigger differences after 1994 were found for Lena, Amur, and, in part, Yenisey.

d. Trends

With regard to the results of the trend analysis, recal that the causes of interdecadal variability of many natural phenomena are not well understood and cannot be satisfactorily described by linear trends (e.g., Saito and Cohen 2003). The results of the trend analysis should therefore always be connected with the studied period. Trend analysis in this study was used solely as a tool to assess the value of reanalyses in the description of snow characteristics.

Slopes of trends and standard errors of trends for SWE and SD are given in Table 4. Severe underestimation of snow-depth data by JRA-25 for the period of 1979–84 [the reasons reported by Onogi et al. (2007) were mentioned above] resulted in an artificial positive trend for all river basins. Significant underestimations of SWE data by ERA-40 in the 1991–94 period for all studied river basins also influenced the values of the trends. The NCEP–DOE reanalysis reproduced the trends correctly (with the exception of Severnaya Dvina). The trends for the Don and Pechora River basins were comparable to those shown by measured data. In other river basins (with the exception of Neva), the increasing trend from NCEP–DOE was much higher than from measured data.

5. Conclusions

Measured SWE and SD data in the main Russian river basins in the period of 1979–2000 were compared with the corresponding data from the ERA-40, NCEP–DOE, and JRA-25 reanalyses. The comparison included mean basin values, correlations of anomalies, seasonal and interannual variability, and trend analyses. The results showed that the SWE and SD data from reanalyses can be used in the research of snow cover in the studied river basins, especially from the point of view of inadequate in situ data. However, it should be kept in mind that different characteristics in different river basins have varying accuracy. Mean SWE values for river basins from ERA-40 were with one exception closer to measured values than the SWE values given by NCEP–DOE. NCEP–DOE provided mostly overestimated SWE values. SD values from JRA-25 were systematically underestimated. The biggest differences were found for Pechora, Lena, and Amur.

The best correlations among the anomalies from the reanalysis and measured data were provided by ERA-40. Forty-eight percent of stations had correlation coefficients above 0.5 (in the case of NCEP–DOE it was only 17% of the stations). The spatial distribution of correlation coefficients showed weak correlations, especially for the Lena River basin and NCEP–DOE reanalysis.

The reanalyses reproduced seasonal variability of SWE and SD well, but the differences in the absolute SWE and SD values in particular months and river basins were highly variable. Better results were obtained for the European rivers, and the worst results were found for the eastern Asian rivers (Yenisei, Lena, Amur). Maximum SWE values, especially from ERA-40, were generally acceptable in most river basins, but the reanalyses strongly underestimated SWE during snowmelt (April, May). Seasonal evolution of SD was reproduced by JRA-25 correctly, but absolute values were significantly underestimated.

Interannual variability of SWE confirmed the documented errors of ERA-40 and JRA-25 in some periods. Except for these periods, the interannual variability

TABLE 5. Summary of comparison of measured and reanalysis SWE and SD data.

Snow characteristic	SWE ERA-40 (mm)	SWE NCEP–DOE (mm)	SD JRA-25 (cm)
Long-term mean for river basins	Acceptable for most basins except Pechora; bigger differences for Don, Lena, Amur	Big differences for Pechora, Severnaya Dvina, Don, Yenisei, Lena, Amur	Underestimation for all river basins (by 38%–20%)
Correlations of anomalies	48% of the stations had correlation coef >0.5; the best in Europe, low coefficients for Lena	17% of the stations had correlation coef >0.5; the worst in Europe, low coefficients for Lena	39% of the stations had correlation coef >0.5; intermediate
Seasonal variability	Fair reproduction of seasonal variation; overestimation for Lena and Amur; mostly acceptable maxima; underestimation during snowmelt	Fair reproduction of seasonal variation; overestimation at the beginning of the season; underestimated maxima for northern Europe; underestimated values during snowmelt	Fair reproduction of seasonal variation; underestimation in all basins and months
Interannual variability	Coding error in 1992–94, otherwise fair reproduction of interannual variation; big differences for Lena, Amur (Pechora)	Fair reproduction of interannual variation; big differences for northern Europe and eastern Asia	Severe underestimation in 1979–83; good reproduction of variability after 1984, often very good absolute values except northern Europe and eastern Asia
Trends	Trend influenced by the coding error in 1992–94	Realistic reproduction of the trend, negative trend for Neva, positive trends for the Asian rivers	Trend influenced by the underestimation in 1979–83

was generally well reproduced. The differences in absolute values were bigger for the northern European and eastern Asian rivers. Absolute values of SD from JAR-25 were comparable to measurements after 1992–94 in most basins. Underestimation of SD by JRA-25 in the period of 1979–84 and underestimation of SWE by ERA-40 in the period of 1991–94 has an effect on the trends computed from the cited reanalyses for snow characteristics. An overall summary of the comparison of measured and reanalysis data is given in Table 5.

The results of this study can be useful in the evaluation of GCM models, statistical studies based on SWE and snow depth reanalyses data, assessment of reasons for changes in hydrological regime, and so on. The source of the information on snow cover characteristics should be chosen with regard to the task, temporal resolution, and study region.

Measured snow data were used in this study to evaluate the performance of reanalyses. We realize that such an approach compared "point" data from stations of snow courses with the large-scale areal (gridded) data from reanalyses. Considering the spatial resolution aspect, a more correct approach would be based on gridded SWE and SD data prepared by interpolating measured values. However, given the studied area and number of stations with measured data, the preparation of gridded SWE and SD data was not possible, especially for the Asian river basins. Another fact that was taken into account was that snow characteristics do not depend only on meteorological variables, but are affected by many other phenomena that influence accumulation and melting of snow at a particular location. In such conditions, a physically reasonable model (such as the procedures applied in reanalyses) can represent snow cover evolution better than any statistical/geometric algorithm used in interpolation techniques. The results of this study show that more work and data assimilation efforts are needed before the reanalyses will be able to do this task across northern Eurasia.

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