Simulation of snow cover formation and melt with publication of the output data on the web map service (on the example of Kama river basin)

S V Pyankov¹, N A Kalinin², A N Shikhov¹, R K Abdullin¹ and A V Bykov²

¹ Department of cartography and geo-informatics, Perm State University, Bukireva str. 15, 614990, Russia
² Department of meteorology and atmosphere protection, Perm State University, Bukireva str. 15, 614990, Russia

and3131@inbox.ru

Abstract. It is performed an assessment of the use of daily precipitation forecasts of global numerical weather prediction (NWP) models GFS (U.S.), GEM (Canada), SLAV (Russia) and ICON (Germany) as input data for snow accumulation and melt modelling in the Kama river basin for two cold seasons. It is shown, that maximum snow water equivalent (SWE) calculated on the basis of NWP models output has an error less than 27% of the measured values, in the conditions of 2017-2018 snow accumulation season. However, this is preliminary assessment, which requires verification by several seasons. It is rather difficult to conclude which model provides highest accuracy of SWE calculation, because each of them has its specific limitations. In 2018-2019 cold season, we additionally obtained ICON model data, which provides the most accurate forecast of precipitation. The simulated SWE and meltwater outflow data are published on the online web map service.

1. Introduction
Monitoring and short-term forecasting of floods with providing the free-available data for authorities and citizens is the actual problem for many regions of Russia. Last years, a GIS-based flood forecasting and early warning systems are developed in many countries to reduce flood-related damage [1]. However, the similar systems in Russia are developed only for Amur [2] and Kuban [3] river basins, where the most devastating floods happen. For other river basins of Russia, where the main risks are related predominantly with snowmelt floods, the development of GIS-based flood monitoring systems is also relevant.

Nowadays, the snow surveys data, as well as any other data on the spatial distribution of snow water equivalent (SWE), which is needed for snowmelt runoff forecasting, is not available at open access web-services. In addition, snow survey observations in mountainous regions are located mainly in river valleys and are not representative to estimate SWE. At the same time, the spatially distributed snowpack models provide increasingly accurate assessment of SWE [4]. In this regard, the development of online web map service for operational publication of simulated SWE fields and other snowpack characteristics (snow-covered area and meltwater outflow) is important to improve snowmelt runoff forecasting and early warning of flood.
Last years, the experiments of snow cover formation and melt modeling based on Weather Research and Forecasting (WRF) mesoscale atmospheric model data have been performed for the Votkinsk reservoir basin, which located on the north-east of Kama river basin [5, 6]. It was found, that the errors of simulated SWE not exceeded 25% of measured values in most cases. However, SWE was systematically overestimated at the second half of cold season. At 2018, the similar results have been obtained with the use of CMC/GEM global atmospheric models data [7].

The purpose of this study is to develop an operational method for calculate snowpack characteristics for a large river basin, on the basis of the free-available weather stations data and global numerical weather prediction (NWP) models forecasts. The simulated snow cover characteristics are published at online web map service, developed with the use of ArcGis Server platform.

2. Data and methods

The studied Kama river basin is located in the eastern part of the East-European plain, and western slope of the Ural mountains, between 52° and 62° N, 47° and 61° E. It has an area of 507 thous. sq.km. Elevation ranges from 36 m to 1640 m, with an average value of 235 m.

The GMTED-2010 digital elevation model (DEM) with 250 m spatial resolution and land cover map are used to estimate some parameters of snow cover formation and melting model. Three various data sources such as Russia’s Forest Map [8], GlobCover-2009 [9] and Global Forest Change dataset [10] are unified to create an update the reliable land cover map of the studied basin with 350 m spatial resolution. According to the created map, forest-covered area in the Kama river basin is 55.2%.

Short-term forecasts of air temperature, humidity, precipitation and wind speed of four global NWP models with 27-h lead time were obtained for the snow accumulation and melt seasons, excluding ICON model data, which are downloaded only for 2018-2019 (table 1). NWP models data were projected to Lambert projection coordinate system, with resampling to a 3 km grid by the bilinear interpolation method.

The spatial resolution of NWP models data ranges from 0,125° to 0,25°, that is not enough for snow accumulation and melt simulation. Also, DEMs in global NWP models are strongly smoothed. Taking into account this limitation of global NWP models data, we applied a statistical downscaling technique, which is based on a more detailed DEM (with 1 km spatial resolution) and statistical relationship between altitude and accumulated precipitation during cold season [7]. The altitude-dependent gradient of precipitation was estimated as 10% increase by 100 m. We calculated the difference between two DEMs (more detailed “true” DEM and DEM extracted from NWP data) for each model cell. So, the precipitation amount in each cell increases or decreases according to difference of altitude between the smoothed DEM (extracted from NWP data) and the true DEM. The proposed downscaling scheme significantly improved the reliability of snow accumulation modeling in mountainous part of the basin. The calculation is performed with ArcGis 10* software package.

Assessment of the accuracy of simulated monthly precipitation is performed based on comparing with measured precipitation from 101 weather stations, located within the studied basin (70 stations) and near it (31 stations). The weather stations data were automatically downloaded from https://rp5.ru/.

The SWE calculation technique is similar to previously used with WRF and GEM model data [4-6]. The main components of the SWE balance are precipitation (taking into account their phases), snow melting during thaws, snow sublimation and blowing, and interception of solid precipitation by vegetation cover (with subsequent sublimation), which are calculated with daily step. Snowmelt intensity during thaws is calculated according to degree-day method [12]. The degree-day factor value ranges from 1.5 mm/day×°C to 5 mm/day×°C, determining by vegetation types. Daily snow sublimation is estimated according to PP Kuz’mín formula [13]:
Table 1. Short information on the global atmospheric models data [11].

| Model  | Developers                                      | GRID resolution, km | Number of vertical levels | Output data grid resolution | Download URL                                                                 |
|--------|-------------------------------------------------|---------------------|---------------------------|----------------------------|--------------------------------------------------------------------------------|
| GFS    | National Center for Environmental Prediction (NCEP), U.S. | 13                  | 64                        | 0.25°                      | http://nomads.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/                           |
| GEM    | Canadian Meteorological Center (CMC)            | 23                  | 80                        | 0.24°                      | http://dd.weatheroffice.gc.ca/model_gem_global/25km/grib2/lat_lon/               |
| SLAV   | Institute of Computational Mathematics, Russia  | 0.18° × 0.225°      | 51                        | 0.18° × 0.225°             | Data are provided by model developers                                           |
| ICON (only for 2018-2019) | Deutscher Wetterdienst (DWD), Germany          | 13                  | 90                        | 0.125°                     | http://ftp-outgoing2.dwd.de/gds/ICON/grib/europe/                                |

Where $E$ denotes snow sublimation intensity (mm/day), $U_{10}$ signifies wind speed at 10 m height (m/s), which were estimated by NWP data, and $d$ is moisture deficit at 2 m (hPa).

Snow interception by vegetation cover is calculated on the basis of simplified relationship with leaf area index (LAI) and air humidity [14]:

$$E_i = k \cdot d \cdot LAI$$  \hspace{1cm} (2)

Where $E_i$ signifies the sublimation of intercepted snow (mm/day), $k$ is the empirical coefficient, which is equal 0.065 according to [13], and $LAI$ denotes leaf area index. LAI values are estimated by MOD15A2 (8-day LAI and FPAR) data product, downloaded from NASA web service (https://ladsweb.nascom.nasa.gov/). We used winter cloudless MODIS images (March 2015) to estimate LAI values.

When calculating the snowmelt intensity during spring season, we used the scheme proposed by [15], which provides a simplified assessment of two main heat fluxes to snow cover, such as heat exchange with the atmosphere and incoming solar radiation.

$$M = K_1 \cdot \theta + K_2 \cdot (Q + q)$$  \hspace{1cm} (3)

Where $M$ is snowmelt intensity (mm/day), $\theta$ denotes average daily temperature (°C) and $Q + q$ signifies potential incoming solar radiation under clear sky conditions (MJ/m$^2$ × day), which were calculated with SAGA GIS. The values of $K_1$ and $K_2$ coefficients, which determine the contribution of heat exchange and solar radiation to snowmelt intensity, are related to latitude and weather conditions. In this study, we accepted these values as 2.2 and 0.15 respectively. Also we added the correction factors for various types of underlying surface, similar to those used in calculating the snowmelt intensity by degree-day factor.

3. Results and discussion

3.1. Accuracy assessment of simulated precipitation amount for 2017-2018 cold season

Table 2 and fig. 1 presents a comparison of measured (averaged values by 101 weather stations) and simulated precipitation for 2017-2018 snow accumulation season. The data for October were processed from 19.10, when snow accumulation process started. According to fig. 1, the measured and simulated monthly precipitation (averaged over the Kama river basin) varied no more than 30% from Oct 2017 to Feb 2018. Such a moderate difference between simulated and measured precipitation provides a possibility for calculating SWE with a satisfactory accuracy.

CMC/GEM model overestimate the average monthly precipitation throughout all studied period. Other models also tend to overestimate precipitation amount. Root mean square error (RMSE) of simulated monthly precipitation varies from 26% to 38% of average measured precipitation between
October and February. RMSE was significantly higher (up to 47%) only for CMC/GEM model data in January. In turn, in the eastern mountainous part of the basin any NWP models underestimate precipitation amount between October and February, most significantly the SLAV model.

In March and especially in April, the precipitation amount is significantly overestimated according to any models, especially the SLAV model. Thus, the overestimation of the precipitation in the spring season, which was previously identified for the WRF model [4, 5], take place also for other NWP models.

**Figure 1.** Measured (1) and simulated precipitation amount by GEM (2) GFS (3) and SLAV (4) NWP models for 2017-2018 snow accumulation and snowmelt season over the Kama river basin.

**Table 2.** RMSE of calculated monthly precipitation by NWP data (numerator) and its ratio to the average measured precipitation (denominator).

| NWP model | Oct 2017 | Nov 2017 | Dec 2017 | Jan 2018 | Feb 2018 | March 2018 | April 2018 |
|-----------|----------|----------|----------|----------|----------|------------|------------|
| GEM       | 7.9/0.30 | 11.2/0.32 | 16.5/0.38 | 13.6/0.47 | 7.1/0.31 | 11.1/0.40 | 14.8/0.32 |
| GFS       | 8.0/0.30 | 9.17/0.26 | 11.6/0.26 | 9.2/0.32  | 8.2/0.36 | 14.5/0.53 | 25.5/0.55 |
| SLAV      | 9.0/0.34 | 9.8/0.28 | 16.7/0.38 | 9.7/0.33  | 8.1/0.36 | 18.2/0.66 | 40.4/0.87 |

3.2. Assessment of accuracy of SWE simulation

Maximum SWE over the Kama river basin during the 2017-2018 cold season has been observed at the end of March. The results of SWE simulation for 31 March 2018 are presented at figure 2. According to the GEM, GFS and SLAV models, SWE averaged over the entire basin was 151.7, 145.5 and 135.5 mm respectively. Spatial distribution of the SWE, simulated by different models output, varies significantly. According to the GFS model, the spatial variations of SWE in the studied basins are most significant – from 50-60 mm in the southeastern forest-steppe areas to 500 mm and higher in the Northern Ural. Also, the GFS model simulated many local extremums in the accumulated precipitation and SWE fields, which not confirms according to other models data.

The distribution of SWE, simulated according to the GEM and SLAV models, is more smoothed and reliable. However, according to SLAV model SWE is significantly lower than by GEM model. The SLAV model significantly underestimates snow accumulation in the mountainous part of the basin and in the forest-steppe zone, which is confirmed by the snow survey data. The underestimation of simulated SWE in the Ural mountains according to the SLAV model is due to the same tendency for precipitation forecast (table 3). In turn, the underestimation of SWE in the forest-steppe zone may be due to overestimation of the snow sublimation (which exceeded 40 mm in the southern part of the basin).
Figure 2. Simulated SWE distribution in the Kama river basin according to GEM (1), GFS (2) and SLAV (3) NWP models data for 31 March 2018.

Accuracy assessment of simulated SWE is performed based on comparing them with snow survey data, provided by Perm and Udmurt Centers for hydrometeorology and environmental monitoring. In total, we obtained the data of 67 snow survey routes, including 40 routes in treeless areas and 27 routes in forests for the territory of Perm, Kirov regions and Udmurt Republic. Table 4 presents the general assessment of SWE simulation accuracy, based on averaged SWE values from all snow survey routes. Figure 2 shows the comparison of measured and simulated SWE of several representative snow survey routes.

In general, the maximum SWE (at 31 March 2018), simulated based on short-term precipitation forecast of GEM, GFS and SLAV model, have a RMSE between 24.6 and 40.6 mm, which is 16-27% of average measured SWE. The most accurate SWE assessment, with a RMSE of 24.6 mm, is obtained based on SLAV model data, in comparison with snow survey routes in forest.

Maximum SWE, simulated by GEM model data, is overestimated by 9.8 mm for treeless routes and by 19.2 mm for forest routes. According to GFS model data, SWE is significantly overestimated (by 19.8 mm in average) only for snow survey routes in forest. According to the SLAV model, SWE averaged over the entire basin is not biased in comparison with the measured values. However, a significant underestimation of simulated SWE takes place for the eastern mountainous part of the basin.

It can be assumed, that significant overestimation of the SWE for snow survey routes in forest, which is found for the GFS and GEM models, may be related to the features of the location of these routes. Indeed, most of the stations with snow survey routes in forest are located in the northern part of the studied basin, and treeless routes are most typical for the southern part. As a result, above-mentioned overestimation of snow sublimation in the southern part of the basin has a more significant influence on the simulation results for treeless snow survey routes, than for routes in forest.
Table 3. RMSE of simulated SWE (numerator) and its ratio to average measured SWE (denominator), according to averaged values for snow survey routes in forest and in treeless areas.

| Data source | Snow survey routes | 20 Dec 2017 | 20 Jan 2018 | 31 Jan 2018 | 10 Feb 2018 | 20 Feb 2018 | 28 Feb 2018 | 10 Mar 2018 | 20 Mar 2018 | 31 Mar 2018 |
|-------------|--------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| GEM model   | treeless area      | 17.8/0.44   | 17.5/0.25   | 25.2/0.28   | 30.0/0.31   | 27.5/0.27   | 26.9/0.23   | 27.5/0.22   | 30.2/0.22   | 30.4/0.21   |
|             | forest             | 23.1/0.60   | 29.8/0.45   | 35.6/0.41   | 37.5/0.38   | 37.1/0.35   | 37.4/0.33   | 35.5/0.28   | 32.8/0.28   | 35.3/0.23   |
| GFS model   | treeless area      | 12.9/0.32   | 14.5/0.21   | 21.6/0.24   | 26.7/0.28   | 25.9/0.25   | 26.5/0.23   | 26.6/0.21   | 31.0/0.23   | 31.6/0.22   |
|             | forest             | 21.3/0.55   | 29.0/0.43   | 34.3/0.39   | 37.7/0.38   | 39.1/0.37   | 40.1/0.35   | 39.3/0.30   | 39.6/0.27   | 40.6/0.27   |
| SLAV model  | treeless area      | 15.3/0.39   | 14.3/0.20   | 20.2/0.23   | 22.7/0.24   | 20.7/0.24   | 22.4/0.20   | 24.8/0.20   | 29.7/0.22   | 29.1/0.20   |
|             | forest             | 16.8/0.44   | 15.9/0.24   | 21.0/0.24   | 24.8/0.28   | 26.0/0.25   | 26.7/0.24   | 23.8/0.18   | 23.2/0.16   | 24.6/0.16   |

Figure 3. Comparison of simulated and measured SWE by selected snow survey routes: a – Cherdyn’ (60.39° N, 56.48° E), treeless area, b – Bol. Sosnova (57.69° N, 54.60° E), treeless area, c – Oktyabr’skiy (56.50° N, 57.20° E), forest, d – Nagorsko (59.32° N, 50.79° E), forest.

1 – Snow survey data, 2 – GEM model, 3 – GFS model, 4 – SLAV model
3.3. Publication of the simulated SWE fields on the online web map service
At 2018-2019 cold season, we used short-term forecasts of GFS, SLAV and ICON atmospheric models as input data for snow accumulation and snowmelt modeling in near-real-time mode. Among other models, ICON model provided the most accurate data on accumulated precipitation. RMSE of simulated monthly precipitation was 4.4 mm for December 2018, 10.5 for January 2019 and 12.0 mm for February 2019. It is 20%, 25%, and 26% of average measured precipitation according to weather stations data respectively for December 2018, January 2019 and February 2019. So, ICON model provides more reliable estimates of accumulated monthly precipitation, than any other NWP model during 2017-2018 snow accumulation season (table 2). Also, we calculated snow accumulation based on GFS model and weather stations data (figure 4).

Simulated SWE and meltwater outflow data according to ICON and GFS models output are published on the online web map service http://hydromonitor.maps.psu.ru (in Russian) in real-time mode. The service is based on the ArcGis Server 10 software and the JavaScript programming language.

The main purpose of the web map service development is to provide the real-time data on snow accumulation, snowmelt and flood risks in the studied basin for regional hydro-meteorological services and for the state institution “Kama basin water administration”. Since observational network in the basin is quite sparse, especially in the mountainous area, it is a lack of the data on the snowpack characteristics, which are needed for snowmelt runoff forecasting and estimates of water inflow to three large reservoirs.

Service user’s can not only see the spatial distribution of the SWE and snowmelt outflow over entire Kama river basin, but also calculate the average SWE and daily snowmelt outflow for any of the 160 watersheds, included in the studied basin. They can also view the animation of snow accumulation and melting processes. Thus, providing the results of snow accumulation and snowmelt modeling can improve an accuracy of long-term (seasonal) and short-term (daily and weekly) hydrological forecast for the studied basin, including short-term prediction of the probability of snowmelt floods formation.

Also many other data related to hazardous hydrological events, such as points of the frequent ice jams occurrence, regularly flooded settlements and flooded areas, estimated by full archive of Landsat satellite images (from 1984 to the present) are published on the web map service.

Figure 4. Simulated SWE distribution in the Kama river basin according to ICON model (1), GFS model (2) and weather stations data (3) for 15 March 2019.
4. Conclusion
The performed experiment on the use of the free-available global NWP models data as input for snow accumulation and melt modelling is one of the first for Russia. Three years ago, the data of global NWP models was too low spatial resolution to use them for snowpack modelling. Under the condition of 2017-2018 snow accumulation season, we have obtained the maximum SWE estimates with RMSE of 16-27% in comparison with the measured values. This is satisfactory results, taking into account the multiple uncertainties in modelling snow accumulation and melting on a large-scale basin. However, the obtained estimates of SWE simulation accuracy are preliminary and require verification by several seasons.

Acknowledgement
The study was funded by the RFBR Project No 17-05-01001-a. The authors thank the team of the Laboratory of advanced numerical methods in atmospheric models of the Hydro-meteorological Center of Russia and M.A. Tolstykh personally for the providing of the SLAV atmospheric model data.

References
[1] Thielen J, Bartholmes J, Ramos MH, de Roo A. 2009. The European Flood Alert System – Part 1: Concept and development. Hydrol. Earth Syst. Sci. 13 125–140
[2] Frolov AV, Asmus VV, Borschh SV, Vil’fand RM, Zhabina RM, Zatyagalova VV, Krovyotyntsev VA, Kudryavtseva OI, Leont’eva EA, Simonov YuA, Stepanov YuA. 2016. GIS-Amur system of flood monitoring, forecasting, and early warning. Rus Meteor and Hydrol. 41 (3) 157–169
[3] Borsh SV, Simonov YuA, Schristoforov AV 2016. The system of flood forecasting and early warning on the rivers of the Black Sea coast of Caucasus and Kuban basin. Proc. of the Hydrometeorological Centre of Russia. Spec. 356 247 p [in Russian]
[4] Churyulin EV, Kopeikin VN, Rozinkina IA, Frolova NL, Churyulina AG. 2018. Analysis of snow cover characteristics using satellite and model data for various basins on the European territory of Russian Federation. Hydromet. Stud. and forecasts. 368 120–143 [in Russian]
[5] Kalinin NA, Sviyazov EM, Shikhov AN. 2015. Simulation of snow accumulation and melt in the Votkinsk reservoir catchment using the WRF-ARW model. Rus. Meteor. and Hydrol. 40 (11) 749–757
[6] Pyankov SV, Shikhov AN, Kalinin NA, Sviyazov EM. 2018. A GIS-based modeling of snow accumulation and melt processes in the Votkinsk reservoir basin. J. of Geogr. Sci., 28 (2) 221–237
[7] Shikhov AN, Bykov AV 2018. Snow water equivalent calculation on a large-scale basin with the use of global weather forecast models. Hydromet. Stud. and forecasts. 367 (1) 64–79 [in Russian]
[8] Bartalev SA, Ershov DV, Isaev AS, Potapov PV, Turubanova SA, Yaroshenko AYu. 2004. Russia’s Forests — Dominating Forest Types and Their Canopy Density. Moscow: Greenpeace Russia and RAS Centre for Forest Ecology and Productivity. (Map, scale 1:14 000 000)
[9] Arino O, Bicheron P, Achard F, Latham J, Witt R, Weber JL 2008. GlobCover: the most detailed portrait of Earth. Eu Space Agency Bull. 136 24–31
[10] Hansen MC, Potapov PV, Moore R, Hancher M, Turubanov SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO Townshend JRG 2013 High-Resolution Global Maps of 21st-Century Forest Cover Change. SCIENCE 342 850–853
[11] WGNE Overview of Plans at NWP Centres with Global Forecasting Systems — 2018. Available at: http://wgne.meteoinfo.ru/nwp-systems-wgne-table/wgne-table/
[12] Yu M, Chen X, Li L, Bao A, de la Paix MJ 2013. Incorporating accumulated temperature and algorithm of snow cover calculation into the snowmelt runoff model. *Hydrol. Processes* **27** (25) 3589–3595

[13] Kuzmin PP. 1961. *The process of snowmelt*. Leningrad, Gidrometeoizdat 346 p. [in Russian]

[14] Karpechko YuV, Bondarik NL 2010 *Hydrological role of forestry and logging in the taiga zone of the Russian European North*. Petrozavodsk. Karelian Scientific Center of RAS 225 p [in Russian]

[15] Gordeev IN. 2012. The method of snowmelt intensity calculation for the forecasts of spring runoff of Siberian rivers. Sci.-pract. school-seminar for young scientists and specialists in the field of hydrometeorology. URL: [http://sibnigmi.ru/documents/school/Gordeev.pdf](http://sibnigmi.ru/documents/school/Gordeev.pdf) [in Russian]