Responses to anonymous Reviewer #1

We thank the respected reviewer for the criticism that helped us in improving the manuscript. We hope that the material added in the revised version of the manuscript will contribute to illustrate the performances of the developed approach. Below our responses to all criticisms of the reviewer are presented.

Specific Comments

1. The title of the paper could be more focused. The term "satellite information" is too general. The term "forecasting" is not really discussed in the following write-up.

We change the manuscript title to make it more focused. The revised title is:
"Use of satellite-derived data for characterization of snow cover and simulation of snowmelt runoff through a distributed physically based model of runoff generation"

2. The motivation for the work needs more justification…The title tells that the ultimate objective of the study is to improve runoff simulation. However, description on current runoff simulation (e.g. models applied, simulation procedure in snow dominated areas, accuracy, etc.) is missing in the text. Why is it necessary to incorporate satellite data for improved runoff simulation? What if the current runoff simulation is satisfactory enough for practical purposes?

> The following two paragraphs are added in the Introduction to justify the objective of the study.
>
> The accurate representation of spatial snow distribution is of crucial importance in hydrological studies in cold regions, particularly, in improving hydrological models for runoff prediction and forecasting. Development of such models for cold region watersheds is often complicated because of sparse observational networks and the enormous spatial variability of runoff formation factors including processes of snow accumulation and melt. The value of snow cover data in hydrologic modeling has been demonstrated by many authors (see, for example, Blöschl, 1999 and references herein). Grayson et al. (2002) summarized many examples of using snow cover data in addition to runoff and demonstrated that these data are useful for model calibration and validation if available as spatial distribution over the whole basin and its parts. Daly et al. (2000) used maps of snow water equivalent (SWE) built from merging AVHRR-derived snow coverage area and interpolated SWE for calibration and validation of the DSMP snow model; then the DSMP model was used as a component of the HEC-HMS hydrological model and improvement of the performance of the hydrological model was demonstrated. Corbari et al. (2009) showed that calibration of a distributed hydrological model against satellite snow images results in reducing the error in the simulation of river flow.
>
> At the same time, there are studies demonstrating that applicability of satellite-derived snow products are of doubtful value for improvement of runoff simulation (Guneriussen et al., 2000; Clark et al., 2006; Udnæs et al., 2007). Clark et al. (2006) found that the assimilation of satellite-derived SCA data results in only minor improvements in the accuracy of streamflow simulations and supposed that this information could be most useful in basins where snow cover is ephemeral. Guneriussen et al. (2000) showed that updating the HBV hydrological model with remotely sensed SCA data tended to reduce the model performance. Udnæs et al. (2007) demonstrated that HBV model calibrated against SCA in addition to the observed discharge has the same accuracy as the model calibrated against discharge only. In the listed examples, the simplified, conceptual models were used for simulations of snow and runoff generation processes. The parameters of the conceptual models do not have specific physical meaning, so the parameters values adjusted against satellite-derived snow data can significantly differ from the values of the same parameters providing the better fitting to observed streamflow discharges. This is not the case for the physically based models which parameters are related to the physical properties of snow and basin characteristics. Consequently, calibration of physically based snow model using satellite-derived data on spatial snow distribution together with ground based snow observations can lead to more visible improvement of runoff simulations in comparison with a conceptual model.

3. There are numerous snowpack models and runoff generation models. What is the rationale of using the ones applied in the current study?

Two authors of the manuscript took part in developing the used snow model (Gelfan et al., 2004). This model demonstrated ability to reproduce forest snow processes with satisfactory accuracy (Gelfan et al., 2004; Rutter et al., 2009). That is why we applied this model to make corrections in snow satellite data for the forested areas.
The same motivation was for using runoff generation model developed by the authors and comprehensively tested in (Kuchment et al, 2008)

Gelfan, A. N., Pomeroy, J. W., Kuchment, L. S. (2004) Modelling Forest Cover Influences on Snow Accumulation, Sublimation, and Melt, J. Hydrometeorology, Vol. 5, No. 5, 785–803.
Kuchment L.S., Gelfan A.N., Demidov V.N. (2008) Aassessment of magnitude and frequency of disastrous flood using a physically based model of runoff generation. In: Disastrous natural events in the land surface: physical mechanisms and catastrophic consequences (Edited by V.M. Kotlyakov), Moscow, Institute of Geography Publ., 124-147 (in Russian)
Rutter, N. et al. (2009). Evaluation of forest snow processes models (SnowMIP2), J. Geophys. Res., 114, D06111, doi:10.1029/2008JD011063

4. The presentation of results and the discussion, which would be a major contribution of the work, should be significantly expanded.

The presentation of results and discussion are expanded (see our responses below).

5. The snowpack model is calibrated against snow depth, but it is used to predict SWE. This might raise concerns about the validity of applying a depth-oriented model in predicting SWE. Discussion on this point would be helpful.

We carried out an additional test of the model to assess its ability to predict SWE. As a result, the following paragraph is added in the end of Section 3.

> “In order to test validity of the model calibrated against the snow depth measurements in predicting SWE, we used the snow survey observations within the Vyatka basin for 9 snow seasons: from 1971-1972 to 1979-1980. Both snow depth and SWE observations are available for that period. The model demonstrated satisfactory accuracy in predicting SWE for 9 seasons: the overall mean error is 1.2 mm, the root mean square error is 10.6.mm.”

Figure illustrating the results of SWE simulations for 9 seasons at one of the meteorological stations is shown below (this figure is not included in the manuscript).

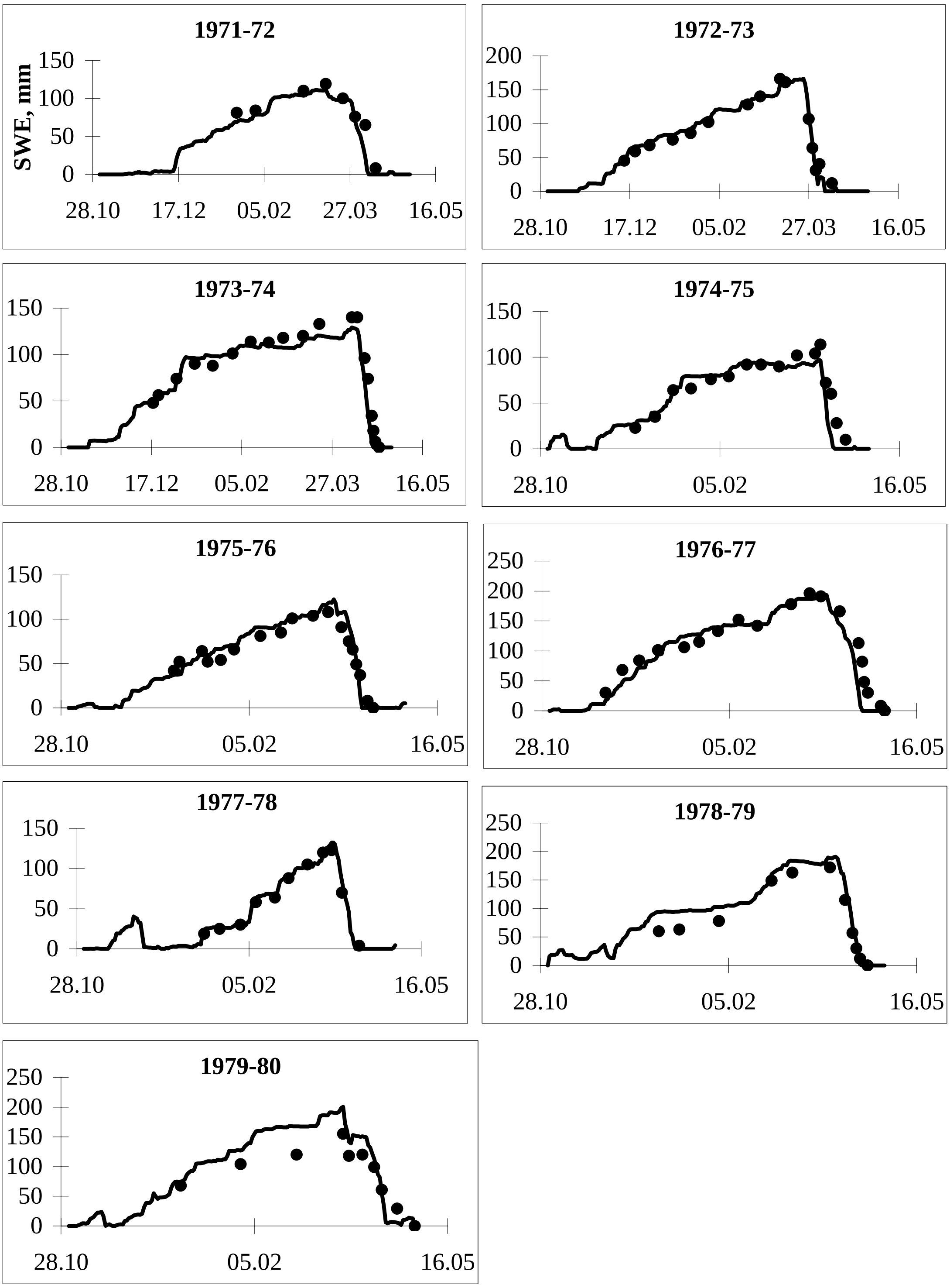

Figure Observed (points) and calculated (lines) snow water equivalent at the Kirov meteorological station.

6. The model is calibrated at point scale (19 meteorological stations) using ground-based measurements and applied to areal scale using gridded satellite data and interpolated ground-based data. Are model parameters calibrated from the point scale representative? Discussion on scale issues and the corresponding uncertainty would be helpful.

We agree that the model calibrated at point scale is not apparently ready for direct application at areal scale. So we refined the parameters values adjusted against the point measurements by the use of SCA satellite data. The following paragraphs and new Figure

7 presenting the procedure of refinement of snow model parameters are added in the end of Section 5.

> "Using the assumptions formulated above, we simulated daily maps of SCA and compared them with NASA MOD10_L2 maps for the snowmelt season of the years 2002 to 2005. The comparison was carried out in order to refine the snow model parameters adjusted against the ground-based point measurements (see previous section) and use the refined parameters for further characterization of snow fields. The region was divided on to 19 Thissen polygons according to the location of the meteorological stations. Simulated, SCA_{calc}, and satellite-derived, SCA_{sat}, values were estimated for each polygon and the dates when most of the polygons were free of cloudiness. The value of SCA was calculated as the number of open (free of forest) pixels covered by snow divided on the total number of open pixels within the polygon. When calculating SCA_{sat}, only free of cloudiness pixels were taken into account. Two criteria were applied to summarize the goodness of fit of the simulated and satellite snow maps for each selected date: (1) mean relative error $ME = \frac{1}{19}\sum_{i=1}^{19}\left(1 - \frac{SCA_{calc_i}}{SCA_{sat_i}}\right)$ and (2) root mean square error $RMSE = \sqrt{\frac{\sum_{i=1}^{19}\left(SCA_{sat_i} - SCA_{calc_i}\right)^2}{\sum_{i=1}^{19}\left(SCA_{sat_i} - \overline{SCA}_{sat}\right)^2}}$ where $\overline{SCA}_{sat}$ is the satellite SCA estimated for the whole polygon. It was appeared that minimum values of the both criteria are achieved under almost the same values of the snow model parameters (α =1.03, q_T =0.98 J m^{-2} s^{-1}, and q_E = 0.12 J Pa^{-1} s^{-1}) as the values obtained through the model calibration against the ground-based point measurements.
>
> As an illustration of the obtained results, temporal changes of the criteria ME and RMSE are shown in Fig. 7 for 3 of 19 polygons.

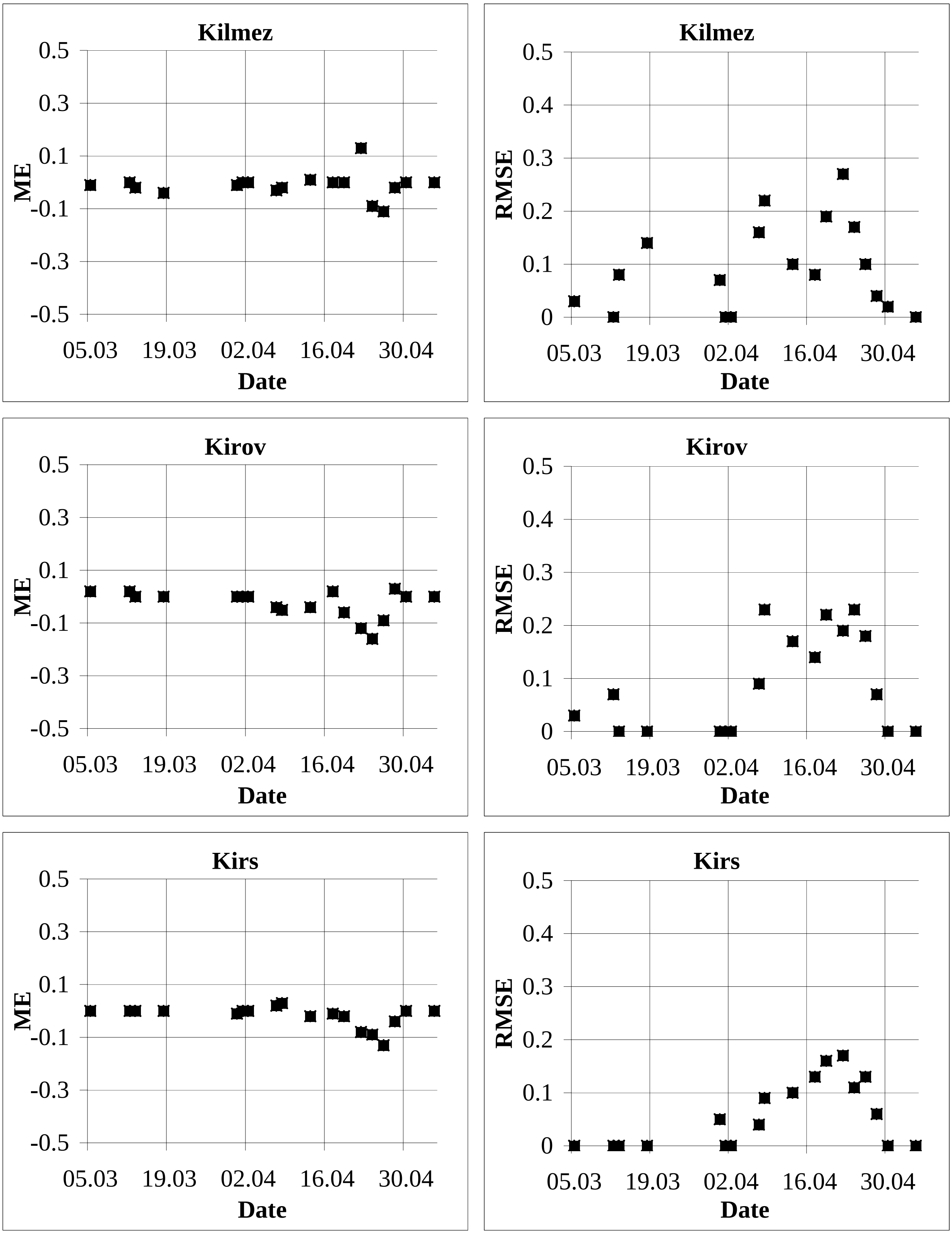

Fig. 7 Mean error (ME) and root mean square error (RMSE) of simulated snow covered area in comparison with one obtained from NASA MOD10_L2 maps for three Thissen polygons surrounding meteorological stations Kilmez, Kirov, and Kirs (forested pixels are not taken into account).

One can see from Fig. 7 that ME and RMSE are close to zero in the beginning of spring, then the both criteria increase in the period of intensive melt and return to small values in the end of melt season. In general, the model allowed us to reproduce well temporal changes of SCA for the open areas.

The results are much worse if we take into account forested pixels in addition to open ones when SCA calculating. Fig. 8 shows the temporal change of SCA for two polygons which are located correspondingly in the south-eastern and north-eastern corners of the study area and have the coniferous forest percentage of 9 % and 76 % respectively. It can be seen from this Fig. 8 that, again, for the sparsely forested area the calculated values of SCA are close to the values defined from the satellite data while for the area with dense forest there is a significant difference between these values.”

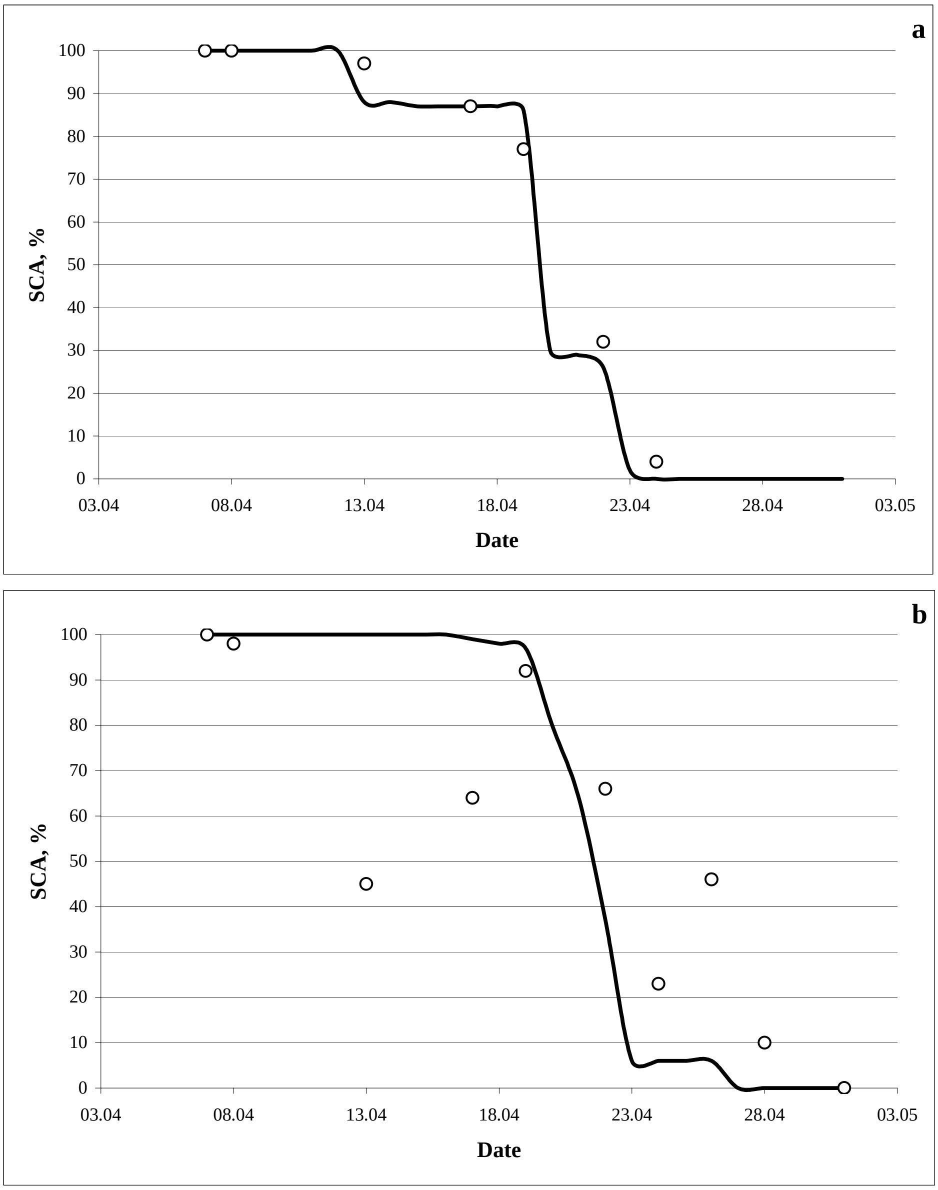

Fig. 8. Changes of the calculated (line) and MODIS-based (points) SCA for two Thiessen polygons with different cover percentages of coniferous forest (a - 9%; b – 76%).

7. Initialization of the snowpack model (Section 4) could be improved. Specifically, assumptions on the initial volumetric moisture and snow density seem not robust.

We assigned the initial (on March 1st) moisture content of snow equaled to zero because winters are always cold in the Vyatka region, winter thaws are very rare, period of intensive melt begins 3-4 weeks later than March 1st , thus, one can conclude that liquid water does not exist in snowpack on this date. Spatial variance of density of deep and dry snowpack is much smaller than the variance of snow depth or SWE (e.g. Kuusisto, 1984; Kuz’min, 1963). Snowpack accumulated in the Vyatka basin on March 1st is typically deep and dry and this fact gave us opportunity to assign initial snow density as constant defined from the available measurements at the single meteorological station.

Kuusisto E. 1984. Snow accumulation and snowmelt in Finland. *Pubications of the Helsinki Water Research Institute Series* **55**: 151pp.
Kuzmin PP. 1963. *Snow cover and snow reserves*. Israel Program for Scientific Translation: Jerusalem; 140pp.

8. Using AE_DySno SWE map on March 1st as initial SWE is questionable since it is of low accuracy.

In fact, AE_DySnow SWE maps are of low accuracy, that is why we used data from these maps for only the open pixels and for only the initial date when snowpack is not wet yet. The objective was to show that assigning satellite-derived SWE as the initial condition for opened areas and using the presented correction procedure for forested areas allow one to simulate spatial fields of snow characteristics and snowmelt over the river basin. To assess accuracy of this simulation, we used the simulated snowmelt as input to runoff generation model that results in satisfactory simulated runoff hydrographs.

9. Inaccuracy in SWE could propagate to runoff during runoff simulation. Therefore, the resulting snowmelt hydrograph is questionable. The paper would be stronger if alternative hydrographs are available for comparison. A candidate might be the one simulated from the snowpack model without using satellite data.

According to the suggestion of the reviewer, we calculated alternative hydrographs without using satellite data and the obtained results are discussed in the 5th section. The following new discussion and new Figure 12 for illustration of this discussion are added in the revised manuscript.

> Numerical experiment was carried out to assess whether or not utilizing satellite data in the model of runoff generation can result in improving hydrograph simulations when comparing with simulations utilizing meteorological observations only. Meteorological observations at the Vyatka basin were used to simulate processes of runoff generation from the beginning of snow accumulation in the previous autumn to the end of snowmelt flood. Satellite data were not used in the experiment. Two sets of hydrographs were simulated distinguishing in the number of meteorological stations providing meteorological inputs into the model. The first set of hydrographs was simulated using all available 19 stations and only 4 stations were used for calculation of the second set. The results of the numerical experiment are shown in Fig. 12. As one can see from Figure 12, utilizing the satellite data does not improve hydrograph simulations in comparison with the case when relatively dense network of meteorological observations exists. Moreover, hydrographs simulated using the data of 19 meteorological stations appeared to be slightly more accurate than ones calculated with the use of satellite data. This result can be explained by lower accuracy of the initial SWE field derived from satellite data in comparison with one calculated from meteorological data. However, in the case of scarce meteorological observations (only 4 stations per 120,000 km^2), the result is opposite, as it is seen from Fig. 12. It means that initial SWE field taken from satellite date is more accurate than ground-based SWE data and has advantage for hydrograph simulation in the case of a catchment poorly gauged by snow observations.

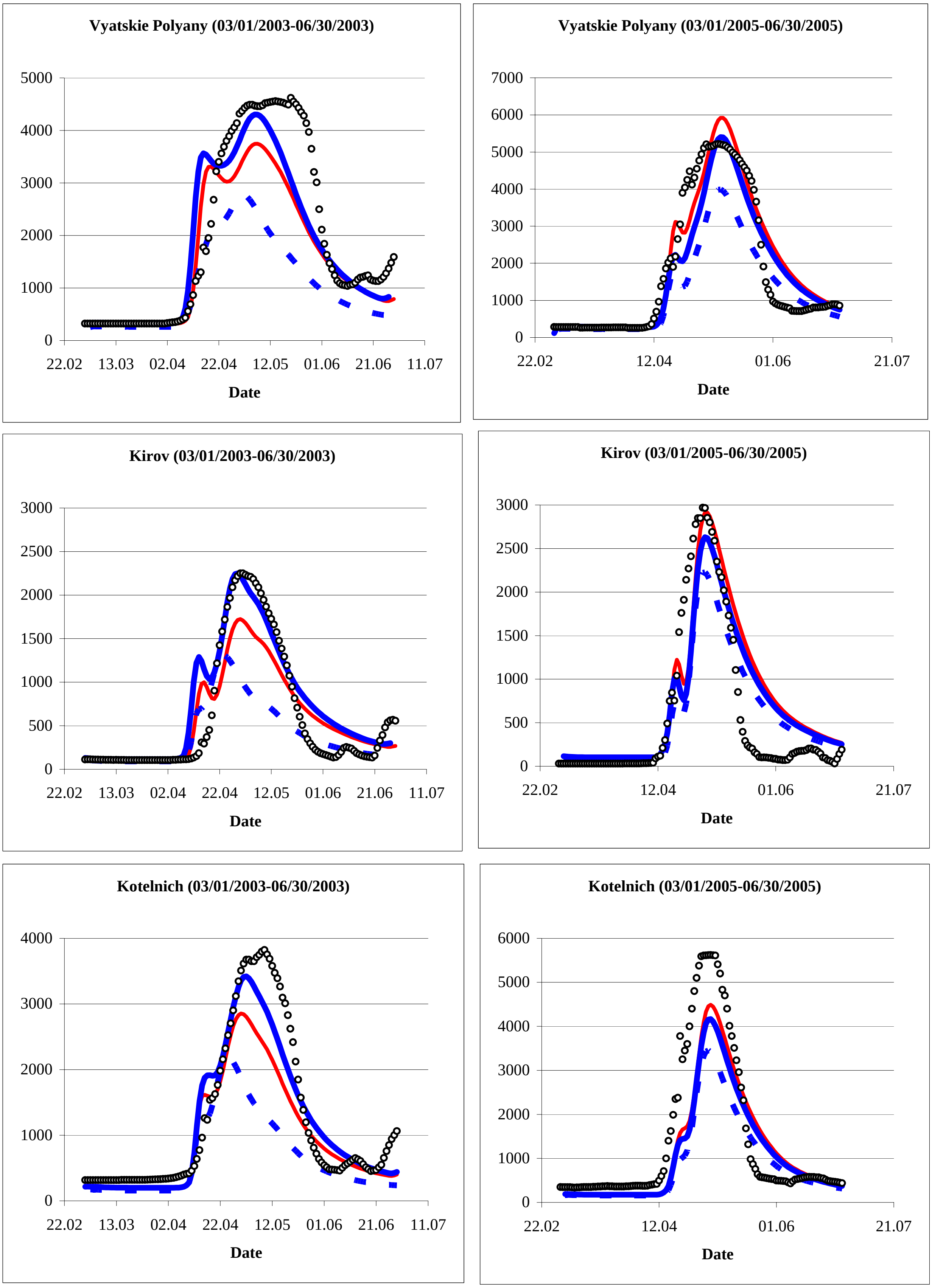

Fig. 12. Observed (circles) and calculated (lines) hydrographs of the Vyatka river:

red line – calculated with satellite data

blue lines – calculated without satellite data (continues line - data of 19 meterological stations are used, dashed line – data of 4 meteorological stations are used)

Technical Corrections:

1. Both “physical based model” (e.g. p.5506, line 5) and “physically-based model” (e.g. p.5506, line 20) are used in the text. It is better to make them consistent.

“Physically based model” is used everywhere in the corrected text

2. p.5506, line 14, are “maps of surface albedo” weekly? From Table 1, it might not the case.

Made in accordance with Table 1

3. p.5506, line 21-22, the “spring seasons” should be specified. In addition, should the comma in “2003, 2005” be “and”?

Corrected

4. p.5508, line 29, the “)” before “(Fig.1)” should be deleted.

Corrected

5. p.5509, line 4, “The snow seasons lasts. . .” needs revision.

Corrected

6. p.5509, line 20, “(Chang, Rango, 2000)” should be “(Chang and Rango, 2000)”.

Corrected

7. p.5511, lines 9-10, is snow depth (used for model calibration) also measured at the ground-based stations?

Yes, the paragraph is corrected.

8. The article could use a grammatical review for all the equations described

Agree. All suggestions of the reviewer are taken into account.

9. p.5516, lines 15-16, model input, output, simulation time step could be specified.

Input, output, and simulation time step are specified.

10. p.5517, line 4, “random fitting procedure” needs clarification.

The following clarification is added

> Monte Carlo simulation was used to randomly generate one hundred parameter sets, from which optimal parameter set was identified. The parameters were assumed to be uniformly distributed within the pre-determined intervals.

11. p.5517, lines 8-9, the cold season is from November to June as told from Figure 5. However, in p. 5509, lines 3-4, the cold season is defined as “(October to March)”. It should be consistent.

Corrected

12. p.5517, lines 9-11, what is “standard error”? “training dataset”? “independent dataset”? Are “7 cm” and “9 cm” site-averaged values?

The paragraph is clarified.

13. p.5517, line 14, “spring season” needs clarification (how is it defined?).

The time period is clarified

14. p.5517, line 15, “model was run for each 0.01 grid cell. . .”, how is the SWE map (“March 1 data is used as initial SWE”, p.5517, lines 23-24, which has the grid size of 0.2 degree) incorporated into the model?

The following clarification is added in the text

> The initial spatial distribution of SWE for the open or forest-free area was assigned using AE_DySno SWE maps on March 1. The SWE values for all forested pixels as well as the missed SWE values for open pixels were estimated by interpolation from open pixels where satellite-derived SWE values were available. The interpolated SWE was further multiplied by the factor ksnow, representing the average ratio of the pre-melt SWE in the forest to the pre-melt SWE in the neighboring open area.

15. p.5518, lines 2-3, “winter season” needs clarification.

“winter season” is replaced with “snow season”

16. p.5518, lines 9-11, the statement is too strong. It is valid for the studying period (2000-2004), but might not be valid “from year to year”.

We prolonged the studying period up to 14 snow seasons: from 1970-1971 to 1979-1980 and from 2000-2001 to 2003-2004. The same result has been obtained, namely, that the variations of the value of k_{snow} from year to year for the same forest area are small and can be negligible. The Figure below illustrates this conclusion for coniferous forest.

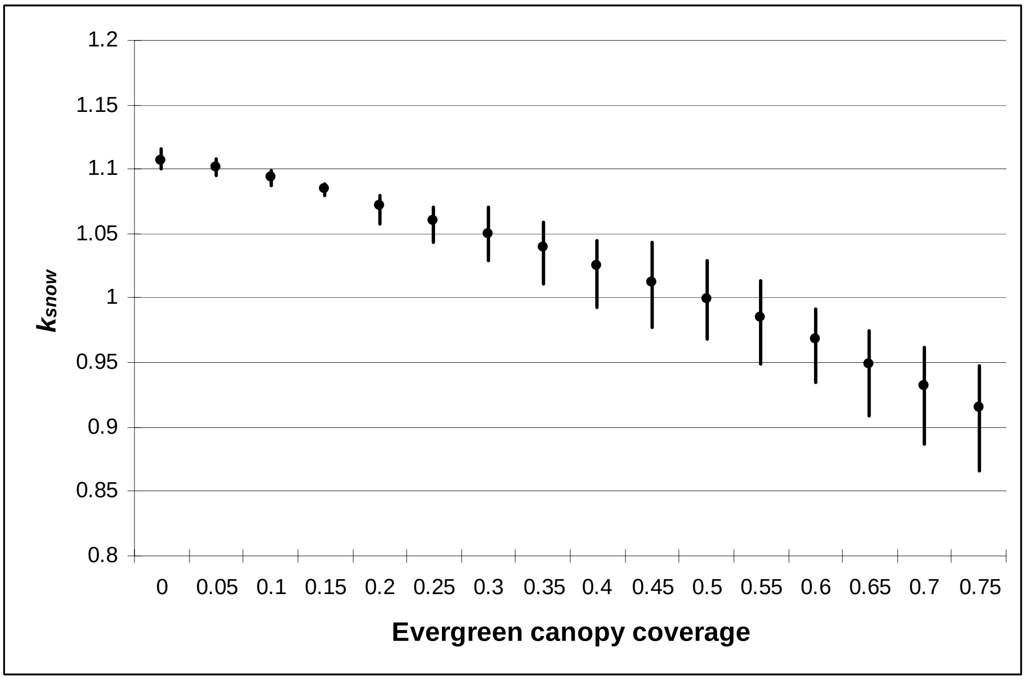

Figure. Changes in the factor k_{snow} with changes of canopy coverage in coniferous forest (points are the values of k_{snow} averaged for 14 snow seasons; bars show ranges of deviations of k_{snow} from year to year).

17. p.5518, “Figure 7” is used in line 23 while “Fig. 7” is used in line 26. It should be consistent. p.5522, “Fig. 9” is used in line 1, and “Fig. 10” is used in lines 8 and 11. Previously in the text, “Figure” is used instead.

Corrected

18. p.5519, line 8, “. . .to simulate runoff generation”. “generation” here could be deleted.

Deleted

19. p.5519, line 18, “Eq. (1)-(26)” should be “Eqs. (1)-(26)”.

Corrected

20. p.5522, line 12, “. . .accuracy of hydrographs simulation” grammatical check is required.

Corrected

21. p.5522, line 13, “maximum error” needs clarification.

Clarified

22. p.5531, Fig. 5, numbers and texts on the axis are hard to read. Changes to font size are recommended.

Changed