Evaluation of climate change impact on soil and snow processes in small watersheds of European part of Russia using various scenarios of climate

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Beurteilung des Klimaänderungseinflusses auf Boden- und Schneeprozesse kleiner Einzugsgebiete in Russland unter Verwendung verschiedener Klimaszenarien

Introduction

Despite continuing scientific debates surrounding climate change, the issue can not be ignored in current studies. One of the unresolved key issues of climate change is how the hydrological cycle responds to global change in different landscapes. The hydrological cycle affects both the terrestrial and aquatic systems and is intimately coupled with the atmospheric system. A number of studies revealing climate change impact on the hydrological cycle have been undertaken worldwide (Woo M.-K. et al., 2008, Adam J.C. et al., 2009, Bonnel M., 1998) and in Russia as well (Kislov et al., 2008, Arzhanov et al., 2008).

Impacts of climate change on the hydrological cycle may be reflected not only in frequency and magnitude of extreme hydrological events but also in seasonal change of its components. Understanding these changes at a small scale is critical to assessing its impact on ecology, agriculture, infrastructure, and whether those changes in hydrological processes provide any feedback into climate change per se. Therefore, different processes and components of the hydrological cycle should be studied.

The goal of this research was to assess the possible changes in soil water/heat dynamics and snow cover processes in different landscapes of European Russia, base on deterministic-stochastic modelling using several IPCC climate change scenarios.

The key stages of the research are listed as follows:

- Generate ensembles of daily meteorological series according to selected IPCC climate change scenarios using the developed stochastic model.
- Simulate water and energy fluxes at selected sites with

Zusammenfassung

Der vorliegende Beitrag präsentiert Ergebnisse von Modellanwendungen zur Abschätzung der Auswirkungen von Klimaänderungsszenarien auf den Bodenwasserhaushalt, den Wärmehaushalt und die Schneebedeckung an verschiedenen Standorten Russlands. Dabei gelangte ein deterministisch-stochastisches Modell zum Einsatz. Die Anwendung erfolgte an drei experimentellen Einzugsgebieten im europäischen Teil Russlands. Es waren dies die Forschungsstationen Valday, Nizhnedevickaya und Podmoskovnaya.

Schlagwörter: Kleineinzugsgebiete in Russland, Deterministisch-stochastische Modellierung, Beobachtung Wasserhaushalt.

Summary

The paper presents the results of assessing possible changes in soil water, heat dynamics and snow cover processes in different Russian landscapes based on a deterministic-stochastic model using IPCC climate change scenarios. The simulations and climate change impacts analysis were conducted for three experimental watersheds located in the European part of Russia (so called water-balance stations): Valday research station, Nizhnedevickaya and Podmoskovnaya stations.

Key words: Deterministic-stochastic modelling, state variables, IPCC climate change scenarios, water-balance station.

randomly-generated series of meteorological elements as forcing data using the developed deterministic model of runoff formation processes.
- Assess, evaluate and compare changes in soil and snow state variables within three different sites and according to different climate change scenarios.

The approach

For this study, the previously developed Deterministic-Stochastic Modelling System (DSMS) (Vinogradov & Vinogradova, 2008; Semenova, 2009) was applied. Its deterministic component (the Hydrograph model) was successfully tested for small (Semenova, 2010) and large scale river basins (Semenova and Vinogradova, 2009; Vinogradov et al., 2010); the stochastic component (the Stochastic Model of Weather, "SMW") was verified at the small watersheds (Semenova, 2009).

A detailed description of DSMS may be found in Vinogradov et al. (2010), Vinogradov and Vinogradova (2009, 2010), Semenova (2009).

The Hydrograph model is used to distinguish between landscapes with different soil and vegetation properties, while the SMW is used to derive ensembles of meteorological forcing data according to future climate scenarios and ensure a framework linking global climate models in a dynamic environment with land surface components. This provides a quantifiable probabilistic outlook of the impact of climate change on hydrological processes.

Site description and data

The simulations and climate change impacts analysis were conducted for three experimental watersheds located in the European part of Russia (so called water-balance stations, see Figure 1): Nizhnedevickaya on the river Devica (Don River tributary, forest-steppe landscape), Valday research station (on the upper Volga, taiga) and Podmoskovnaya (Volga middle course, mixed and broad-leaved forest). The climate of the region is relatively temperate.

The Valday water balance station (58 °N, 33.3 °E) is situated in the northwestern part of European Russia in the southern taiga forest zone. Mean annual air temperature is 4.7 °C, and for January -9.7 °C. Mean annual precipitation is about 700 mm, of which 30% is snowfall. We chose for our study the small forested watershed – Taezgny Creek (area 0.45 km^2). The main part (73%) of its catchment is covered by a mature spruce forest. The remaining part of the catchment is a marshy area covered by pine stands.

Figure 1: Objects of research: 1 – Valday station, 2 – Podmoskovnaya station, 3 – Nizhnedevickaya station
Abbildung 1: Forschungsstationen: 1 – Valday station, 2 – Podmoskovnaya station, 3 – Nizhnedevickaya station

The Podmoskovnaya water balance station (55.7 °N, 37.6 °E) is located in the centre of the European part of Russia in the mixed, broad-leaf forest zone. The mean annual temperature is almost the same as the Valday station (4.3 °C), but the precipitation is less (about 650 mm). The selected site is the catchment of Progony Creek (area 0.8 km^2). Almost half of the area is arable land (44%) or covered by mixed forest (42%), and the rest of the area is pasture and settlements.

The Nizhnedevickaya water balance station (51.3 °N, 38.2 °E) is situated in the southwest European part of Russia in the forest-steppe zone. This is the warmest station within the selection. The mean annual temperature is 6.2 °C, precipitation is about 680 mm per year. The simulation was conducted for a small catchment of the Dolgii Creek (2,57 km^2). 44 % area is covered by oak forest, the rest of territory is arable land.

Daily meteorological data (air temperature, relative humidity and precipitation) for modelling and estimating parameters of the SMW were available for the following periods: the Nizhnedevickaya station from 1970 to 1984, the Valday station from 1973 to 1991, and the Podmoskovnaya station from 1973 to 1984.

Results

The state variables including snow depth and snow water equivalent (SWE), soil moisture in the 1-meter layer and soil temperature at the different depths were simulated at three sites using available historical meteorological data as forcing data on the base of the deterministic Hydrograph model. Some examples are shown at Figure 2–4.

The simulations of snow formation are quite accurate although the calculated melting period may be shorter than the observed one (Figure 2). In general the soil temperature is well-simulated, especially for the summer period (Figure 3). We assume that the discrepancies between observed and simulated values for the winter period are due to the results of soil moisture simulations. During the winter period the observed content of soil moisture in the 1-meter layer often is higher than the calculated one, but during the rest of the year they are close to each other.

The analysis of the results showed that the Hydrograph model performs reasonably well for most cases. Therefore the Hydrograph model can be implemented for assessment of possible climate change impacts on state variables of snow and soil (Figure 4).

Next the parameters of the Stochastic Model of Weather were derived using meteorological observations. Within emission scenarios and existing General Atmospheric-Ocean Cirlulation Models the A1F1, B1 and ECHAM4/OPYC3 (Max-Planck Institute for Meteorology, Germany) were chosen. According to A1F1 scenario the air temperature and solid precipitation go up 4.491 °C and 22.74% respectively. It is greater than according to B1 (3.241 °C and 18.46% respectively). The summer precipitation is projected to be almost invariable. The chosen period of calculation is 2010–2039. All data in numerical format is available from the IPCC website.

Parameters of Stochastic Model of Weather for three water-balance stations were changed according to the chosen climate change projections for the region of European Russia. The historically derived stochastic model parameters that control precipitation and temperature generation

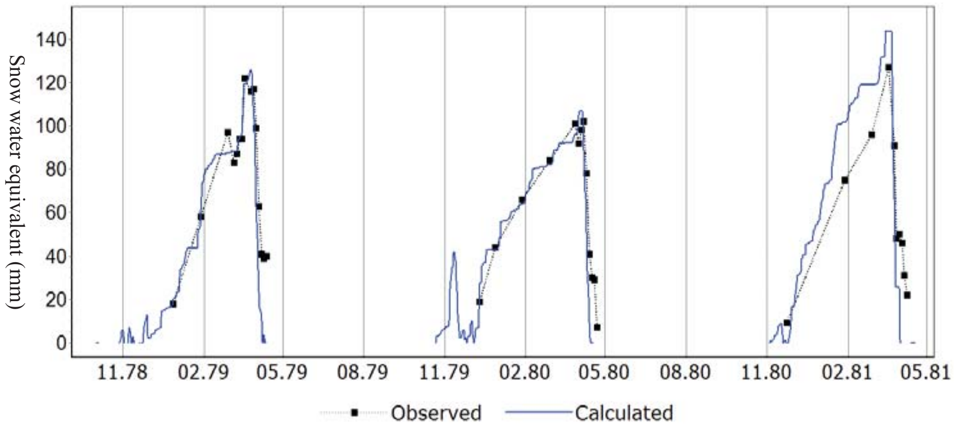

Figure 2: Observed and calculated snow water equivalent (mm). Podmoskovnaya station, Progony Creek. 1978–1981

Abbildung 2: Beobachtetes und simuliertes Scheewasseräquivalent (mm). Podmoskovnaya station, Progony Creek. 1978–1981

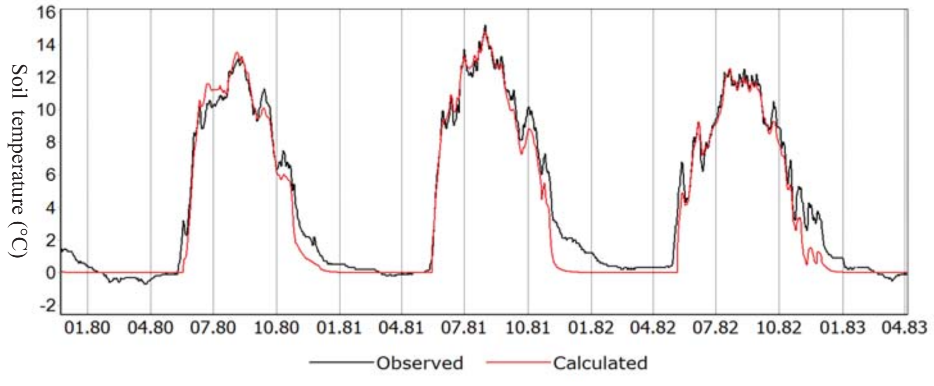

Figure 3: Observed and calculated soil temperature (°C) at a depth of 40 cm, Valday station, Taezhny Creek. 1980–1983

Abbildung 3: Beobachtete und simulierte Bodentemperatur (°C) in einer Tiefe von 40 cm, Valday station, Taezhny Creek. 1980–1983

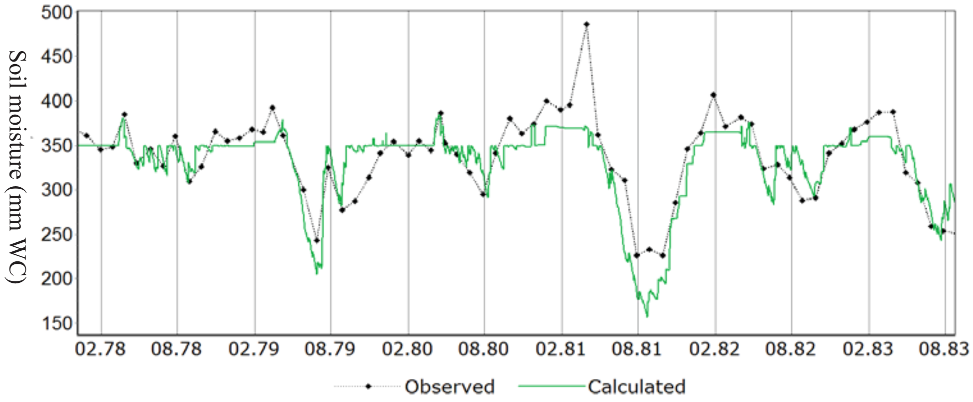

Figure 4: Observed and calculated soil moisture in 1-meter layer (mm WC). Nizhnedevickaya station, Dolgii Creek. 1978–1983

Abbildung 4: Beobachteter und simulierter Bodenwassergehalt in 1-Meter Schicht (mm WC). Nizhnedevickaya station, Dolgii Creek. 1978–1983

were modified to reflect each of the scenario projections. Twenty ensembles of daily meteorological data were generated for the period 2010–2039 for each scenario and site. The deterministic Hydrograph model was run using the generated meteorological series.

For the assessment of possible changes in the snow and soil processes, the following characteristics were chosen: maximum SWE, dates of established snow formation and melting, minimum soil moisture in 1 meter layer, maximum soil temperature at a depth of 40 cm and their dates. The comparison of probabilistic curves derived form historical observations of variable states and those simulated using the projected ensembles of meteorological data are shown in the Figure 5–6.

Increased winter precipitation is projected according to both scenarios, A1F1 and B1. However it does not necessarily mean the increase of projected maximum SWE. Thus the results of simulations predict growth of maximum SWE for Podmoskovnaya station but there are no changes projected at Nizhnedevickaya station. The reason is that the projected winter temperature rise in the relatively warm Nizhnedevickaya station can result in snow melting during winter period, and less snow will not accumulate.

The results of simulations show that there may be a significant decrease in projected minimum soil moisture in Podmoskovnaya station. We attribute it to an increase of evaporation rates because of increasing temperatures.

The projected maximum soil temperature at a depth of 40 cm rises in the forest zone (Valday and Podmoskovnaya stations), but there is no change for this parameter at the forest steppe site. These results require additional analysis concerning reasons for different responses from different landscapes. The possible change in vegetation and its role in heat dynamics should be investigated.

Conclusions

The deterministic-stochastic modelling performed for small watersheds with different landscape conditions have shown ambiguous results. They confirm the necessity of studies revealing the climate change impacts at small scale.

Validation of the deterministic hydrological model and the stochastic model were conducted separately for selected small catchments in three landscape zones using historical data. They showed a satisfactory coincidence of observed and simulated variable states of soil and snow cover. Therefore the deterministic-stochastic approach proposed herein was applied for the assessment of possible changes in soil and snow processes according to two climate change scenarios for three sites in the European part of Russia.

The next task would be a detailed investigation into the reasons for the different responses from different landscapes and, given the adaptable framework of the DSMS, evaluation of possible land use change impacts on the hydrological cycle at a small scale.

The possible feedback on climate consists of increased soil evaporation due to soil warming. Furthermore changes in soil temperature and moisture can be influenced by the soil type and vegetation composition.

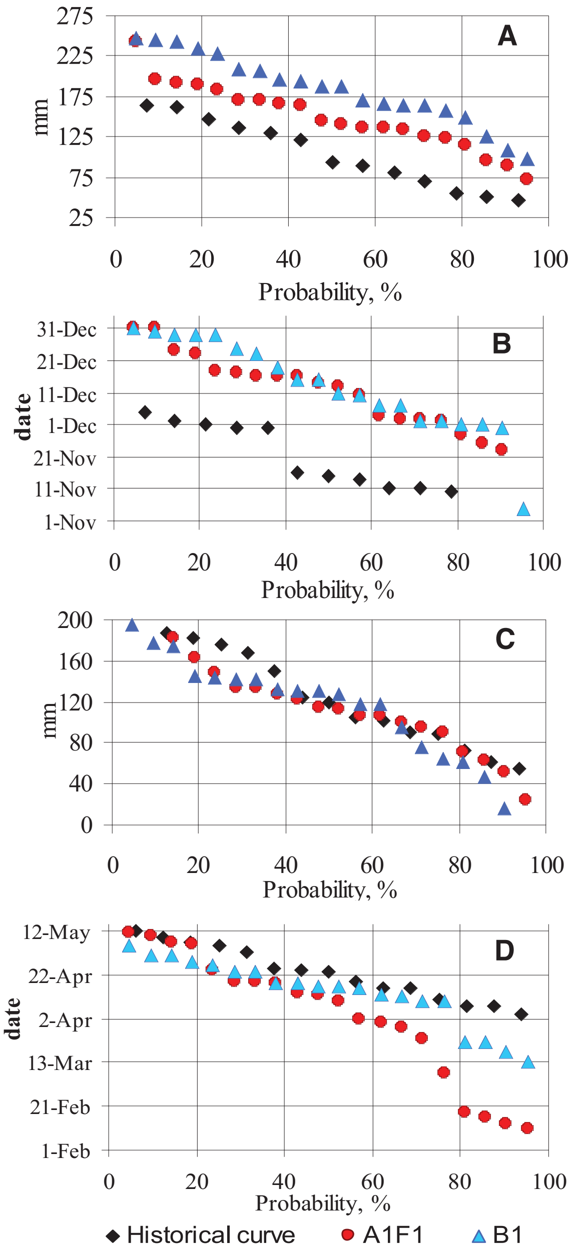

Figure 5: Probabilistic curves of snow characteristics (observed and calculated according to A1F1 and B1 scenarios) (%). A – maximum SWE (mm), Podmoskovnaya station, Progony Creek; B – date of the last snowless day, Podmoskovnaya station, Progony Creek; C – maximum SWE (mm), Nizhnedevickaya station, Dolgii Creek; D – date of the first snowless day, Nizhnedevickaya station, Dolgii Creek

Abbildung 5: Auftrittswahrscheinlichkeit (%) von Schneeeigenschaften gemäß A1F1 und B1 Szenario. A – Maximales SWÄ (mm), B – Datum des letzten schneefreien Tags, C – Maximales SWÄ (mm), D – Datum des ersten schneefreien Tags

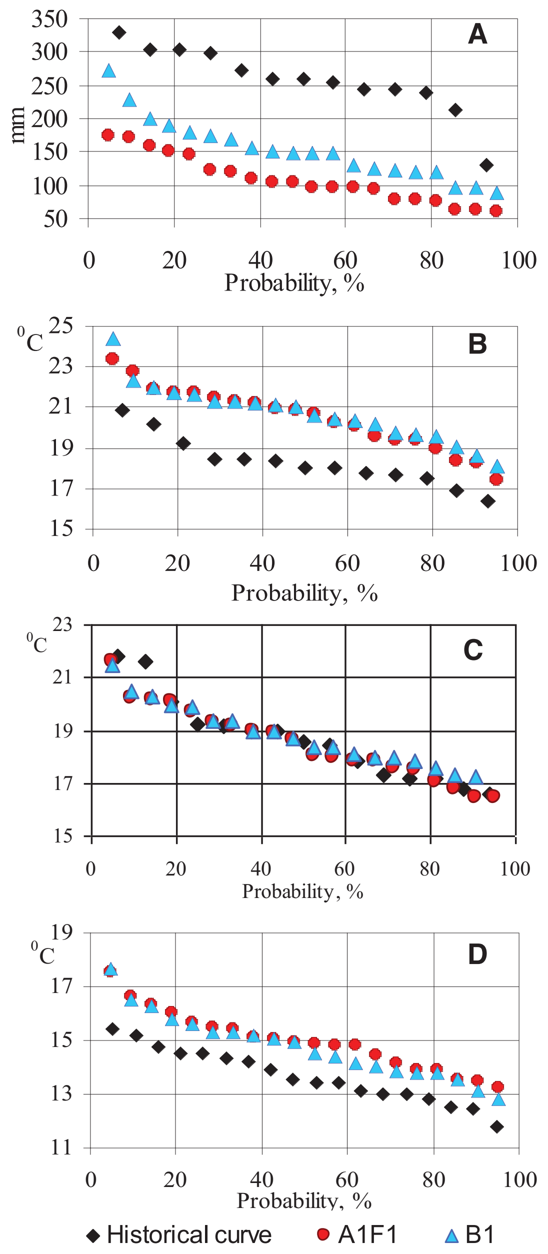

Figure 6: Probabilistic curves of soil variable states (observed and calculated according to A1F1 and B1) (%). A – minimum soil moisture in 1 meter layer (mm WC), Podmoskovnaya station, Progony Creek; B – maximum soil temperature (°C) at the depth of 40 cm, Podmoskovnaya station, Progony Creek, C – maximum soil temperature (0C) at the depth of 40 cm, Nizhnedevickaya station, Dolgii Creek; D – maximum soil temperature (0C) at the depth of 40 cm, Valday, Taehznii Creek

Abbildung 6: Auftrittswahrscheinlichkeit (%) von Bodenzustandsgrößen gemäß A1F1 und B1 Szenario. A – Minimaler Bodenwassergehalt (mm WC), B – Maximale Bodentemperatur (°C) in 40 cm Tiefe, C – Maximale Bodentemperatur (°C) in 40 cm Tiefe, D – Maximale Bodentemperatur (°C) in 40 cm Tiefe

References

Adam, J. C., Hamlet, A. F., Lettenmaier, D. P. (2009): Implications of global climate change for snowmelt hydrology in the twenty-first century. Hydrobiological processes 23(7), 962–972.

Arzhanov, M. M., Demchenko P. F., Ellseev A. V., Mokhov I. I. (2008): Simulation of characteristic of thermal and hydrological soil regimes in equilibrium numerical experiments with a climate model of intermediate complexity. Izvestiya. Atmospheric and Oceanic Physics 44(5), 548–566 (in Russian).

Bonnel, M. (1998): Possible impacts of climate variability and change on tropical forest hydrology (2009). Change Climatic 39(2–3) 215–272.

IPCC, http://www.ipcc-data.org/

Kislov, A. V., Evstigneev, V. M., Malkhazova, S. M., Sokolikhina, N. N., Surkova, G. V., Toropov, P. A., Chernyshov, A. V., Chumachenko, A. N. (2008): Prognosis of the climatic resources provision at the Eastern-European plain in the conditions of warming. Maks-Press, Moscow, 290. (in Russian; ISBN 978-5-317-02481-9).

Semenova, O. M. (2009): Deterministic-stochastic modelling of hydrological extremes in small basins. Technical Documents in Hydrology 84, 55–60.

Semenova, O. M. (2010): Experience with modelling of runoff formation processes at basins of different scales using data of water-balance stations. In: Status and Perspectives of Hydrology in Small Basins (Proc. of the Workshop held at Goslar-Hahnenklee, Germany, 30 March–2 April, 2009). IAHS publ. 336, 167–172.

Semenova, O. M., Vinogradova, T. A. (2009): An universal approach to runoff processes modelling: coping with hydrological predictions in data scarce regions. In: New Approaches to Hydrological Prediction in Data Sparse Regions. IAHS publ. 333, 11–19.

Vinogradov, Yu. B, Semenova, O. M., Vinogradova, T.A. (2010): An approach to the scaling problem in hydrological modelling: The Deterministic Modelling Hydrological System. Hydrological Processes. Special Issue (in press).

Vinogradov, Yu. B., Vinogradova, T. A. (2008): Current problems in hydrology. Academia Publishers, Moscow. (in Russian).

Vinogradov, Yu. B., Vinogradova, T. A. (2010): Mathematical modelling in hydrology. Academia Publishers, Moscow (in Russian).

Woo, M.-K., Thorne, R., Szeto, K., Yang, D. (2008): Streamflow hydrology in the boreal region under the influence of climate and human interference. Philosophical transactions of the Royal Society of London. Series B: Biological Sciences 363, no. 1501, 2251–2260.

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