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Changes in eco-hydrological systems under recent climate change in eastern Siberia

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Abstract Global warming is likely to transform Siberian environments. Recent eco-hydrological evidence indicates that water and carbon cycles have been changing rapidly, with potentially serious effects on the Siberian flora and fauna. We have comprehensively analysed dendrochronological, hydrological, and meteorological data and satellite remote sensing data to track changes in vegetation and the water and carbon cycles in the Lena River Basin, eastern Siberia. The basin is largely covered with larch forest and receives little precipitation. However, from 2005 to 2008 the central part of the basin experienced an extraordinarily high level of precipitation in late summer and winter. This resulted in the degradation of permafrost, forest, and hydrological elements in the region. Dendrochronological data implied that this event was the only incidence of such conditions in the previous 150 years. Based on data collected before and after the event, we developed a permafrost-ecosystem model, including surface soil freeze-thawing processes, to better represent the heat, water, and carbon fluxes in the region. We focused on the surface soil layer, in which an increased thawing depth is now apparent, surface soil moisture, and net primary production. An analysis of observed and model-simulated data indicated that the annual maximum thawing depth (AMTD) had increased gradually on a decadal scale and deepened abruptly after 2005. Climatological analyses of atmospheric water circulation over the region indicated that the recent increases in precipitation over the central Lena River Basin were partly related to cyclone activity. Consequently, the increased precipitation from late-summer to winter resulted in increases in soil moisture, soil temperature, and AMTD in the region.

Key words global warming; Lena River Basin, Siberia; extraordinarily high precipitation; permafrost-ecosystem model; annual maximum thawing depth (AMTD)

INTRODUCTION

Global warming is likely to transform Siberian environments. Early evidence indicates that water and carbon cycles are currently undergoing rapid change (Ohta *et al.*, 2008; Iijima *et al.*, 2010), with potentially serious impacts on Siberian flora and fauna. Human inhabitants, who have adapted to great changes in their social structure and environment in the past (Nakada, 2012; Yoshida, 2012), will be forced to adapt again, but this time to a cascading series of environmental changes whose dimensions are only understood in outline.

Regional climate in Siberia is based on energy and water exchanges and, particularly, on changes in the surface reflectance of snow, ice and vegetation cover. Therefore such changes need to be continuously monitored for as long as possible. The Lena River Basin in eastern Siberia is covered in larch forest but receives little precipitation (Ohta *et al.*, 2008). The area is therefore an ideal setting in which to study the effects of climate warming, as the forest–permafrost symbiosis (Zhang *et al.*, 2011) is extremely susceptible to abnormal variations in temperature and precipitation.

We started the monitoring of energy and water exchanges between larch forest and the atmosphere in 1998 at Yakutsk, in the central part of the Lena River Basin (Ohta *et al.*, 2001). This monitoring programme has revealed that the region suffered from extraordinarily high precipitation in late summer to winter from 2005 to 2008 (Iijima *et al.*, 2010). This might lead to degradation of permafrost (Fedorov *et al.*, 2013), forest, and hydrological elements in the region. This study aimed to identify such permafrost–forest environmental degradations in the region.

METHODS

We use our own monitoring data as well as some operational hydro-meteorological data and atmospheric re-analysis data sets. Most of the data used in this study were from surface meteorological monitoring systems that track changes in water and carbon cycles and the cryosphere. Additionally, we have revised our model of surface soil freeze-thawing processes to better represent energy, water, and carbon fluxes in permafrost ecosystems. Here we were particularly concerned with the surface soil layer.

Atmospheric reanalysis data and basin-scale precipitation data sets

In order to understand the climatology of Siberia, the JRA-25/JCDAS (1.25° × 1.25°, Jan. 1979–Aug. 2012) re-analysis data set (Onogi *et al.*, 2007) was used. Atmospheric water vapour (precipitable water) and the water vapour flux divergence/convergence were evaluated.

Global Precipitation Climatology Project (GPCP) one-degree daily resolution precipitation data (Huffman *et al.*, 2001) were used to determine spatio-temporal variations of precipitation in the central part of the Lena River Basin.

Tower observation

The meteorological and flux monitoring site was located at Spasskaya Pad (SP) near Yakutsk city, eastern Siberia. Its latitude and longitude is 62°15′N and 129°14′E (Ohta *et al.*, 2001; Dolman *et al.*, 2004; Ohta *et al.*, 2008). The average annual precipitation during the period of 1986–2004 was 230 mm at Yakutsk. Almost 70% of the annual average precipitation fell as rain during May to September. The dominant species at SP are larch (*Larix cajanderi*), mixed with birch (*Betula pendula*). The stand density of larch trees obtained in 2012 was 700 trees ha^{-1} (1800 trees ha^{-1}, including birch). The mean stand height of the upper canopy, composed of larch trees, was around 20 m. The average leaf area index (*LAI*) was 1.5. Soils consisted of an alluvial sandy loam classified as permafrost pale-solodic (Kononov *et al.*, 2012).

Fluxes of CO_2, water vapour, and energy between the larch forest and the atmosphere were measured by the eddy covariance method using an observation tower. For flux determination, an ultrasonic anemometer-thermometer (R3: Gill Instruments Ltd., Hampshire, UK) and an open-path infrared gas analyser (LI-7500: LI-COR Biosciences Inc., Lincoln, NE, USA) were installed at a height of 32.0 m (approx. 10 m above the upper canopy layer).

Several environmental variables, which have been described in detail by Ohta *et al.* (2008), were measured on and around the observation tower. The main variables measured in this study were net radiation (*Rn*) (or shortwave and longwave radiation), air temperature (*Ta*), water vapour pressure deficit (*VPD*) (or air humidity), soil water content (*SWC*), ground (soil) temperature (*Tg*), and precipitation (*Pr*).

Dendrochronological analysis

Larch trees collected in SP were used for the dendroclimatological analysis of tree-ring widths and carbon isotope ratios ($\delta^{13}C$). The samples were cross-dated with ITRDB's (International Tree-Ring Data Bank's) ring-width records in eastern Siberia. Based on the dendroclimatological analysis, soil moisture for the past 150 years was reconstructed from the tree-ring (latewood) $\delta^{13}C$ (Tei *et al.*, 2012).

Hydrological and biogeochemical model

The land surface model (2LM) used in this study was the 1-D model described in Yamazaki *et al.* (2004). The simulation method is described in Yamazaki *et al.* (2007). Initially, relationships in the meteorological data between Yakutsk meteorological station and the tower site (SP) were established from 1998 to 2000. Past meteorological conditions over the larch forest were then estimated using these relationships. Finally, sensible and latent heat fluxes and soil/snow condition were simulated using the 2LM 1-D land surface model.

The 2LM model calculates water and energy fluxes above and within the forest, if meteorological data over the forest are given as inputs. 2LM includes three submodels, i.e. vegetation, snow, and soil submodels. The snow submodel is multi-layer and calculates profiles of snow temperature, density and liquid water content, as well as the snow depth. In this submodel, the number of snow layers depends on the snow depth. The soil submodel is a multi-layer model, which uses a thickness of 0.1 m except for the top layer (0.2 m). It can calculate profiles of soil temperature and water content. The heat of fusion of frozen soil is taken into account using a method in which the heat capacity is regarded as larger in a small temperature range between –1 and 0°C.

A coupled hydrological and biogeochemical model (CHANGE: Park *et al.*, 2011) was also used to predict the spatio-temporal variations of annual maximum thawing depth (AMTD) in permafrost ecosystems of the circumpolar Arctic regions. CHANGE is a physically-based land surface model designed to integrate interactions in a complex soil–vegetation–atmosphere system, especially in the Arctic regions (Park *et al.*, 2011). It consists of four modules: land surface module, vegetation phenology module, carbon balance module, and vegetation dynamic module. It simulates the hourly exchanges of water, energy, and CO_2 in the soil–vegetation–atmosphere system and includes the snow surface during the winter seasons. Vegetation is considered to be a single layer in the model and it solves energy, water, and carbon balances. Snow accumulation and melt were estimated by a two-layer energy and mass balance model. The energy balance components were used to simulate snowmelt, refreezing, and changes in the snowpack heat content.

RESULTS AND DISCUSSION

Based on a climatological analysis of atmospheric water vapour transport and GPCP precipitation records over the region, summer precipitation from 2005 to 2007 was of a relatively strong intensity (the number of days with more than 10 mm of precipitation were higher than the average for the 14 years from 1997 to 2010.) This pattern continued into 2008, when the number of days with precipitation was also higher than the 14-year mean value. The number of days with precipitation in the late-summer to winter of 2005 and 2006 was also abnormally high. Climatological analysis of atmospheric water vapour transport over the region indicated that the recent increases in precipitation over the central Lena River Basin were partly related to cyclone activity (Fig. 1). These precipitation increases from 2005 to 2008 ensured surface soil humidification at SP site from 2006 to 2009 (Fig. 2).

The surface soil humidification at SP resulted in changes in the canopy-scale evapotranspiration and photosynthesis of larch trees. The relationships between *SWC* and canopy-scale evapotranspiration efficiency in the summer season after 2007 clearly differed from those before 2006. Interestingly, the relationships between *SWC* and the canopy-scale photosynthetic activities after 2008 differed from those before 2007. The reason for the one-year time difference between the appearance of a relationship for evapotranspiration efficiency and photosynthetic activities is not yet clear.

In relation to evapotranspiration and carbon sequestration, stomatal conductance is an important variable for deducing a tree's physiological signature, especially due to *SWC*. Because the tree-ring $\delta^{13}C$ over the boreal region is closely related to stomatal conductance, it is a good indicator of historical *SWC* in the region. We sampled 150-year-old dead larch trees at SP to determine the $\delta^{13}C$ and found less than 50 year variations of relative $\delta^{13}C$ values. This indicates strong dry periods in the region with no wet events. In contrast, it was shown that the tree experienced a severe wet event from 2006 to 2007. This indicates that the humidification that occurred from 2006 to 2007 was the first such event in 150 years.

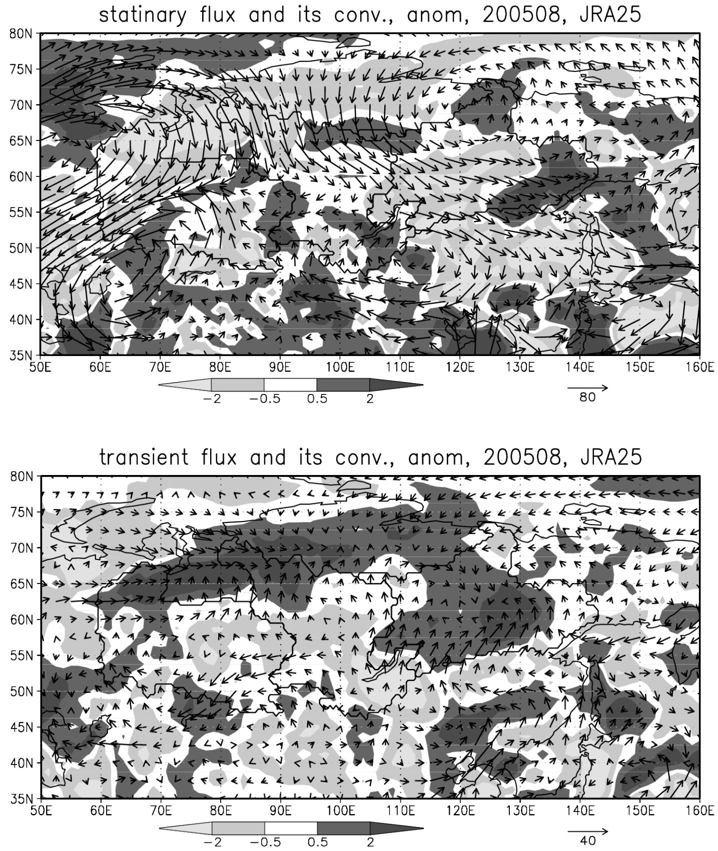

Fig. 1 Atmospheric water vapour transport in August 2005 over Siberia. Arrows in the upper figure show stationary fluxes and those in the lower figure show transient fluxes. Dark grey indicates water vapour convergence.

It should also be noted that the soil temperature from the surface to 120 cm depth at the SP site was higher than that observed before 2005 and after 2010 (Fig. 2). The land surface model (2LM) and the coupled hydrological and biogeochemical model (CHANGE) indicated that the AMTD had gradually increased (deepened) on a decadal scale. Decadal variations of the AMTD were estimated from the 2LM (Fig. 3) and appeared to be related to similar variations in precipitation (both in late-summer and in winter). Consequently, increases in precipitation could be related to increases in surface soil moisture and the AMTD. These decadal increases also had positive correlations with terrestrial evapotranspiration (*ET*) and net primary production (*NPP*).

Such permafrost degradation has been mostly determined from *in situ* observations in the soil profile. Thus, we propose to relate low river flows (or baseflows) during the open water season with the rate of change of the active groundwater layer thickness resulting from permafrost thawing, at the scale of the upstream river basin of the Lena River (Brutsaert & Hiyama, 2012). The results indicated that over the period of 1950–2008, the active layer thickness, i.e. the AMTD, has been increasing at an average rate of around 1 cm year^{-1} in the area. Interestingly, from the 1990s onwards, basin-scale AMTD has been experiencing an average growth rate as large as 2 cm year^{-1}.

CONCLUSIONS

This study considered permafrost–forest environmental degradation due to extraordinarily high precipitation in the late-summer to winter of 2005 to 2008 in the central part of the Lena River Basin, eastern Siberia. Dendrochronological data demonstrated that the years of extraordinarily high precipitation constituted the first such event in 150 years. Climatological analysis of atmospheric water vapour transport over the region indicated that the increases in precipitation

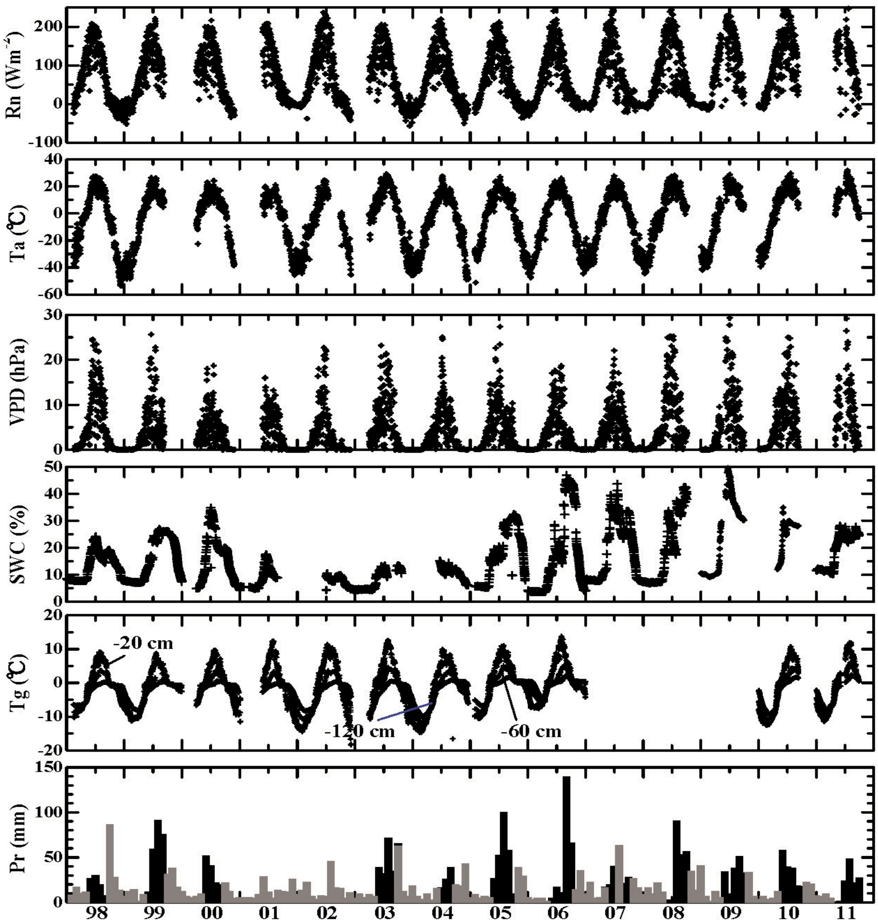

Fig. 2 Time series of net radiation (*Rn*), air temperature (*Ta*), water vapour pressure deficit (*VPD*), soil water content (*SWC*), soil temperature (*Tg*) and precipitation (*Pr*) at the Spasskaya Pad (SP) site.

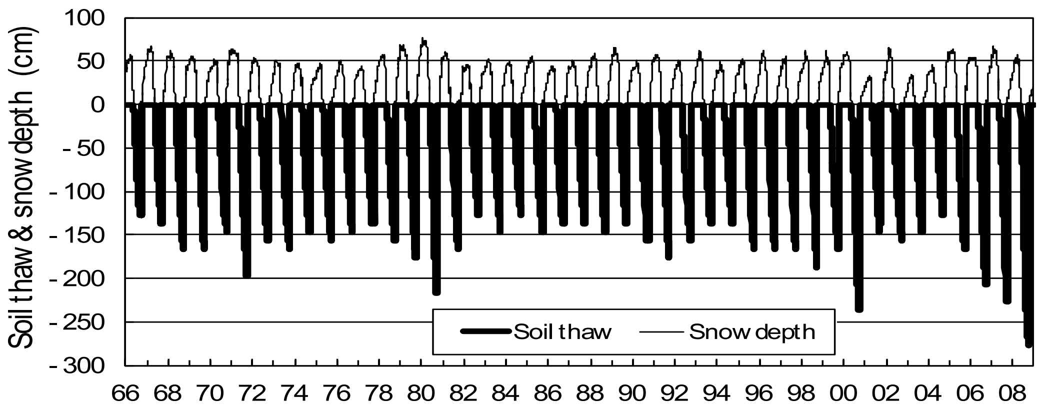

Fig. 3 Time series of estimated snow depth (above 0 cm) and soil thawing depth (below 0 cm) at the SP site using the 2LM model.

over the central Lena River Basin were partly related to cyclone activity. A permafrost-ecosystem model including surface soil freeze-thawing processes indicated an increased thawing depth, *SWC*, *ET*, and *NPP*. The analyses of observed and model-simulated data indicated that the AMTD had increased gradually on a decadal scale and deepened abruptly after 2005. The increased precipitation from late-summer to winter is likely to result in increased soil moisture, soil temperature and AMTD in the region.

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REFERENCES

Brutsaert, W. & Hiyama, T. (2012) The determination of permafrost thawing trends from long-term streamflow measurements with an application in eastern Siberia. *J. Geophys. Res.* 117, D22110, doi:10.1029/2012JD018344.

Dolman, A. J., Maximov, T. C., Moors, E. J., Maximov, A. P., Elbers, J. A., Kononov, A. V., Waterloo, M. J. & van der Molen, M. K. (2004) Net ecosystem exchange of carbon dioxide and water of far eastern Siberian Larch (*Larix cajanderii*) on permafrost. *Biogeosciences* 1, 133–146, doi:10.5194/bg-1-133-2004.

Fedorov, A. N., Gavriliev, P. P., Konstantinov, P. Y., Hiyama, T., Iijima, Y. & Iwahana, G. (2013) Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia. *Ecohydrol.* doi:10.1002/eco.1378.

Huffman, G. J., Adler, R. F., Morrissey, M., Bolvin, D. T., Curtis, S., Joyce, R., McGavock, B. & Susskind, J. (2001) Global precipitation at one-degree daily resolution from multi-satellite observations. *J. Hydrometeorol.* 2, 36–50.

Iijima, Y., Fedorov, A. N., Park, H., Suzuki, K., Yabuki, H., Maximov, T. C. & Ohata, T. (2010) Abrupt increases in soil temperatures following increased precipitation in a permafrost region, central Lena River Basin, Russia. *Permafrost and Periglacial Processes* 21, 30–41.

Kononov, A. V., Maksimov, A. P., Petrov, R. E. & Maximov, T. C. (2012) Key features of soil CO_2 efflux in taiga larch forests of Central and South-Eastern Yakutia. In: *Proceedings of 1st International Conference on Global Warming and the Human-Nature Dimension in Siberia: Social Adaptation to the Changes of the Terrestrial Ecosystem, with an Emphasis on Water Environments*, 7–9 March 2012, Research Institute for Humanity and Nature, Kyoto, Japan, 15–18.

Nakada, A. (2012) Reindeer herding and environmental change in the Tompo district, Sakha Republic. In: *Proceedings of 1st International Conference on Global Warming and the Human-Nature Dimension in Siberia: Social Adaptation to the Changes of the Terrestrial Ecosystem, with an Emphasis on Water Environments*, 7–9 March 2012, Research Institute for Humanity and Nature, Kyoto, Japan, 97–99.

Ohta, T., Hiyama, T., Tanaka, H., Kuwada, T., Maximov, T. C., Ohata, T. & Fukushima, Y. (2001) Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. *Hydrol. Processes* 15, 1459–1476.

Ohta, T., Maximov, T. C., Dolman, A. J., Nakai, T., van der Molen, M. K., Kononov, A. V., Maximov, A. P., Hiyama, T., Iijima, Y., Moors, E. J., Tanaka, H., Toba, T. & Yabuki, H. (2008) Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006). *Agric. For. Meteorol.* 148, 1941–1953.

Onogi, K., Tsutsui, J., Koide, H., Sakamoto, M., Kobayashi, S., Hatsushika, H., Matsumoto, T., Yamazaki, N., Kamahori, H., Takahashi, K., Kadokura, S., Wada, K., Kato, K., Oyama, R., Ose, T., Mannoji, N. & Taira, R. (2007) The JRA-25 reanalysis. *J. Meteorol. Soc. Japan* 85, 369–432, doi:10.2151/jmsj.85.369.

Park, H., Iijima, Y., Yabuki, H., Ohta, T., Walsh, J., Kodama, Y. & Ohata, T. (2011) The application of a coupled hydrological and biogeochemical model (CHANGE) for modeling of energy, water, and CO_2 exchanges over a larch forest in eastern Siberia. *J. Geophys. Res.* 116, D15102, doi:10.1029/2010JD015386.

Tei, S., Sugimoto, A., Yonenobu, H. & Maximov, T. C. (2012) Changes in relationship between larch tree growth and climate in eastern Siberia over past 100 years. In: *Proceedings of 1st International Conference on Global Warming and the Human-Nature Dimension in Siberia: Social Adaptation to the Changes of the Terrestrial Ecosystem, with an Emphasis on Water Environments*, 7–9 March 2012, Research Institute for Humanity and Nature, Kyoto, Japan, 24.

Yamazaki, T., Yabuki, H., Ishii, Y., Ohta, T. & Ohata, T. (2004) Water and energy exchanges at forests and a grassland in eastern Siberia evaluated using a one-dimensional land surface model. *J. Hydrometeorol.* 5, 504–515.

Yamazaki, T., Ohta, T., Suzuki R. & Ohata, T. (2007) Flux variation in a Siberian taiga forest near Yakutsk estimated by a one-dimensional model with routine data, 1986–2000. *Hydrol. Processes* 21, 2009–2015.

Yoshida, A. (2012) Reindeer herding and environmental change in Kobyai and Olenëk districts, Sakha Republic. In: *Proceedings of 1st International Conference on Global Warming and the Human-Nature Dimension in Siberia: Social Adaptation to the Changes of the Terrestrial Ecosystem, with an Emphasis on Water Environments*, 7–9 March 2012, Research Institute for Humanity and Nature, Kyoto, Japan, 92–96.

Zhang, N., Yasunari, T. & Ohta, T. (2011) Dynamics of the larch taiga–permafrost coupled system in Siberia under climate change. *Environ. Res. Letters* 6, 024003, doi:10.1088/1748-9326/6/2/024003.