Northern Research Basins Water Balance (Proceedings of a workshop held at Victoria, Canada, March 2004).
IAHS Publ. 290, 2004

Estimation of annual water balance in Siberian tundra using a new land surface model

HIROYUKI HIRASHIMA[1], **TETSUO OHATA**[1,2],
YUJI KODAMA[1] & **HIRONORI YABUKI**[2]

1 *Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan*
hirasima@bosai.go.jp

2 *Frontier Observational Research System for Global Change, Yokohama 236-0001, Japan*

Abstract Annual water balance was estimated from simulation results of a land surface model that can simulate a full year's hydrological cycle. Simulated results of snow distribution and river runoff agreed with observation results reasonably well. Simulation results suggest that snow redistribution and sublimation by wind are important processes for the water balance of this region. An increase in wind speed in winter increases movement and quantity of drifting snow and snowdrift. These result in the delay of snowmelt, decrease of river runoff in the first half of summer, and an increase in the second half of summer.

Key words annual water balance; climate change; land surface model; Siberia; snow distribution; sublimation

INTRODUCTION

In the Arctic tundra region winter is very long. The duration of snowfall is usually from the middle of September to the end of May. Accumulated snow in winter has an important role for the hydrological cycle in summer. Therefore, the solid water balance in winter is just as important as the liquid water balance in summer when discussing the annual hydrological cycle. In the Siberian tundra region, snow depth was observed at a few points, and it is unlikely that these local point observations are representative of the general snow conditions. Snowpack on the flatlands and mountains is eroded by strong winds, with snow accumulating in depressions; this mechanism results in a non-uniform distribution of snow.

Furthermore, spatial distribution of snow water equivalent is important for modelling the timing, amplitude, and persistence of the snowmelt freshet (Marsh & Pomeroy, 1995). For some time, a sophisticated hydrological model that can simulate hydrological processes through the entire year for variable surface conditions has been needed. A distributed land surface model that can reproduce hydrological terms and thermal conditions in a tundra region for a full year was recently developed by Hirashima (2004). In this study, annual water balance is discussed using simulation results for a small arctic catchment of this land surface model.

LOCATION

The studied watershed (5.5 km^2 in area) is located near Tiksi, eastern Siberia (71°40′N, 128°50′E). It is located near the mouth of the Lena River and 5 km west of the Laptev

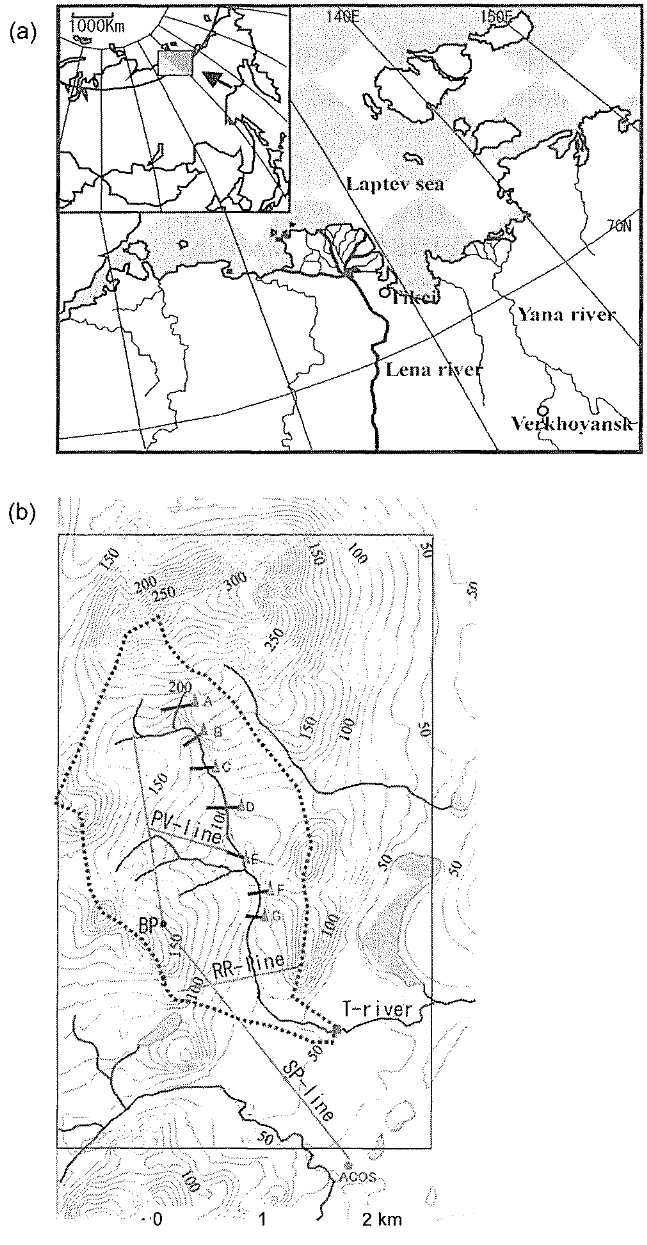


Fig. 1 (a) Location of Tiksi in Lena river delta, (b) The solid square is simulated area. The broken line is the boundary of the watershed.

Sea coast. The location and a map of the watershed are shown in Fig. 1. The simulation was carried out in a wider area than the area of this watershed in order to take snow blowing into and out of the watershed into account. Figure 1(b) shows the area (15 km^2), including the watershed, for which the simulation was carried out.

SETTING

Permafrost completely underlies this region; its thickness reaches over 500 m (Fartyshev, 1993). The maximum active layer depth, observed at the end of August, ranged from 0.2 to 1.2 m and averaged 0.4 m (Watanabe *et al.*, 2003). The vegetation consists mostly of water-tolerant plants such as sedges and mosses, accompanied by lichens and low shrubs. The soil is a multi-layered system consisting of 0–0.2 m of live and accumulated organic material on 0.05–0.3 m of partially decomposed organic matter, over a mineral silt above the bedrock (Watanabe *et al.*, 2000). The topography of this watershed consists of rolling hills with elevations of 200–300 m and gently sloping hillslopes. The bottoms of the slopes form marshy wetlands. The ground surface is covered by snow from October to May. In the melt period (June and July), snow patches are distributed over the watershed.

DATA COLLECTED

The Automatic Climate Observation System (ACOS) station was established at an altitude of 40 m at a flat site (ACOS point in Fig. 1(b)) at the end of August 1997, and most of the input data used in the simulations were obtained from this site. Measured items at the ACOS stations are shown in Table 1 (Sato *et al.*, 2001). These data are included in GAME CD-ROM no. 8, edited by Suzuki & Ohata (2003).

Table 1 List of hydrological and meteorological variables measured and instruments at the ACOS station.

Measurements	Period	Interval	Equipment	Simulation
Air temperature	After Sept 1997	10 min. average	1, 2, 4, 10 m height (HMP-35,Vaisala)	Input data
Relative humidity	After Sept 1997	10 min. average	1, 2, 4, 10 m height (HMP-35,Vaisala)	Input data
Wind speed	After Sept 1997	10 min. average	2, 4, 10 m height (AC860, Makino, Japan)	Input data
Net radiometer	After Sept 1997	10 min. average	1.5 m height (Q7, REBS)	
Upward shortwave radiation	After Sept 1997	10 min. average	1.5 m height (MS-801F, EKO, Japan)	
Downward shortwave radiation	After Sept 1997	10 min. average	1.5 m height (MS-801F, EKO, Japan)	Input data
Upward longwave radiation	After Sept 1997	10 min. average	1.5 m height (MS-201F, EKO, Japan)	
Downward longwave radiation	After Sept 1997	10 min. average	1.5 m height (MS-201F, EKO, Japan)	Input data
Air pressure	After Sept 1997	10 min. average	(PTB100B, Vaisala)	Input data
Soil temperature	After Sept 1997	10 min. average	–0.01, –0.05, –0.10, –0.20, –0.30, –0.48 m depth, Pt100	Validation data
Volumetric water content	After Sept 1997	1 hour	–0.05, –0.15, –0.30 m depth, TDR (TRIME–MUX6, IMKO)	Validation data

Snow distribution data was obtained by helicopter observation, snow surveys on three traverse lines, and surveys of snowdrifts; all were carried out at the end of the winters of 1998/1999 and 1999/2000 to estimate the amount and distribution of snow (Hirashima *et al.*, 2004).

A hydrological station was located at the outlet of the watershed (HS in Fig 1(b)). At the hydrological station, the stream water level was continuously measured by a pressure transducer at 30-min intervals. The continuous river runoff was calculated from the relationship between the water level and river runoff discharge. In order to obtain the water level–river runoff relationship, the river runoff discharge was calculated from manually measured flow rates and cross-sectional area measurements of the stream from data collected several times over the summer season. Snow data and river runoff data was used for validation of the land surface model.

METHODS USED FOR FLUX DETERMINATION

Fluxes and hydrological storage terms are estimated by the land surface model. Figure 2 shows the structure of the land surface model (Hirashima, 2004). The meteorological input data are air temperature, relative humidity, wind speed, wind direction, air pressure and precipitation. Digital Elevation Model (DEM) is used as topographic input data. The upper parts (of Fig. 2) show the energy (left) and hydrological (right) processes in winter, and the lower parts show those in summer. The algorithms for each process had previously been developed independently in various regions of the Arctic and combined in this study. Models developed in the arctic Alaska tundra region (Hinzman *et al.*, 1998; Liston & Sturm, 1998; Zhang *et al.*, 2000) were adopted for various components of the land surface model, except for the snow modelling component (Yamazaki, 2001). The grid scale of the model was set to 100 m. Triangular-shaped elements were used to represent the watershed. Triangular-shaped elements conform more closely to the three-dimensional (3-D) geometry of an irregular watershed and are more efficient for calculating the water flow directions than rectangular elements (Zhang *et al.*, 2000). The surface condition for each element was classified into wetlands with vegetation and dry land with gravel, based on the result of helicopter observation in summer (Sato *et al.*, 2001).

WATER BALANCE CALCULATION

In winter, solid water is supplied by snowfall. When blowing and drifting snow occurs, snow particles travel into and out of the watershed: this is coupled with sublimation from both the snow surface and blowing snow particles which decrease solid water storage of the watershed. The equation of solid water balance is:

$$P_s + F - Q_{sub} - M = \Delta Sn \tag{1}$$

where P_s is snowfall (mm), F is the difference between the amount of blowing snow entering (F_{in}) and leaving (F_{out}) the watershed (F_{in}–F_{out} (mm)), Q_{sub} is sublimation (mm), M is snowmelt (mm), and ΔSn is the change in snow water equivalent in the

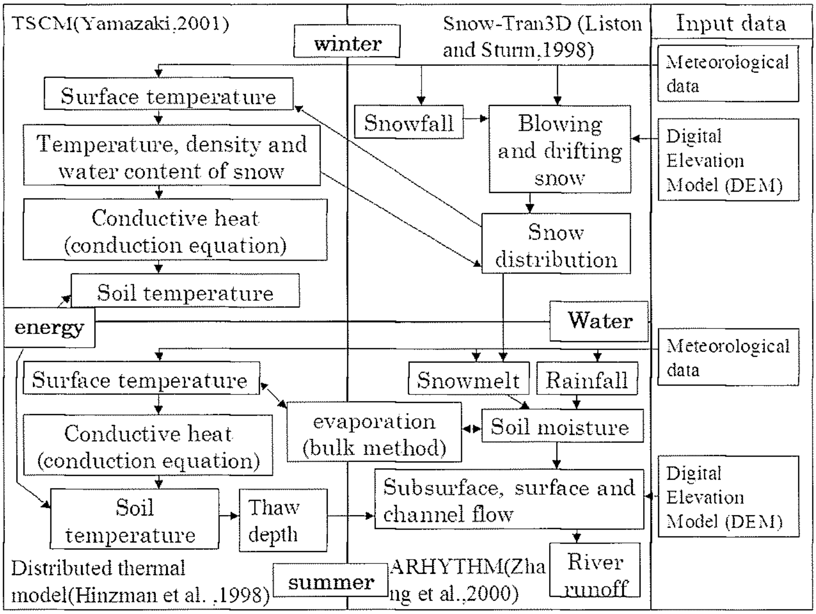


Fig. 2 Outline of land surface model. Diagram of processes and pathways of land surface model.

watershed (mm). Accumulated snow contributes to the liquid water balance in summer. The equation of liquid water balance is:

$$P + M - E - R = \Delta S \tag{2}$$

where P is liquid precipitation (mm), M is snowmelt (mm), E is evaporation (mm), R is river runoff (mm), and ΔS is water storage (mm). These terms of water balance were estimated from simulation results using the land surface model.

Table 2 shows monthly water balance results from June 1998 to August 2000. Snow accumulation starts in September and continues into May. A part of the accumulated snow is sublimated. For this catchment, the amount of snow gained (F_{in}) by wind redistribution is greater than that lost (F_{out}): consequently, F is positive, meaning that this watershed is a sink for blowing and drifting snow. The estimation of water balance suggests that 40% of winter precipitation was sublimated. Increase and decrease of solid water lead to significant changes in the supply of snowmelt water to the watershed. Therefore, snow redistribution and sublimation are important processes for water balance. At the end of May, snowmelt was initiated: however, no runoff was generated at first. In June, additional snow melted, and most of this snowmelt water was discharged as river runoff. In July and August, rainfall is a major source for liquid water in the watershed. The liquid water leaves the watershed as both evaporation and river runoff.

Tables 3 and 4 show annual water balance for liquid water and solid water, respectively. In 1999, since air temperature was high (mean air temperatures in summer (from 1 June to 20 September) are 5.3, 7.2 and 5.0°C in 1998, 1999 and 2000, respectively), evaporation was also large. These circumstances resulted in small river

Table 2 Simulated water balances in the watershed for each month (from June 1998 to August 2000).

	Water balance elements for liquid water					Water balance elements for solid water				
	M (mm)	P (mm)	E (mm)	R (mm)	ΔS (mm)	P_S (mm)	F (mm)	Q_{sub} (mm)	M (mm)	ΔS (mm)
Jun-98	87.6	20.1	14.7	89.6	3.4	6.2	0.0	0.0	87.6	–81.4
Jul-98	36.9	44.1	30.0	66.8	–15.8	0.0	0.0	0.0	36.9	–36.9
Aug-98	0.0	35.9	20.6	6.8	8.5	0.0	0.0	0.0	0.0	0.0
Sep-98	0.9	1.0	7.3	1.3	–6.7	4.6	0.0	2.3	0.9	1.4
Oct-98	0.0	0.0	0.0	0.0	0.0	7.4	0.2	3.0	0.0	4.6
Nov-98	0.0	0.0	0.0	0.0	0.0	13.5	–0.3	2.2	0.0	11.0
Dec-98	0.0	0.0	0.0	0.0	0.0	3.7	0.9	4.1	0.0	0.5
Jan-99	0.0	0.0	0.0	0.0	0.0	52.0	7.4	14.1	0.0	45.3
Feb-99	0.0	0.0	0.0	0.0	0.0	22.8	5.4	11.1	0.0	17.1
Mar-99	0.0	0.0	0.0	0.0	0.0	5.7	–0.1	0.4	0.0	5.2
Apr-99	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.1	0.0	1.7
May-99	9.8	0.8	2.1	0.6	7.9	7.3	0.1	3.0	9.8	–5.4
Jun-99	79.3	14.8	30.1	71.9	–7.9	0.2	0.0	0.1	79.3	–79.2
Jul-99	1.4	28.0	34.1	9.7	–14.4	0.0	0.0	0.0	1.4	–1.4
Aug-99	0.0	65.7	23.2	21.1	21.4	0.0	0.0	0.0	0.0	0.0
Sep-99	5.4	14.7	8.4	3.6	8.1	23.5	0.0	5.9	5.4	12.1
Oct-99	0.0	0.0	0.0	0.0	0.0	34.9	1.2	17.7	0.0	18.5
Nov-99	0.0	0.0	0.0	0.0	0.0	18.5	6.4	11.7	0.0	13.3
Dec-99	0.0	0.0	0.0	0.0	0.0	27.0	–0.6	14.9	0.0	11.5
Jan-00	0.0	0.0	0.0	0.0	0.0	89.0	12.4	35.6	0.0	65.8
Feb-00	0.0	0.0	0.0	0.0	0.0	56.0	0.8	20.2	0.0	36.6
Mar-00	0.0	0.0	0.0	0.0	0.0	22.9	–1.7	6.0	0.0	15.3
Apr-00	0.0	0.0	0.0	0.0	0.0	15.6	–0.8	4.3	0.0	10.4
May-00	35.1	2.1	2.7	24.1	10.4	16.3	3.0	6.4	35.1	–22.2
Jun-00	109.3	56.9	29.0	129.1	8.1	6.4	0.0	0.0	109.3	–102.9
Jul-00	43.0	56.7	21.1	89.9	–11.3	0.0	0.0	0.0	43.0	–43.0
Aug-00	11.9	60.0	18.6	36.5	16.8	0.6	0.0	0.0	11.9	–12.5

runoff in 1999. In 2000, the precipitation amount was large in both winter and summer. This large amount of water contributed not to an increase in evaporation, but to an increase in river runoff.

Table 3 Estimation of water balance for liquid water.

	M (mm)	P (mm)	E (mm)	R (mm)	ΔS (mm)
1998	124.5	100.1	65.3	163.2	–3.9
1999	91.4	110.3	96.8	104.6	0.3
2000	204.7	190.4	79.8	283.2	32.1

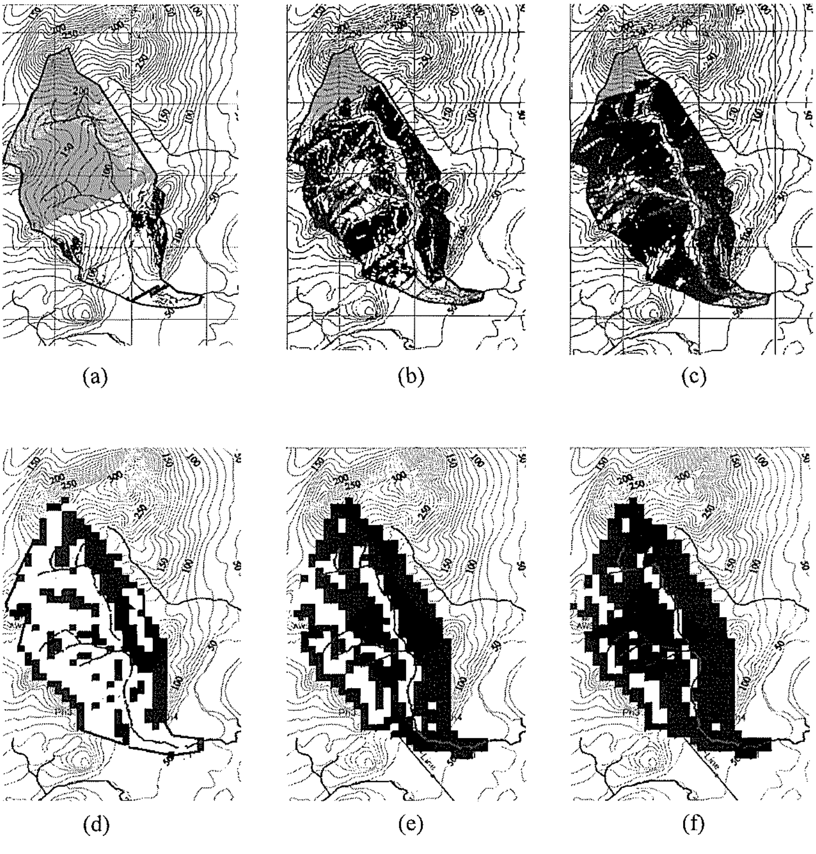
Table 4 Estimation of water balance for solid water.

	P_S (mm)	F (mm)	Q_{sub} (mm)	M (mm)	ΔS (mm)
1998/99	119.0	13.6	40.4	91.4	0.8
1999/00	310.7	20.7	122.7	204.7	2.9

DISCUSSION OF STRENGTHS AND WEAKNESSES OF WATER BALANCE DATA AND CALCULATIONS

The strength of the estimation using the land surface model is that annual water balance can be estimated from meteorological and topographical data, even if the hydrological data was not obtained completely. The simulated results were validated by comparing with the observed data for snow and river runoff. Comparisons of snow distribution and river runoff are shown in Figs 3 and 4, respectively. Mean snow water equivalent, snow area, and main snowdrift distribution in the watershed model agreed well with the results of observations.

Therefore, it is demonstrated that this model can sufficiently reproduce snow distribution. Simulation results of river runoff during the melt periods agreed with observation results fairly well. However, simulated river runoff is underestimated in August. Runoff ratios above 1.0 were observed in the measurements of late August


(a) (b) (c)

(d) (e) (f)

Fig. 3 Snow distributions obtained by helicopter observation. White shows snow cover, black snow free, and gray are areas of missing data. (a) on 16 May 2000, (b) on 26 May 2000, (c) on 5 June 2000. (d), (e) and (f) show results of simulation at the same date as (a), (b) and (c), respectively.

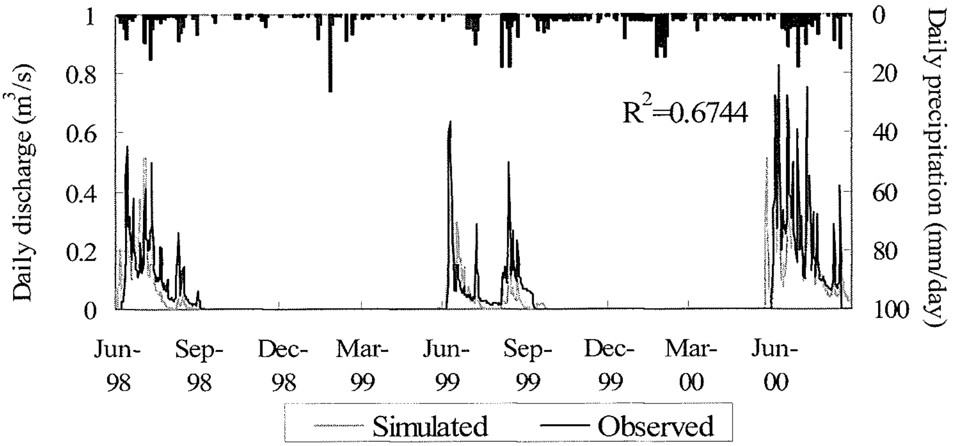


Fig. 4 Comparison of simulated and observed river runoff.

1999 (Ishii, 2001). Those cases occurred mainly due to an increase in baseflow. The reason why the baseflow increases in late August is still unsolved. It also produced a discrepancy between modelled and measured runoffs.

This model can simulate a change in the response of the hydrological cycle by altering meteorological conditions through sensitivity analysis. Sensitivity experiments for air temperature, precipitation and wind speed were carried out. Results of air temperature and precipitation changes were similar to those of previous studies (Kane *et al.*, 1991; Hinzman & Kane, 1992; Lynch *et al.*, 2001). The sensitivity experiment of wind speed suggested that an increase in wind speed in winter increases blowing and drifting snow and snowdrift amount, and results in the delay of snowmelt, and a decrease of river runoff in the early half of summer and an increase in the latter half of summer (Hirashima, 2004).

CONCLUSION

Annual water balance was estimated from simulation results of a land surface model that can simulate a full-year hydrological cycle. Simulated results of snow distribution and river runoff agreed with observation results fairly well. The quantity of snow that enters into the watershed by blowing and drifting snow is larger than the amount that leaves. These findings suggest that this watershed is a sink for blowing and drifting snow. The estimation of water balance also suggests that 40% of winter precipitation was sublimated. Therefore, snow redistribution and sublimation are important processes for water balance calculation. At the end of May, snowmelt was initiated. Snowmelt water is a major source for liquid water in June, whereas rainfall is a major source in the watershed for the remainder of the warm season.

An increase in wind speed in winter increases blowing and quantities of drifting snow and snowdrift, and results in the delay of snowmelt, and a decrease in river runoff in the early half of summer and an increase in the later half of summer.

REFERENCES

Fartyshev, A. I. (1993) Peculiarities of the coastal-shelf cryolitozone of the Laptev Sea. Novosibirsk, Nauka, 136.

Hinzman L. D. & Kane, D. L. (1992) Potential response of an Arctic watershed during a period of global warming. *J. Geophys. Res.* **D3**, 2811–2820.

Hinzman L. D., Goering, D. J. & Kane, D. L. (1998) A distributed thermal model for calculating soil temperature profiles and depth of thaw in permafrost regions. *J. Geophys.* Res. **D22**, 28975–28991.

Hirashima, H. (2004) Influence of climatic change to hydrological cycle in arctic tundra using new land surface model. Doctoral thesis, Hokkaido University, Hokkaido, Japan.

Hirashima, H. T., Ohata, Y., Kodama, H., Yabuki, N., Sato, N. & Georgiadi, A. (2004) Non-uniform distribution of tundra snow cover in eastern Siberia. *J. Hydromet.* **5**(3), 373–389.

Ishii, Y., Nomura, M., Kodama, Y., Sato, N. & Yabuki, H. (2001) Runoff characteristics of a small stream in the Siberian Tundra and their seasonal changes. In: *GEWEX in Asia and GAME* (Proc. Fifth Int. Study Conf.), 670–673.

Kane, D. L., Hinzman, L. D. & Zarling, J. P. (1991) Thermal response of the active layer in permafrost environment to climatic warming. *Cold Res. Sci. Technol.* **19**(2), 111–122.

Liston, G. E. & Sturm, M. (1998) A snow-transport model for complex terrain. *J. Glaciol.* **44**, 498–516.

Lynch, A. H., Mcllwaine, S., Beringer, J. & G. Bonan, G. B. (2001) An investigation of the sensitivity of a land surface model to climate change using a reduced form model. *Clim. Dyn.* **17**, 643–652.

Marsh, P., & Pomeroy, J. W. (1995) Water and energy fluxes during the snowmelt period at an Arctic treeline site, In: *International GEWEX Workshop on Cold Season/Region Hydrometeorology.* International GEWEX Project Office Publ. Series no. 15. 197–201

Sato, N., Ishii, Y., Kodama, Y., Nomura, M., Ishikawa, N. & Kobayashi, D. (2001) Characteristics of summer water balance in eastern Siberian tundra watershed. *Polar Met. Glaciol.* **15**, 91–106.

Suzuki, R. & Ohata, T. (2003) Dataset for water & energy cycle in Siberia Version 1. Produced by GAME-Siberia & Frontier Observational Research System for Global Change. GAME CD-ROM no. 8. See URL: http://www.suiri.tsukuba.ac.jp/Project/game/CD-ROM.html#siberia1.

Watanabe, K., Mizoguchi, M., Kiyosawa, H. & Kodama, Y. (2000) Properties and horizons of active layer soils in tundra at Tiksi, Siberia. *J. Japan Soc. Hydrol. Water Resour.* **13**, 9–16 (in Japanese with English summary).

Watanabe, K., Kiyosawa, H., Fukumura, K., Ezaki, T. & Mizoguchi, M. (2003) Spatial and temporal variation in thaw depth in Siberian tundra near Tiksi. In: *Permafrost* (Proc. Eighth Int. Conf., Zurich), 1211–1216.

Yamazaki, T. (2001) A one-dimensional land surface model adaptable to intensely cold regions and its applications in eastern Siberia. *J. Met. Soc. Japan* **79**(6), 1107–1118.

Zhang, Z., Kane, D. L. & Hinzman, L. D. (2000) Development and application of a spatially-distributed Arctic hydrological and thermal process model (ARHYTHM). *Hydrol. Processes* **14**, 1017–1044.