Soil–Vegetation–Atmosphere Transfer Schemes and Large-Scale Hydrological Models (Proceedings of a symposium held during the Sixth IAHS Scientific Assembly at Maastricht, The Netherlands, July 2001). IAHS Publ. no. 270, 2001.

Hydrological modelling of river ice processes in cold regions

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Abstract River ice covers for the Lena River basin are simulated using a simple accumulated degree-day method from October 1986 to September 1987, which is equal to the period of hydrological modelling of the basin without river ice process. The forcing data are routine daily meteorological data and river water temperature data. The result shows that estimated ice cover breakup dates are consistent with those observed for 60% of the 51 river sections in the Lena River basin. It is expected that the simulations of hydrological processes in cold regions will become more reasonable by linking ice cover estimates into river routing models.

Key words Lena River basin, Siberia; hydrological modelling; river ice growth and decay; ice cover breakup date

INTRODUCTION

Freshwater empties into the Arctic Ocean mainly from four large rivers, the Obi, Yenisei and Lena rivers in Siberia and the Mackenzie River in Canada. All of these river basins are widely covered by seasonal snowcover and are underlain by permafrost. Since the variation of freshwater inputs changes the saline concentration and hydrological and thermal conditions of the Arctic Ocean, it is clear that the freshwater plays an important role in the Arctic climate and water cycle studies. The GAME-Siberia project, was established to understand the mechanism of energy and water cycle for the Siberian region, and the Lena River basin was selected as the main field site for this study. Using hydrological data of the Lena River, it can be found that the flood peak appears in spring, despite the fact that a great number of rainfall events occur in the summer season. To understand the hydrological processes of the Lena River, a hydrological study (Ma *et al.*, 2000) was made using a combined model. Since river-freezing processes were not considered in that study, the resulting calculated floods were earlier than those observed.

There are two basic approaches to predicting river ice-cover events (Greene, 1981). One is statistical, extrapolating from past records to predict future events. On the other hand, theoretical models based on heat balance, integrate the understanding of all relevant processes such that models simulate both the intermediate steps and the eventual outcome. However, this method requires more detailed observed environmental data to simulate. The two methods mentioned above have been applied to the upper St Lawrence River (Greene, 1981). In this study, a simple, accumulated degree-day method, was used to estimate ice-cover growth and decay events using daily routine meteorological data and applied to the Lena River. The estimated duration is from October 1986 to September 1987, the same as that for hydrological modelling (Ma *et al.*, 2000).

METHOD

Assuming that the heat flux from the river bed and heat movement from upstream to downstream need not to be considered for wide and deep rivers, the transfer of heat in the vertical direction is from the river water through the ice and snow layer to the air (Greene 1981). Based on the energy balance, the heat flux between the ice and the water is expressed as:

$$Q_i - Q_w = \rho_i \lambda \frac{\mathrm{d}Z_i}{\mathrm{d}t} \tag{1}$$

where Q_i is the flux of heat within the ice layer and Q_w is the flux from the water to the ice, ρ_i is ice density, λ is the latent heat of fusion and Z_i is the ice thickness. Under equilibrium conditions, when no flux divergence is taking place, the temperature gradient through the ice layer is constant. So Q_i can be defined as:

$$Q_i = \frac{K_i(T_m - T_s)}{Z_i} \tag{2}$$

where T_s and T_m are the temperatures at the top and bottom of the ice layer, respectively, and K_i is thermal conductivity. Similarly, Q_w is expressed by:

$$Q_w = h_i(T_w - T_m) \tag{3}$$

$$h_i = B_i \frac{U_w^{\ 0.8}}{Z_w^{\ 0.2}} \tag{4}$$

where B_i is an experimentally derived coefficient, T_w is the water temperature, U_w is velocity of flow and Z_w is water depth.

Ice growth

It is difficult to describe ice growth under all but the most simplified conditions. A common set of boundary conditions is that air temperature is equal to the surface temperature and does not vary with time. Turbulent transfer between the water and ice is neglected and the snow layer is not present. Therefore, equation (1) can be rewritten as:

$$\rho_i \lambda \frac{\mathrm{d}Z_i}{\mathrm{d}t} = \frac{K_i(T_m - T_s)}{Z_i} \tag{5}$$

Integration over time leads to the classic Stefan solution, and:

$$Z_i = \left(\frac{2K_i}{\rho_i \lambda}\right)^{0.5} \left[\int_0^t (T_m - T_s)\mathrm{d}t\right]^{0.5} \tag{6}$$

This is a simple method of accumulated degree-day for ice cover growth processes.

Ice decay

Once water temperature starts to rise, the effect of Q_w is significant in equation (1). An integrated form of equation (1) developed by Ashton (1973), can be rewritten as follows:

$$\Delta t = \frac{-\rho_i \lambda (Z_t - Z_0)}{Q_w} - \frac{K_i \rho_i \lambda (T_m - T_s)}{(Q_w)^2} \ln \left[\frac{1 - \dfrac{Q_w Z_t}{K_i (T_m - T_s)}}{1 - \dfrac{Q_w Z_0}{K_i (T_m - T_s)}} \right] \tag{7}$$

where Δ_t is interval of time, Z_t and Z_0 are the final and initial value of ice thickness at the time step period. Similarly, setting the air temperature equal to the surface temperature, the value of ice depth at the end of time step can be calculated.

APPLICATION AND RESULTS

The simple method was applied to the Lena River basin. The GAME-Siberia project measured river ice thickness and water temperature for 51 sections of the river over the Lena River basin. Those sections are used in the study to check the method. Considering the hydrological modelling of the Lena River basin by Ma *et al.* (2000), the duration of the application for river ice cover testing was set to be the same period (October 1986–September 1987). Forty meteorological stations were used to derive the forcing data. It was assumed that water depth was 10 m and velocity was 0.4 m s^{-1} for all rivers. Table 1 shows the result of estimated river ice cover breakup date for all river sections. Three types of estimates are noted: O is estimated date for the observed ten days; E represents the estimated date earlier than the observed one; and L is the estimated date later than observed one. For about 60% of all river sections, the estimated dates are consistent with the observed ones. Figure 1 shows the inter-relationship of observed and estimated breakup dates for all sections. Most vary by less than ten days. On the other hand, the estimated date is later than observed for most of the plots after 20 May. This is due to the river condition being considered a simple and static state in this study. In fact, the breakup date for the river is controlled not only by the local meteorological condition, but also by the thermal and hydraulic conditions of the upper stream. Sometimes, it is also influenced by manmade conditions. Especially, to reduce flooding, the river ice cover will be intentionally broken-up during the river ice melting period. Therefore, it is reasonable that the estimates of river ice breakup date are later than the observed dates during this season.

Table 1 Estimated river ice cover thickness and breakup date at the 51 river sections over the Lena River basin in 1987.

No.	Station code	Maximum thickness (cm) (cal.)	Ice-cover breakup date: Observed	Calculated	Remark*
1	3003	127.3	10 May	2 May	O
2	3005	135.6	30 April	28 April	O
3	3021	148.7	30 April	5 May	L
4	3029	148.6	10 May	5 May	O
5	3036	157.3	20 May	5 May	E
6	3042	180.2	20 May	21 May	O
7	3057	137	20 April	24 April	O
8	3065	127.3	10 May	2 May	O
9	3074	142.1	10 May	4 May	O
10	3087	148.7	10 May	5 May	O
11	3096	146.2	20 May	26 April	E
12	3100	161.1	10 May	5 May	O
13	3106	152.5	20 April	4 May	L
14	3122	161.1	30 April	5 May	L
15	3130	146.2	10 May	26 April	E
16	3145	149.3	10 May	4 May	O
17	3153	151.8	10 May	5 May	O
18	3155	153.7	10 May	4 May	O
19	3157	157.3	20 May	5 May	E
20	3159	157.3	10 May	5 May	O
21	3160	157.3	10 May	5 May	O
22	3169	157.2	20 May	6 May	E
23	3178	157.3	20 May	5 May	E
24	3180	157.3	10 May	5 May	O
25	3198	152.5	10 May	4 May	O
26	3202	157.3	10 May	5 May	O
27	3206	167	N/A	7 May	
28	3208	176.4	10 May	27 May	L
29	3210	180.2	20 May	21 May	O
30	3212	180.2	N/A	21 May	
31	3217	187	N/A	21 May	
32	3218	157.2	10 May	6 May	O
33	3219	169.8	10 May	20 May	L
34	3234	159.3	10 May	6 May	O
35	3246	159.1	N/A	6 May	
36	3252	159.1	10 May	6 May	O
37	3258	159.1	20 May	6 May	E
38	3261	169.8	10 May	20 May	L
39	3271	157.2	10 May	6 May	O
40	3273	176.9	20 May	28 May	L
41	3277	176.9	31 May	28 May	O
42	3280	195.6	N/A	29 May	
43	3291	169.8	20 May	20 May	O
44	3292	180.2	10 May	21 May	L
45	3293	195.6	N/A	29 May	
46	3307	178.9	N/A	21 May	
47	3321	167.9	20 May	6 May	E
48	3329	181	10 June	28 May	E
49	3306	164.6	N/A	7 May	
50	3367	175.3	31 May	25 May	O
51	3397	193.7	31 May	26 June	L

* O: estimated date for observed 10 days; E: estimated date earlier than observed; L: estimated date later than observed; N/A: data not available.

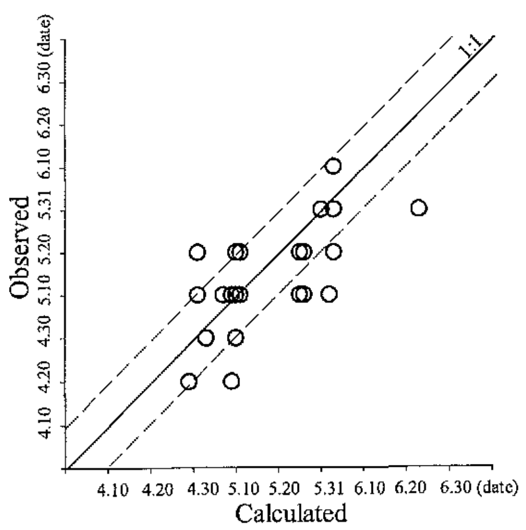

Fig. 1 Estimation of river ice breakup date *vs* that observed for the Lena River Basin between 10 April and 30 June 1987.

CONCLUSIONS

River ice is a general phenomenon in high latitudes. The breakup date influences river discharge during the river ice melting season. Therefore, it is very important to estimate ice cover processes for hydrological modelling in cold regions. In this study, a simple method, accumulated degree-day, was applied to the Lena River basin from October 1986 to September 1987. The results show that for most of the sections of rivers in the Lena River basin, the date of ice break up could be modelled to a good approximation. Although the physical processes of river ice are not known in detail through the method, it is a simple and convenient way to indicate river ice breakup based on air and water temperatures. It can be expected that the hydrograph of the Lena River can be more reasonably estimated if the river ice breakup information is considered in river routing models.

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