Calculation and analysis of Yukon River heat flux

DAQING YANG[1], PHILIP MARSH[1] & SHAOQING GE[2]
1 National Hydrology Research Centre, Environment Canada, 11 Innovation Boulevard, Saskatoon SK S7N 3H5, Canada
daqing.yang@ec.gc.ca
2 Civil and Environmental Engineering Department, Virginia Tech, 351 ICTAS II, Blacksburg, Virginia 24061, USA

Abstract This paper analyses long-term discharge and water temperature records collected near the basin outlet of the Yukon River. It defines the seasonal cycles of discharge, water temperature (WT), and heat flux (HF) for the basin. The Yukon River has low flows in winter and high discharge in summer, with the peak flood in June (about 16 000 m^3/s) due to snowmelt runoff. WT near the basin outlet ranges from 4 to 18°C over the open water season, with the highest peak in mid-summer. The Yukon River transports a large amount of heat to the ocean system, particularly during June and July (about 2380–2500 × 10^9 MJ for June and July). These results are useful for climate/ocean model development, and hydrology/climate change research over the northern regions.
Key words streamflow; water temperature; heat flux; Yukon River

INTRODUCTION

Discharge and water temperature are important hydrologic variables, since they directly reflect physical and thermal features of rivers. River thermal conditions affect biological and ecological processes over the basin and near the coastal regions/shorelines. Discharge, water temperature, and geochemistry data collected near the river mouths are particularly important as they represent the mass and thermal influxes to the ocean system. It is critical to examine the fundamental characteristics of discharge and water temperature and geochemistry at the basin outlet, and document any significant variations and changes over space and time. Holmes *et al.* (2012) and Tank *et al.* (2012) recently studied the seasonal and annual fluxes of nutrient and organic matter, and DIC flux, respectively, from the major Arctic rivers to the Arctic Ocean. Lammers *et al.* (2007) determine the heat flux to the Arctic Ocean from the large Siberian rivers. Liu *et al.* (2005) and Yang *et al.* (2005) carried out systematic analyses of long-term water temperature records for the Lena basin, and discovered significant changes in river thermal conditions due to climate warming and human impacts, particularly dam regulations over Siberia (Ye *et al.*, 2003; Yang *et al.*, 2004a,b).

Little is known about the heat flux from the large northern rivers in North America. This limits our understanding of total northern river heat transport to the Arctic Ocean. To fill this knowledge gap, this study analyses long-term downstream discharge and water temperature data for the Yukon River. This river has been chosen because of its distinct cryospheric environments, unique climatic and hydrological features and recent changes, minor human impact with little regulation, and close interactions and linkages to the northern seas via freshwater, sediment, and heat transports. The main objectives of this study are to define discharge and water temperature regimes, and to quantify heat flux from the Yukon River into the ocean. The methods and results of this study are useful in understanding hydrologic and climatic linkages and variations over northern regions. They are also important for regional hydrology and climate change investigations.

BASIN, DATA, AND METHOD

The Yukon River (Fig. 1) is located in northwest Canada and central Alaska. It is the 4th largest river in North America, with an area of 857 300 km^2 and annual flow of 203 km^3 to the Bering Sea. The Yukon River begins at the Llewellyn Glacier in Canada and flows through the Teslin River; it continues generally westward through Alaska and empties into the Bering Sea. There are three basic runoff patterns over the basin: lake, snowmelt, and glacier runoff (Brabets *et al.*, 2000). There are no large dams in this basin. The basin is underlain by 16% continuous permafrost and

40% discontinuous permafrost (Brown *et al.*, 1997). Glacier and wetland cover about 1% and 29% of the basin, respectively. The Yukon basin has 20 eco-regions, with the most dominant eco-regions being the interior forested lowlands/uplands and the interior highlands. Yukon basin mean annual air temperature is about –5°C with annual total precipitation of 380 mm. The US Geological Survey and Environment Canada maintain a hydrologic network in the Yukon River basin. The Pilot Station (61.9°N, 162.9°W) is located downstream on the main river valley; this is a gauging site closest to the basin outlet, controlling a drainage area of 831 400 km^2. In this study, monthly discharge data during 1975–2010, and water temperature records collected at this location during 1975–2012 have been obtained from the USGS web site (http://www.usgs.gov/) and the UN Environment Programme Global Environment Monitoring System.

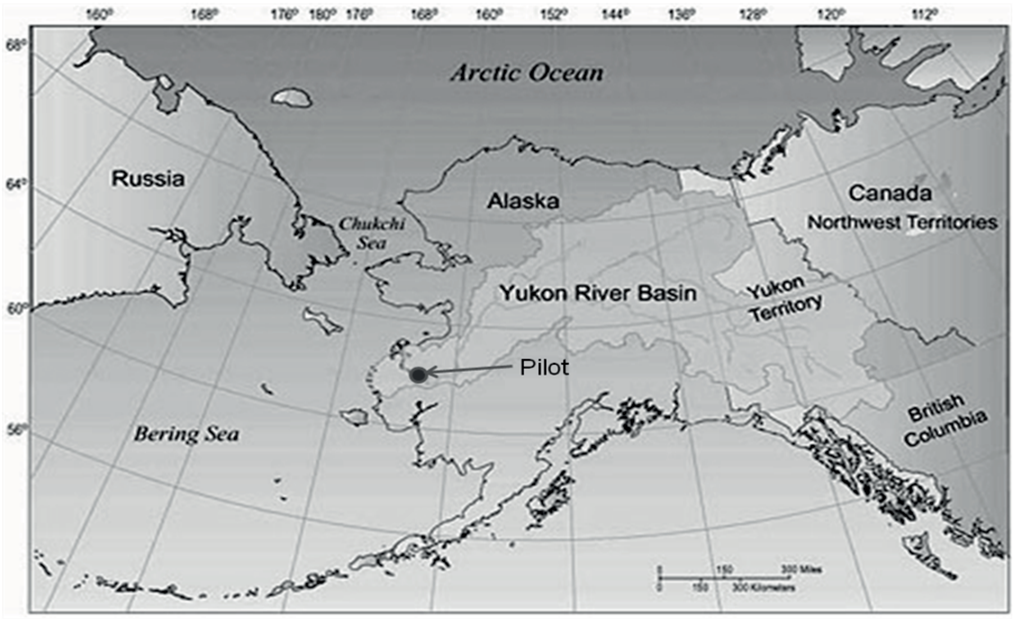

Fig. 1 Yukon River watershed and location of the Pilot Station near the basin outlet.

Water temperatures (WT) data have also been collected regularly by government agencies over the basin at various locations and times (dates) of sediment sampling and during the discharge measurements. The sampling frequency varies from 5 to 35 times/year over the years, but most often in the open water season. Many samples were taken for a given location, although not on the fixed dates. Water temperature was instantaneously measured at 0–1 m below the water surface (on average around 11:30 h local time, with a standard deviation of 2 hours), using a mercury thermometer, battery thermometer, or a conductivity temperature (battery) meter with a precision of 0.1°C (van Vliet *et al*., 2011). For this study, all available WT data collected at the Pilot Station during 1975–2012 have been acquired from the UN Environment Programme Global Environment Monitoring System (GEMS/Water) and used for the analyses.

In this study, we use most recent monthly flow records to calculate the long-term mean flows and to detect its changes with a linear trend analysis and statistical significance test. To determine the river heat flux, mean monthly water temperature is also necessary. The GEMS program provides online tools and displays statistical summaries for many variables, including the mean WT, i.e. an aggregated average of all data available in a given month. WT varies over the open water season, particularly in the early summer of the northern regions (Liu *et al*., 2005, Yang *et al*., 2005). Liu *et al.* (2005) determined monthly mean water temperatures over the Lena basin by averaging two observations taken on the 10th and 20th days of a month. They also compared various methods to calculate the monthly means, and found their method representative and conservative, since it did not overestimate the mean temperatures during the open water season. In this study, we use the aggregated average of all WT data collected on the different dates in a month. This may not be the most accurate way to determine the monthly mean WT. But given the fact that large numbers of water samples (up to 150 observations for June and total of 680 measurements over the open water season at the Pilot Station during 1975–2012) were taken within a given month over the past 30 years, this method is probably appropriate for our analysis to focus on the determination of the seasonal cycles of water temperature and heat flow.

Once the long-term means of monthly discharge and water temperatures have been determined, we calculate the heat flux/transport from the watersheds (Elshin, 1981):

$$H = C_p.\ \rho.Q.T.n \qquad (1)$$

where H is the total heat flux in a given month (10^6 MJ), Q and T are the monthly mean discharge (m^3/s) and the monthly mean stream temperature (°C) at the basin outlet, and n is the number of days in a given month. Although variable with respect to temperature, specific heat and density of river water are set to a fixed value of C_p = 4.184 J/(°C g) and $\rho = 1 \times 10^{12}$ kg/ km^3. Using the Celsius temperature scale here means the H is not an absolute energy flux, but relative to the freezing point of water (Lammers *et al.*, 2007).

RESULTS AND DISCUSSIONS

The Yukon River has low flows during November to April, and high discharge from May to October, with the peak flood in June mainly due to snowmelt floods and ice jams (Fig. 2). The annual mean flow is about 6400 m^3/s. In order to understand the recent changes in basin hydrology, we carry out trend analyses of the monthly flow data up to 2010. The results demonstrate that baseflows during September to April change little. Flows in May strongly increase by 60%, while discharge decreases by 5–15% during June, July, and August (Fig. 2). Flow changes over May to August are statistically significant at 90–95% confidence. The increase in May and decrease in June indicate a shift in discharge pattern, i.e. toward early floods due to early snowmelt in response to climate warming over the northern regions. This result is consistent with other studies of the large Russian rivers (Ye *et al.*, 2003; Yang *et al.*, 2005).

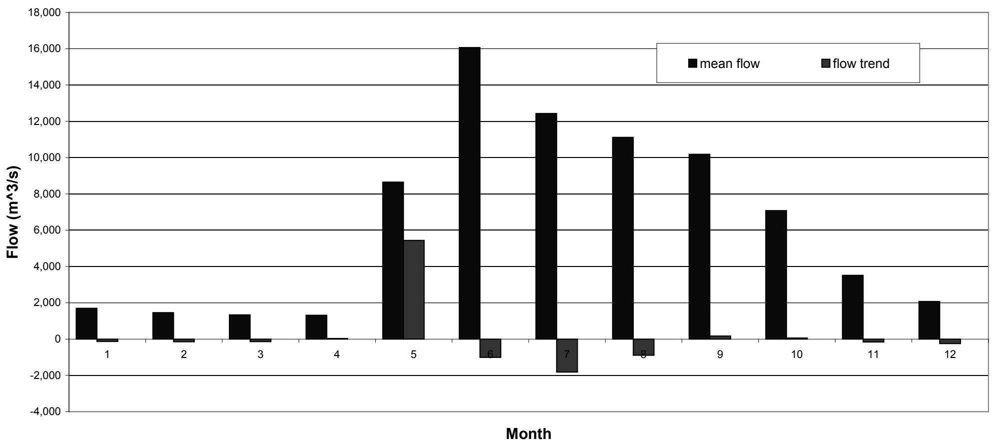

Fig. 2 Yukon River long-term mean monthly flow and trend during 1975–2010.

Ice cover exists in the basin during November to April. Field observations in the ice periods show WTs very close to 0°C. River ice breaks up in late April to early May over the basin. During the open water season (May to October), the WT pattern is distinct (Fig. 3). The long-term mean temperatures in May are about 5°C, and they warm up to 12–14°C in June, and reach the peak (16–18°C) in July. Mean WTs cool down to about 15°C in August, 9°C in September, and 3–5°C for October. The annual mean WTs are about 5.1°C over the Yukon River.

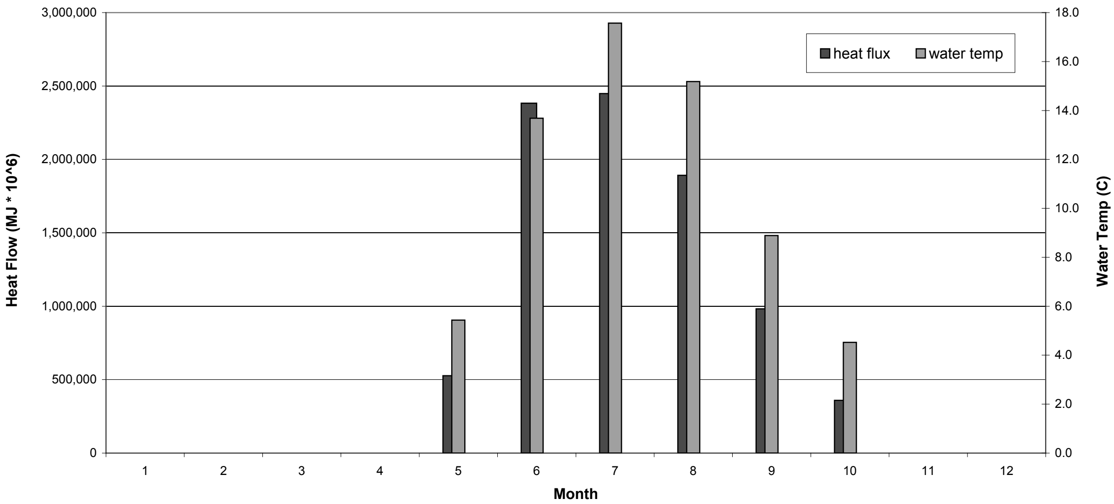

Fig. 3 Yukon River long–term mean monthly water temperature during 1975–2010 and mean heat flux.

Open water season heat flux calculations for the basin are summarized in Fig. 3. The mean monthly values are low in May (about 527 × 10^9 MJ) and very high (2380–2500 × 10^9 MJ) for June and July; they then decrease to 1800 to 300 × 10^9 MJ) from August to October. The total HF is about 8590 × 10^9 MJ from May to October. It is useful to document the difference in seasonal cycles among discharge, water temperature and heat flux over the northern regions. Liu *et al.* (2005) found that Lena River discharge peaks in June, and the highest water temperature coincides with the maximum heat flux in July. The Yukon discharge peaks in June and the warmest WT occurs in July, while the HF is highest for both June and July (Figs 2 and 3). This result is different from the Lena River (Liu *et al.,* 2005) and similar to the Russian Arctic regions (Lammers *et al.,* 2007).

CONCLUSIONS

Lammers *et al.* (2007) determined the energy transport of the large rivers over the Russian Arctic. Little is known of the heat flux from the large North American northern rivers to the Arctic Ocean. This study, based on the analyses of long-term data, clearly defines the seasonal cycles of discharge, water temperature, and energy flux for the Yukon River. The results of this work, when combined with other analyses, such as Lammers *et al.* (2007) and Liu *et al* (2005), enable us to estimate the main river heat flux to the Arctic Ocean and surrounding seas. The Yukon River has low flows in winter and high discharge in summer, with the peak floods in June due to snowmelt runoff. Yukon River WT is about 4–18°C over the open water months. The Yukon River transports a large amount of heat in the mid summer, with the maximum in June and July; the peak HF in June is mainly caused by the higher WT.

Due to the limited WT observations over the northern regions in North America, it is difficult to examine variability and change in thermal conditions. Recent studies reveal many changes in climate and hydrology over the northern regions. For instance, Yukon River annual flow at the basin outlet increased by 8% over the past 40 years; summer flows have a higher fluctuation, and peak snowmelt flow slightly increased with its timing shifted to an earlier date (Ge *et al.*, 2012). The changes in river flow and thermal features indicate basin responses to climate warming over the northern regions. Their impacts on basin biological functions and their effect on ocean thermal processes need further attention.

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