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Heat flux calculations for Mackenzie and Yukon Rivers

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Abstract

This study analyzes long-term (40–60 years) discharge and water temperature records collected near the basin outlets of the Yukon and Mackenzie Rivers. It defines seasonal cycles of discharge, water temperature (WT), and heat flux (HF) for the basins, and compares their main features to understand their similarity and difference. Both rivers have similar hydrographs, i.e. low flows in winter and high discharge in summer, with the peak flood in June due to snowmelt runoff. Mackenzie River has many large lakes and they sustain the higher base flows over the fall/winter season. Mackenzie basin is large with high precipitation, thus producing 50% more discharge than the Yukon River to the Arctic Ocean. The WT regimes are also similar between the two rivers. Yukon River WT is about 2–3 °C warmer than the Mackenzie over the open water months. Both rivers have the highest WT in the mid summer and they transport large amount of heat to the polar ocean system. Yukon River monthly HF is lower by 10–60% than the Mackenzie mainly due to smaller discharge. Mackenzie River heat transport peaks in July, while the Yukon HF reaches the maximum in June and July. These results provide critical knowledge of river thermal condition and energy transport to the northern seas. They are useful for large-scale climate and ocean model development and validation, and climate/hydrology change research in the northern regions.

Keywords: Heat flux; Water temperature; Discharge; Large northern rivers

1. Introduction

Discharge and water temperature are some of the most important hydrologic and climatic variables, as they directly (or indirectly through combination) reflect a river's physical and thermal features. River thermal conditions affect biological and ecological processes over the basin and near the coastal regions/shorelines. Stream temperatures usually follow air temperature closely on a seasonal time scale (Sinokrat and Stefan, 1993). Due to climate change and human impact, stream temperatures have increased by several degrees over the USA, Austrian, and Australian rivers (Webb and Nobilis, 1995; van Vliet et al., 2011). These elevated water temperatures have become an important concern in watersheds where aquatic species such as salmonids are present (Lowney, 2000). In the northern regions, discharge and stream temperature significantly impact the freeze-up/break-up processes, thickness of river ice, and thermal erosion along the riverbanks. Mackay and Mackay (1975) analyzed water temperature data at three locations in the Mackenzie River, described the basic thermal regimes, and determined the river heat transport along the Mackenzie Valley. Marsh and Prowse (1987) studied the influence of

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stream heat on overlying ice cover of the Liard River, and discovered large spatial and temporal variations in water temperatures and heat fluxes. Costart et al. (2003) reported that water temperature and discharge are the major factors controlling thermal erosion of the frozen riverbanks in the Siberian Lena basin, and relatively, water temperature is more important than streamflow, as it has warmed up significantly in the past decades. 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 (i.e. dam regulation). Lammers et al. (2007) conducted a continental-scale river temperature study for the Russian Arctic, they calculated and examined heat energy for the river systems, and found a consistent increase in the decadal maximum temperature (roughly 16–18 °C in the mid-summer) for the basins in the European part of Russia. Studies have established relationships between air and water temperatures over various regions (van Vliet et al., 2011; Webb and Nobilis, 1995; Davies, 1975). For instance, strong positive correlations (statistically significant at 90% confidence) have been found between the Lena basin mean monthly air and water temperatures during the warm season (Liu et al., 2005). Lammers et al. (2007), however, did not detect river temperature rising with air temperature across the Russian Arctic, and they noticed that river energy flux was not coupled closely to water temperature and discharge. They also found a significant decrease in the aggregated energy flux from the three largest Russian rivers (Ob, Yenisey, and Lena); this is not expected given the warming trends over Siberia, but maybe related with large reservoir regulation in these basins, particularly for the Ob and Yenisey rivers. Studies show that dam regulation reduces summer discharge and increases winter base flow over Siberia (Yang et al., 2004a,b; Ye et al., 2003); it also alters downstream water temperature regimes (Liu et al., 2005).

Discharge, water temperature and geochemistry data collected near the river mouths are particularly important as they represent the mass, thermal and geochemistry influxes to the ocean system. It is thus 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 examined and documented changes in the seasonal and annual fluxes of nutrient and organic matter, and dissolved inorganic carbon flux, respectively, from major Arctic rivers to the Arctic Ocean. Lammers et al. (2007) determined the heat flux to the Arctic Ocean from the large Siberian rivers. The knowledge of heat flux is lacking for the large northern rivers in the North America. This limits our understanding of regional heat budget characteristics and total northern river energy transport to the Arctic Ocean. To fill this critical knowledge gap, this study complies and analyzes long-term (40–60 years) downstream discharge and water temperature data for the Yukon and Mackenzie Rivers. These two large rivers have been chosen because of their distinct cryospheric environments (snow cover, glacier, permafrost), unique climatic (cold and dry) and hydrological features (large lakes, snow and glacier contributions) 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, to quantify heat flux from these northern rivers into the polar ocean system, and to examine the similarity and difference in thermal conditions between these two watersheds. The results of this study are useful in understanding climatic and hydrologic linkages and variations over the northern regions. They are also important for regional hydrology and climate change investigations, such as basin-scale mass/energy balance calculations, and land–ocean interactions, particularly large-scale ocean heat/mass budget and model analyses.

2. Basin description

The Mackenzie is the largest North American river (Fig. 1, Table 1). It drains an area of 1.8 million km^2, about 1/5 of the total land area of Canada. Its headwaters, covering parts of British Columbia, Alberta, Saskatchewan and the Northwest Territories, collect a vast system of rivers which flow into Great Slave Lake, from which the Mackenzie River proper flows in a northwesterly direction for about 1600 km before discharging (about 330 km^3/year) through the Mackenzie Delta into the Beaufort Sea. Basin physical features vary widely from the Rocky Mountain system to the flat, mainly treeless barren lands. Permafrost and wetland cover approximately 75% and 49% of the basin. Pingos and pattern-ground features associated with continuous permafrost are found in the north, while agriculture and forestry are important economic activities in the southern parts of the basin. The basin has several climatic regions, including cold temperate, mountain, subarctic, and arctic zones. Mean annual temperatures vary from around −10 to 4 °C, and annual precipitation ranges from more than 1000 mm

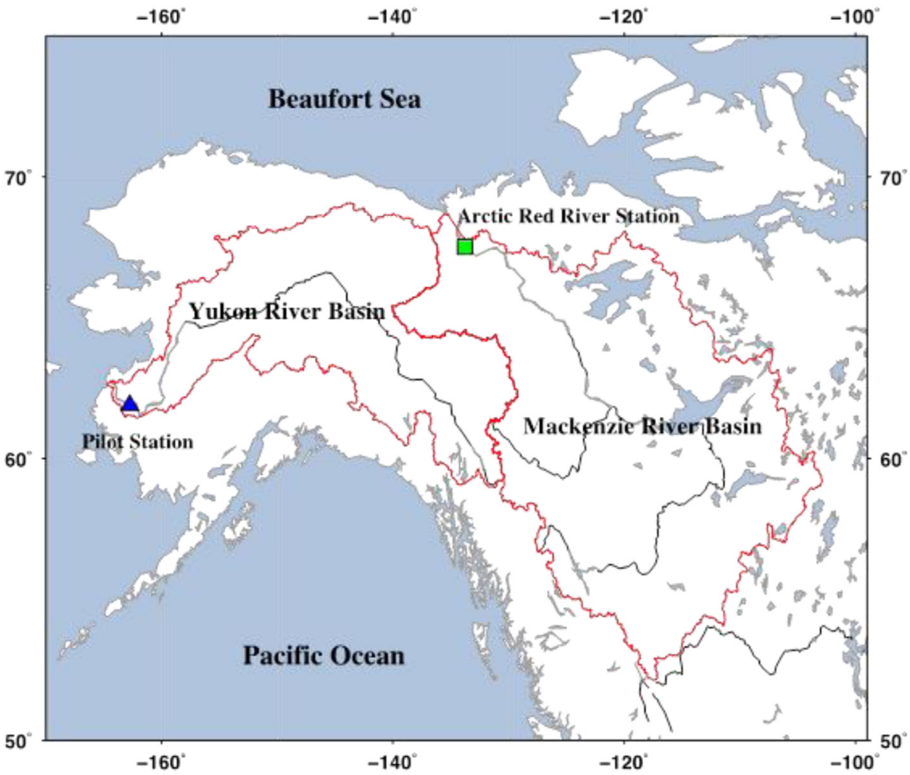

Fig. 1. Mackenzie and Yukon Rivers and their control stations (triangle – the Pilot Station; square – Arctic Red River Station) near the basin outlets.

in the southwest to about 200 mm along the Arctic coast, average about 410 mm/year (Woo and Thorne, 2003). There are large lakes in the basin that provide natural regulation (i.e. smoothing flow process) to the system. One reservoir was built in the Peace River, its operation may substantially influence the water level fluctuations in the Great Slave Lake; but does not significantly affect the flow conditions at the lower Mackenzie (Peters and Prowse, 2001; Woo and Thorne, 2003).

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 about 210 km^3 to the Bearing Sea (Table 1). Yukon River begins at the Llewellyn Glacier in Canada and flows through the Teslin River tributary; 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. 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.

3. Data and methods

The Water Survey of Canada (WSC) has gauged the Mackenzie River at several locations along its main trunk. The flow at Arctic Red River combines the regimes of its sub-basins. Discharge data collected at this location (67.45°N, 133.74°W), before the river branches into many tributaries, are considered as the

Table 1
Physical characteristics of the Mackenzie, Yukon, and Lena rivers, Lena basin is included here to aid in the discussion of the results.

River	Drainage area (1000 km^2)	River length (km)	Annual discharge (km^3)	Mean annual temperature (°C)	Mean yearly precipitation (mm)	Wetland percent (%)	# of dams
Lena	2490	3490	525	−7.8	370	24	1
Yukon	1790	3000	333	−5.1	380	29	0
Mackenzie	850	5470	210	−3.3	410	49	1

total flow for the Mackenzie system. The monthly flow records for this station, available at the Canadian hydrometric database (HYDAT) for the period of 1973–2011, have been obtained and used for this study. Water temperatures (WT) data have also been collected in the Mackenzie River by government agencies regularly over the basin at various locations and times (dates) during sediment sampling and discharge measurements. The sampling frequency varies from 5 to 35 times per year, but most often during the open water season. Many samples are available for a given location, although not on the fixed dates. Water temperature is instantaneously measured at 0–1 m below water surface (on average around 11:30 a.m. local time, with a standard deviation of 2 h), 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 Arctic Red River Station during 1950–2010 have been acquired from the UN Environment Programme Global Environment Monitoring System (GEMS/Water) and used for the analyses.

The US Geological Survey and Environment Canada maintain a hydrologic network in the Yukon River basin. The Pilot Station (61.93N, 162.88W) 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/).

Monthly discharge data for the Yukon and Mackenzie Rivers have been used for statistical analyses so as to define the flow regimes and to quantify its changes (Ge et al., 2012; Woo and Thorne, 2003). In this study, we update the monthly flow records and calculate the long-term mean flows and its changes with a linear trend analysis and statistical significance test (Yang et al., 2004a,b). 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 collected/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). Lammers et al. (2007) detected some discrepancy between the decadal and monthly mean peak WTs for the Lena river, and emphasised the need for a finer than monthly sampling resolution. 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, as it does 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. It is however important to note that large numbers of water temperature samples were taken over the past 40–60 years. For instance, up to 150 observations for June and total of 680 measurements were available for the Pilot Station during 1975–2012. The method of aggregated average thus is 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):

$$H = 864,000\, Cp \cdot Q \cdot T \cdot n \qquad (1)$$

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 $Cp = 4.184$ 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).

We use various statistical approaches for data analyses in this study. We calculate the long-term means of monthly discharge, water temperature, and heat flux for the two rivers. We carry out trend analysis and statistical significance test to identify long-term changes in streamflow at basin outlets. We apply a linear regression to monthly discharge records to determine its changes as a function of time (year). The total trend is defined by the difference of flows shown on the regression line between the first year and the last year (Yang et al., 2004a). The standard *t*-test is used to determine the statistical significance of the trends. We compare the results of trend and regime analyses between the basins and with other relevant studies in the arctic regions, such as the Lena River in Siberia. From this, we generate new information and knowledge to improve our understanding of regional differences in discharge and heat flux contributions of large northern rivers to the Arctic Ocean.

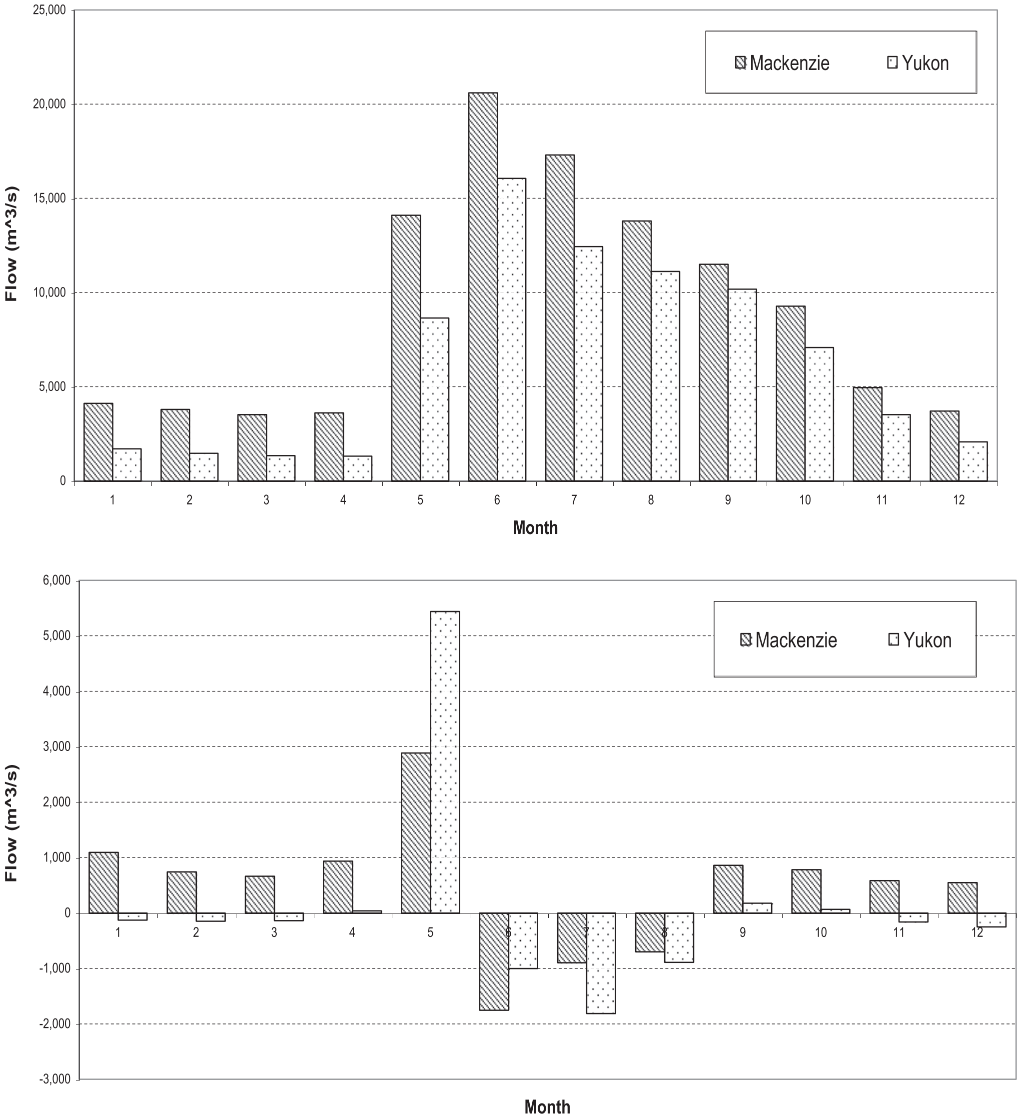

Fig. 2. Long–term mean monthly flow (top) and trend (bottom) for the Yukon River during 1975–2010, and Mackenzie River during 1973–2010.

4. Results

Based on data analyses, we present the main results on monthly discharge regime and change, monthly mean water temperature during the open water season, and monthly mean heat flux for the two rivers.

4.1. Flow regime

The flows at the Arctic Red River reflect the contributions from its major sub-basins at different times of the year (Woo and Thorne, 2003). Long-term flow data measured at this location show low discharge of about 3500–4700 m^3/s during November to April. Flow sharply increases to 14,000 m^3/s in May during the initial snowmelt and river ice breakup period over the basin. Discharge peaks (up to 20,000 m^3/s) in June as the result of snowmelt runoff contribution, and gradually decreases from June to October (Fig. 2). The large basin size and many big lakes in the watershed have a moderating effect to smooth out the minor fluctuations, resulting in a typical nival regime – a hydrograph dominated by peak flow in the snowmelt period and followed by declining flows in the summer and low flow in the winter.

The Yukon River has a similar seasonal flow pattern as the Mackenzie – low flows during November to

April, and high discharge from May to October, with the peak flow in June mainly due to snowmelt floods and ice jams. Yukon River low flows range from about 1300 to 2000 m^3/s, roughly 50% of the Mackenzie low flows; this is because many large lakes exist in northern Canada that supply water to the Mackenzie river and sustain the low flows. In addition, Yukon River high flows in summer months (May, June, July, and August) are also small relative to the Mackenzie (Fig. 2). Annual mean flows are about 6400 m^3/s and 9200 m^3/s, respectively, for the Yukon and Mackenzie rivers. The differences in flows are due to basin size and physical/climatic conditions. In comparison to the Yukon River, the Mackenzie basin is almost 100% larger in size with higher summer/annual precipitation.

Trend results vary with the data periods used for change detections. In order to understand the recent changes in basin hydrology, we carry out trend analyses of the monthly flow data up to 2010 and 2011 for the two rivers. The results demonstrate that base flows during September through April increase by 5–25% over the Mackenzie River and change little for the Yukon. Flows in May strongly increase by 20% and 60%, respectively, for Mackenzie and Yukon, while discharge decreases by 5–15% during June, July, and August (Fig. 2). Flow changes over May to August are statistically significantly at 90–95% confidence levels. 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 (Serreze et al., 2000; Yang et al., 2002). This result is consistent with other studies of the large Russian rivers (Ye et al., 2003; Yang et al., 2005).

4.2. Water temperature regime

Ice cover exists for both rivers 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 basins. During the open water season (May to October), the WT patterns are similar for the two basins (Fig. 3). The long-term mean temperatures in May are about 5 °C for both rivers, 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 mean WT and their seasonality for the Mackenzie basin are more representative and reliable, relative to the estimates from the short-term observations (Davies, 1975; Mackay and Mackay, 1975), as they have been derived in this study from long-term records. It is interesting to note that the Yukon River WTs are warmer for most open water seasons than the Mackenzie, by up to 2 °C in the mid summer (June and July) and 3 °C in October. The annual mean WTs are 5.1 °C and 5.4 °C, respectively, for the Mackenzie and Yukon, reflecting a colder climate over the Mackenzie basin.

4.3. Heat flux regime

Open water season heat flux calculations for the two basins are summarized in Fig. 4. For the Yukon River, the

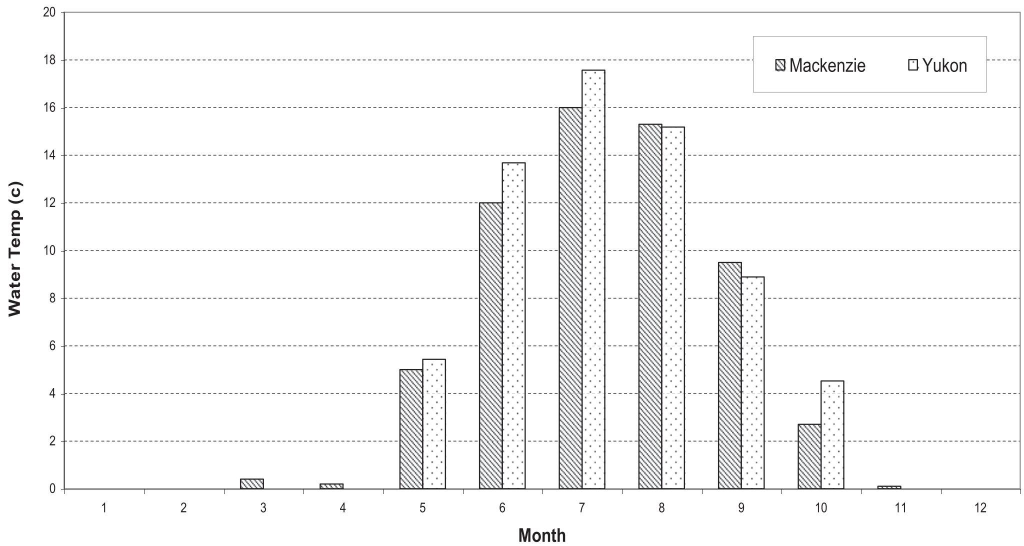

Fig. 3. Long–term mean monthly water temperature for the Yukon River during 1975–2010, and Mackenzie River during 1950–2010.

mean monthly values are low in May (about 527×10^9 MJ) and very high ($2380-2500 \times 10^9$ MJ) for June and July; then they decrease to 3644×10^9 MJ) from August to October. The total HF is about 8590×10^9 MJ during May through October. Mackenzie River shows a similar seasonal HF pattern. The monthly heat transports are relatively low for May, September, and October; and high during June to August, with the highest HF in July. It is interesting to note that, relative to the Yukon River, the Mackenzie WT is slightly cooler and its summer flow is much higher. The Mackenzie monthly HF ranges from 790×10^9 MJ to 3100×10^9 MJ, with the seasonal total of $10{,}430 \times 10^9$ MJ. These values are about 10–50% higher than the Yukon River for May to September, and 21% higher over the entire open water season. This result suggests that higher summer flows in the Mackenzie River dominate the heat transport to the Arctic Ocean.

It is important to examine the difference and similarity in seasonal cycles among discharge, water temperature, and heat flux over the northern regions. Lammers et al. (2007) report, over the Russian Arctic, the long-term decadal mean water temperature peak around late July, highest discharge in early June, and the maximum heat flux at the end of June. 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. Mackenzie River also has the highest flow in June and warmest WT in July, but the HF reaches the peak in July – which lags behind the peak flow by a month (Figs. 2–4). This result is consistent with the Lena River (Liu et al., 2005) and similar to the Russian Arctic regions (Lammers et al., 2007).

5. Summary and discussion

Lammers et al. (2007) calculated the energy transport of the large rivers over the Russian Arctic. Little is known of the heat flux to the Arctic Ocean from the large NA northern rivers, including the Yukon and Mackenzie Rivers. This study fills a knowledge gap, as it, based on the analyses of long-term data and comparisons of results, clearly defines the seasonal cycles of discharge, water temperature, and energy flux for the Yukon and Mackenzie Rivers. The results of this work, when compared and combined with other analyses, such as Lammers et al. (2007), Yang et al. (2005), and Liu et al. (2005), allow us to determine the main river heat flux to the Arctic Ocean and surrounding seas. This study shows that both rivers have similar hydrographs, i.e. low flows in winter and high discharge in summer, with the peak flows in June due to snowmelt runoff. Mackenzie River has many large lakes and they sustain the high base flows over the fall/winter season. Relative to Yukon, the Mackenzie basin is large with high precipitation, thus producing 50% more discharge to the Arctic Ocean. The WT regimes are also similar for the two rivers. Yukon River WT is about 2–3 °C warmer than the Mackenzie over most open water months. Both rivers have the highest WT in the mid summer of July. There are similarity and difference in the HF patterns between the basins. Both rivers transports large amount of heat in the mid summer. Yukon monthly HF values are lower by

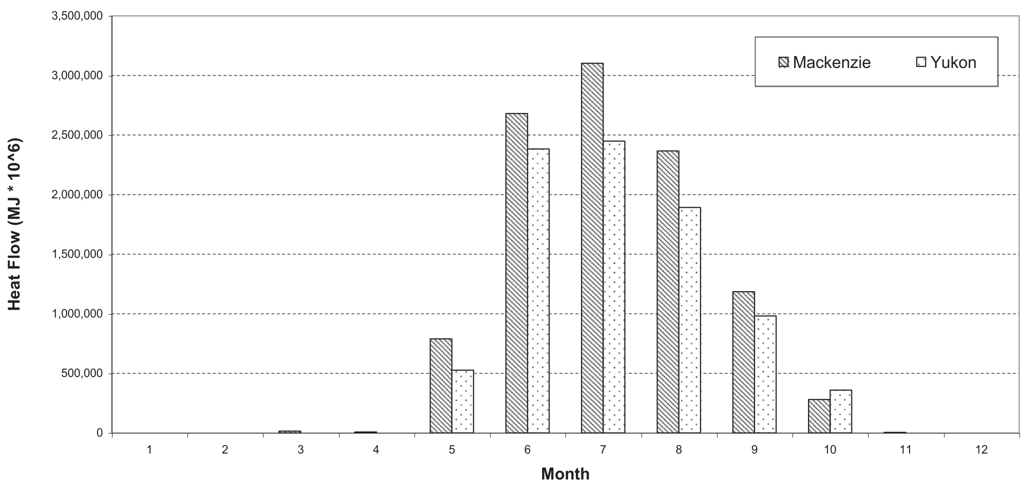

Fig. 4. Long–term mean monthly heat flux for the Yukon and Mackenzie Rivers.

10–60% than the Mackenzie mainly due to small flows. Mackenzie River heat transport peaks in July (the same time with the highest WT), while the Yukon River HF reaches the maximum in June and July; the peak in June is mainly caused by the higher WT. The annual total heat transport from Mackenzie is 20% higher than the Yukon River, mainly because of the larger amount of discharge to the Arctic Ocean. According to Lammers et al. (2007), Lena River heat transport to the Arctic Ocean is the highest among the large Russian rivers. Lena basin WT regimes are similar to Mackenzie, and it caries more energy, i.e. about 14,281 × 109 MJ per year (Liu et al., 2005) or 40% more than Mackenzie, due to its large size (2,490,000 Km^2) and high annual flow (525 km^3) (Table 1).

Due to the limited WT observations and data over the northern regions in the North America, this study focused on the calculation and determination of heat flux regime for the Yukon and Mackenzie Rivers; it also discussed discharge trends, although not much on changes and variations in water temperature and heat flux. It is known that heat flux, depending on the fluctuations in discharge and water temperature, significantly varies at inter-annual time scale (Liu et al., 2005). Consistent increases or decreases in discharge and water temperature strengthen heat flux changes, whereas inconsistent (one positive and one negative) trends weaken heat flux changes (Liu et al., 2005). Recent studies reveal many changes in climate and hydrology over the northern regions. For instance, Yukon River annual flow at the basin outlet increase by 8% over the past 40 years; summer flows have a higher fluctuation, and peak snowmelt flow slightly increases with its timing shifted to an earlier date (Ge et al., 2012). Mackenzie River flows during 1975–2003 did not indicate any obvious trends at annual or monthly time scale, but significant changes in flow variability occurred for several sub-basins in different months. There is also evidence of an earlier breakup in the past few decades maybe related with increasing temperatures during the snowmelt season (Woo and Thorne, 2003). These results are generally similar to our findings of monthly flow changes for the Yukon and Mackenzie rivers (i.e. Fig. 2). On the other hand, Lena River has experienced strong WT warming in the past decades over the entire basin (Liu et al., 2005). Particularly important is the increases in both WT and discharge during the early summer (Ye et al., 2003), i.e. the snowmelt season when the discharge is at the peak. The combined effect of simultaneous rises of discharge and WT drove the heat flux up by 23% in June (Liu et al., 2005). These changes in river flow and thermal features indicate basin responses to climate warming over the northern regions. Their impacts to basin biological functions and their effect to ocean thermal processes (for example, land-fast ice, sea ice, and surface temperature of the northern seas) need further investigations (Bareiss et al. 1999; Nghiem et al., 2014).

Consistent, long-term hydrometric and climatic observations and records are essential for global change research particularly over the vast northern regions which now only have sparse monitoring networks. Long-term monthly mean discharge data have been used in this study to represent the seasonal cycle of hydrology and to calculate basin total heat flux. Monthly flow data satisfy the need of this study on heat flux regime analysis and comparison. Daily flow data,

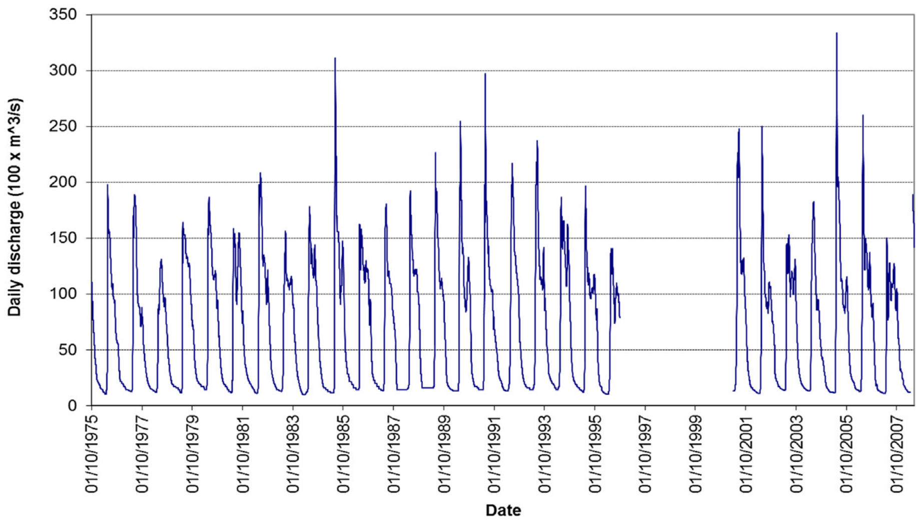

Fig. 5. Long-term daily flow records for the Pilot Station (Yukon River) during 1975–2007.

when available, are also useful to accurately document and characterize discharge seasonal cycle and its change. For example, the daily flow records for the Pilot Station (Yukon River) during 1975−2008 (Fig. 5) show low flows in the cold season (November to April) with little variation, since low flows is dominated by groundwater that does not change significantly over the winter. However, for the warm season (May to October), daily flow fluctuations are quite large among the years due to snowmelt, glacier melt, and rainfall variations. The availability of water temperature data constrains the extent of river heat flux investigations. Water temperature is very important to many applications and relative easy to measure, but it has not been systematically observed at the northern operational/research networks in USA and Canada. In the Mackenzie basin, WT was taken in conjunction on the days when water/sediment was sampled. There is an urgent need to expand and improve WT observations over the northern regions in the USA and Canada. USGS compiled and analyzed existing water temperature data in the Cook Inlet Basin in Alaska (Kyle and Brabets, 2001), and NWS/NOAA recently carried out hourly water temperature observations at many selected locations in Alaska and Yukon. Preliminary data collections by NOAA show large inter-annul and intra-annual variations in water temperatures over Alaska and Yukon (http://aprfc.arh.noaa.gov/gages/ak_g_tw.php), particularly for the small rivers and streams. For instance, recent data from the National Weather Service (NWS)/NOAA at the Klondike River above Bonanza Creek in Alaska during April 2010 to September 2012 display large WT variations over the seasons and among the years (Fig. 6). It is obvious that the hourly data present a clear WT seasonal cycle; it also reveals detailed temperature fluctuations over the open water season. This information, when combined with daily discharge data, is useful for more accurate quantifications of river thermal regime and heat content. Our effort is ongoing to obtain and analyze more water temperature and discharge data for river heat flux calculations over the broader northern regions.

Finally, in addition to climate effect, human activities, such as reservoir regulation and water uses for agriculture and industry, also impact river flow and WT regimes and its changes. It is a challenge to separate the effects of human activities and climate variation on regional flow regime and thermal condition changes (Lammers et al., 2007; Yang et al., 2005). Basin hydrologic and climatic analyses are useful to quantify changes and linkages over various parts of sub-basins (Ye et al., 2003; Yang et al., 2005). More efforts of basin-scale investigations are necessary to better understand the reasons for the changes detected in the long-term records.

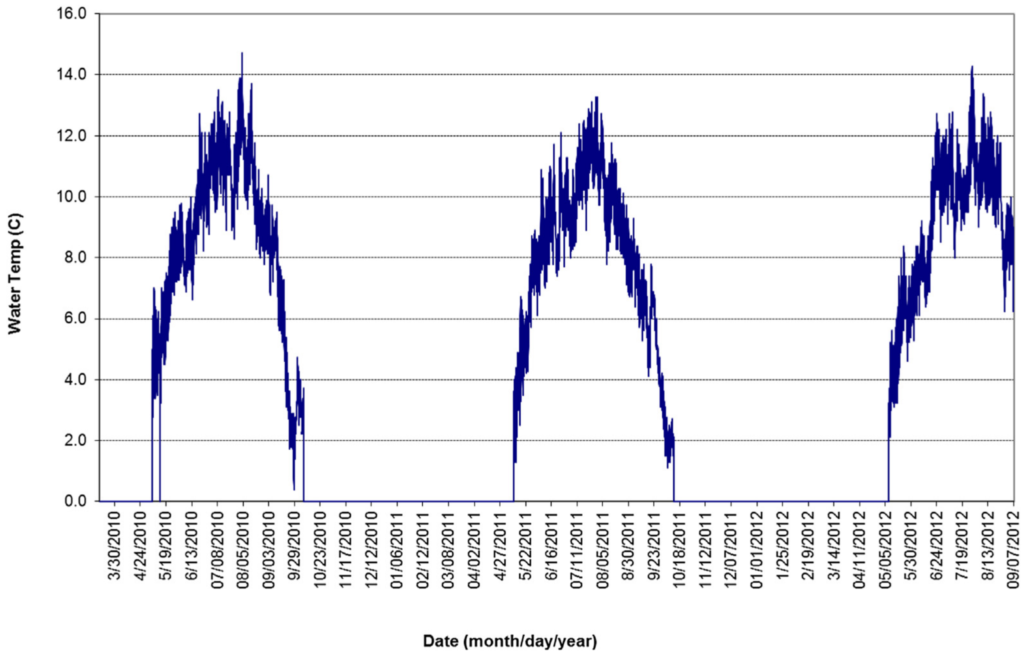

Fig. 6. Hourly water temperature data collected by NWS/NOAA during April 2010 to September 2012 at the Klondike River above Bonanza Creek, Alaska.

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