

River Water Temperature in Relation to Local Air Temperature in the Mackenzie and Yukon Basins

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ABSTRACT. Water temperature has an important impact on many aspects of basin hydrology and ecology. In the northern regions, investigation of river thermal regimes and their changes over space and time is a challenge because of data limitations. This study determines the water temperature regimes at several locations within the Yukon and Mackenzie River basins and examines their relationship with air temperature. The Yukon and Mackenzie Rivers have distinct water temperature dynamics. They remain near zero from freeze-up in the fall to ice breakup in the spring and reach their peak temperature during mid-summer. For the locations examined, peak mean monthly water temperatures ranged from 9° to 15°C, and mean July air temperatures ranged from 13° to 16°C. The lags between water and air temperatures ranged from 1 to 40 days. The largest lag was found at the Great Bear River monitoring location, since water temperature at this site is strongly influenced by the heat storage of Great Bear Lake. Tests of three models, linear regression, logical regression (s-shape), and the physically based air2stream model, show that the air2stream model provided the best results, followed by logical regression. Linear regression gave the poorest result. Model estimates of water temperature from air temperature were slightly improved by the inclusion of discharge data. The water temperature sampling regimes had a considerable effect on model performance; long-term data provide a more robust test of a model. Comparisons of mean monthly water temperatures suggest significant spatial variability and some inconsistency between upstream and downstream sites that is due mainly to differences in data collection schemes. This study strongly demonstrates the need to improve water temperature monitoring in the northern regions.

Key words: rivers; water temperature; air temperature; relationship; northern basins; Canada

RÉSUMÉ. La température de l'eau a de grandes incidences sur de nombreux aspects de l'hydrologie et de l'écologie des bassins. Dans les régions nordiques, l'étude des régimes thermiques des cours d'eau et de leurs changements au fil du temps et de l'espace pose des difficultés en raison des limites qu'imposent les données. La présente étude détermine les régimes des températures de l'eau en maints endroits des bassins de la rivière Yukon et du fleuve Mackenzie et examine leur relation avec la température de l'air. La rivière Yukon et le fleuve Mackenzie ont des dynamiques distinctes en matière de température de l'eau. De la prise de la glace de l'automne jusqu'à la débâcle du printemps, les températures de ces cours d'eau se situent à près de zéro, et c'est vers le milieu de l'été que leurs températures augmentent le plus. Dans le cas des sites à l'étude, les températures mensuelles moyennes les plus élevées de l'eau ont atteint entre 9° et 15 °C, tandis que les températures moyennes de l'air en juillet ont varié entre 13° et 16 °C. Le décalage entre les températures de l'eau et de l'air a fluctué entre un et 40 jours. Le plus grand décalage a été enregistré au site de surveillance de la rivière Great Bear, la température de l'eau à cet emplacement étant fortement influencée par le stockage de la chaleur dans le lac Great Bear. Des essais effectués à l'aide de trois modèles, soit la régression linéaire, la régression logique (en forme de s) et le modèle air2stream aux caractéristiques physiques indiquent que le modèle air2stream a donné les meilleurs résultats, suivi de la régression logique. Les résultats les moins bons ont été obtenus au moyen de la régression linéaire. Les estimations du modèle de la température de l'eau à partir de la température de l'air ont été légèrement améliorées avec l'inclusion des données du débit. Les régimes d'échantillonnage de la température de l'eau ont eu un effet considérable sur le rendement du modèle; les données à long terme ont permis d'obtenir un essai de modèle plus robuste. La comparaison des températures moyennes mensuelles de l'eau suggère une variabilité spatiale importante et certaines incohérences entre les sites en amont et les sites en aval, principalement en raison des différences dans les modes de collecte des données. Cette étude montre à quel point il est important d'améliorer la surveillance des températures de l'eau dans les régions nordiques.

Mots clés : rivières; fleuves; température de l'eau; température de l'air; relation; bassins nordiques; Canada

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INTRODUCTION

River thermal conditions influence biological and ecological processes within the basin and near the coastal regions. Water temperature is a direct measure of a river's physical and thermal conditions. Stream temperatures vary with atmospheric conditions, topography, stream flow, and heat transfer processes (Caissie, 2006), and they generally follow air temperatures on a seasonal time scale (Sinokrot and Stefan, 1993). As a result of climate change and human impacts, stream temperatures have warmed by several degrees over many regions, including the United States, Australia, and Russia (Webb and Nobilis, 1995; Liu et al., 2005; van Vliet et al., 2011). Warmer water temperatures have become an important concern for watershed biology and aquatic species (Lowney, 2000). In high-latitude regions, water temperature and discharge significantly affect the freeze-up and breakup processes, the thickness of river ice, and thermal erosion along the riverbanks. Marsh and Prowse (1987) examined the influence of stream heat on overlying ice cover of the Liard River and reported large spatial and temporal variations in water temperature and heat flux. Costard et al. (2003) found water temperature and discharge to be the main factors in thermal erosion of the frozen riverbanks in the Lena basin. Liu et al. (2005) and Yang et al. (2005), using the long-term water temperature records over the Lena basin, discovered significant trends in river thermal conditions as results of regional climate warming and human impacts, particularly reservoir regulation. Lammers et al. (2007) analyzed water temperature data and calculated heat energy for the large Siberian rivers and reported a consistent increase in the decadal maximum temperature for the basins in the European part of Russia.

Many studies have derived relationships between air and water temperatures over large regions and basins (Davies, 1975; Webb and Nobilis, 1995; van Vliet et al., 2011). Liu et al. (2005), for example, found positive correlations between mean monthly air and water temperatures in the Lena basin during the warm season. 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: the Ob, Yenisey, and Lena. This result is not expected given the recent warming trends across the Siberian region, but perhaps related with reservoir regulation in these basins, as studies show that dam regulation alters downstream discharge and water temperature regimes over Siberia (Ye et al., 2003; Yang et al., 2004a, b; Liu et al., 2005).

Because data on the northern regions are limited, it is a challenge to investigate river thermal regimes and their changes over space and time. Yang et al. (2014) recently analyzed the long-term water temperature and discharge records collected near the basin outlets of the Yukon

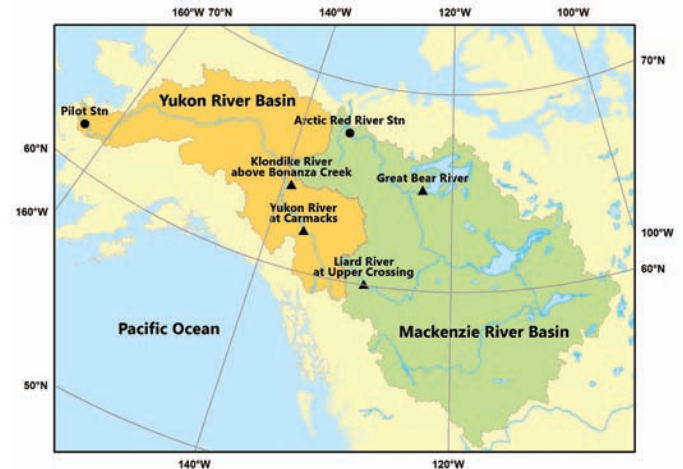


FIG. 1. Map of water temperature monitoring locations in Yukon and Mackenzie Rivers. Triangles show the locations of the four stations examined in detail for this study. The circles represent outlet stations for the Mackenzie and Yukon River basins (Yang et al., 2014).

and Mackenzie Rivers, quantifying the seasonal cycles of discharge, water temperature, and heat flux for the basins. Water temperature projections based on modeled future changes in air temperature and discharge suggest a moderate increase in water temperature in the Yukon and Mackenzie River basins (van Vliet et al., 2011).

This study compiles historical water temperature records from the upper Yukon and Lower Mackenzie regions. The main objectives are to characterize water temperature regimes within large basins and to examine the relationship between water and air temperatures for the northern regions of Canada. The data and results of this study are useful for understanding hydrologic conditions in the cold regions. They are also important for regional hydrology and climate change investigations, including basin energy balance calculations, and interactions of atmosphere, land, and water.

MATERIALS AND METHODS

Data

River water temperature data from several monitoring locations within the Yukon and Mackenzie basins were used in this study (Fig. 1). Air temperature, streamflow, and water level data were also gathered for these locations. The information available for each site is summarized in Table 1, and the physical characteristics of each monitoring site are given in Table 2. These include site coordinates, drainage area, elevation, streamflow, and air temperature. In the Yukon basin, water temperature was monitored on the Yukon River at Carmacks, and on the Klondike River above Bonanza Creek (Brabets et al., 2000). For the Mackenzie basin, water monitoring occurred on the Liard and Great Bear Rivers. These monitoring locations represent two distinct types of water temperature data

TABLE 1. Summary of water temperature, air temperature, and flow data for each monitoring station.

Stations Name & ID	Comments	Water Temperature			Air Temperature	
		Years	Frequency	Source	Measurement	Station & Distance
Great Bear River (10JC003)	3 km from outlet of Great Bear Lake	2002–03, 2012–13	Every three hours	WSC	Daily mean	Deline CS (15 km N)
Klondike River above Bonanza Creek (KLNQ9 & 09EA003)		2010–12	Hourly	NWS	Daily mean	Dawson (15 km E)
Liard River at Upper Crossing (10AA001)		1991–2013	Every two weeks 14:00 ± 4 h	PYLTM study	Daily mean	Watson Lake (11 km NE)
Yukon River at Carmacks (09AH001)		1980–96	Every two weeks 13:30 ± 3 h	PYLTM study	Daily mean	Carmacks (3 km NW)
Mackenzie River at Arctic Red River (10LC014)	Representative of basin outflow	1950–2010	Long-term mean monthly	Yang et al., 2014	Climate normals 1981–2010 ¹	Fort McPherson (100 km W)
Yukon River at Pilot Station (15565447)	Representative of basin outflow	1975–2010	Long-term mean monthly	Yang et al., 2014	Climate normals 1981–2010 ²	Bethel Airport (160 km S)

¹ Data from ECCC (2016c).

² Data from NOAA (2016).

TABLE 2. Physical characteristics of the monitoring locations.

Site ID	Latitude (°N)	Longitude (°W)	Elevation (m)	Peak flow (m ³ /s)	Winter flow (m ³ /s)	Gross drainage area (km ²)	Mean January air temp (°C)	Mean July air temp (°C)	Maximum mean monthly water temp (°C)
Klondike 09EA003	64.0	139.4	370.0	200–400	40	7810	–27.2	15.6	10.8 (July)
Great Bear 10JC003	65.1	123.6	212.8	700	525	146400	–26.0	13.4	9.3 (August)
Liard 10AA001	60.1	128.9	687.4	1000–3000	100	32600	–22.8	15.2	13.5 (July)
Yukon 09AH001	62.1	136.3	524.9	1000–3000	230	81800	–22.9	15.6	15.1 (August)

available for these basins. The first type is high-frequency, short-term data. The most northern monitoring locations in this study are a good example of this type. For the Great Bear River and Klondike River, water temperatures were recorded at sub-daily intervals for 3–4 years. Water temperature data were provided by the Water Survey of Canada (WSC) for the Great Bear River and by the U.S. National Weather Service (NWS) for the Klondike River. The other two sites are examples of the second data type: low-frequency, long-term data. Water temperature has been monitored on the Liard River and Yukon River at Carmacks every two weeks for decades, as part of the Pacific-Yukon Long-term Trend Monitoring (PYLTM) study. The data for these locations, as well as many others in the program, are available from Environment and Climate Change Canada (ECCC, 2014). Measurements from this program are considered to be instantaneous, and observation time in a day was variable. Flow and water level data for the rivers were obtained from the WSC hydrometric database (ECCC, 2016a). Air temperature data were obtained from nearby weather stations operated by the Meteorological Service of Canada. The quality-controlled data were downloaded from the Canadian National Climate Archive (ECCC, 2016b). The daily mean air temperature was determined as the average of the daily maximum and minimum temperatures.

Water Temperature Models and Analysis

The water temperature (T_w) observations were fitted to three different models using air temperature (T_A) and discharge (Q) as input variables. The first model is a simple linear regression equation:

$$T_w = mT_A + nQ + b, \quad (1)$$

where m , n , and b are fitted coefficients. Air temperature and discharge are considered in this model because, as van Vliet et al. (2011) found in a comprehensive study of river water temperatures at 157 monitoring stations around the world, 87% of water temperature estimates were improved by considering discharge in addition to air temperature.

The second method is a non-linear regression model (Mohseni et al., 1998) that estimates water temperature as an s-shape function of air temperature. Van Vliet et al. (2011) modified this function to include discharge data. The equation is given as:

$$T_w = \mu + \frac{\alpha - \mu}{1 + \exp(\gamma(\beta - T_A))} + \frac{n}{Q}; \gamma = \frac{4 \cdot \tan\theta}{\alpha - \mu}, \quad (2)$$

where μ and α are the lower and upper bounds of water temperature, respectively; θ is the angle at the inflection

point; β is the air temperature at the inflection point; and n is a fitted coefficient. In this study, all five of the parameters in Equation 2 were fitted. The lag time between air and water temperatures was incorporated into these two models. The Pearson correlation coefficient (R) was used to evaluate the strength of the linear association and determine the optimal time lag (i.e., the number of days between air and water temperature measurements that provides the best correlation). No lag time was considered for the flow data. The regression models (Eqs. 1 and 2) can still be used if only air temperature data are available, i.e., by removing any terms containing Q .

The regression equations (Eqs. 1 and 2) are purely statistical. Although these models may be able to simulate historical water temperatures, they are not physically based; therefore, their suitability for estimating water temperature into the future, particularly under a changing climate, has been questioned (Toffolon and Piccolroaz, 2015). The third model tested in this study is the air2stream model (Toffolon and Piccolroaz, 2015), which is physically based and uses calibrated parameters. The full equation of the model, using both air temperature and discharge data, is:

$$\frac{dT_w}{dt} = \frac{1}{\delta} \left\{ a_1 + a_2 \cdot T_A - a_3 \cdot T_w + \theta \left[a_5 + a_6 \cdot \cos \left(2\pi \left(\frac{t}{t_y} - a_7 \right) \right) \right] - a_8 T_w \right\},$$

$$\delta = \theta^a; \quad \theta = \frac{Q}{Q_0}, \quad (3)$$

where a_1 – a_8 are calibrated coefficients, t is time, and t_y is the number of time units in a year. The five-parameter version using only air temperature measurements is given as:

$$\frac{dT_w}{dt} = a_1 + a_2 T_A - a_3 T_w + a_6 \cos \left[2\pi \left(\frac{t}{t_y} - a_7 \right) \right]. \quad (4)$$

Model performance was evaluated by the root mean square error (RMSE) and Nash-Sutcliffe efficiency (NSE) statistics. The RMSE, also referred to as the standard deviation of errors, quantifies the spread of data from the estimated values. For a normally distributed data set, 68% of the errors are within \pm RMSE. The NSE is a measure of the predictive power of a model. An NSE of 1 indicates a perfect match between the modeled and observed data, while a negative NSE means that the average observed value is a better estimate than the model.

Comparison of observed water temperature and air temperature provides a basis for discussing the factors controlling water temperature. We produced and examined plots of water temperature, air temperature, and flow to understand water temperature seasonal dynamics and trends for the individual sites and also examined bar graphs of monthly mean water and air temperatures. We determined monthly means of water temperatures by taking an average of all measurements available for a particular month. Results from the four monitoring locations were compared with the information determined by Yang et al.

(2014) for the outlet stations of the Yukon and Mackenzie River basins. Monthly air temperatures for these locations were taken from climate normal records.

RESULTS AND DISCUSSION

High-Frequency Short-Term Data Sets

Water temperature, air temperature, and flow observations from the Klondike River above the Bonanza Creek are presented in Figure 2. This site represents a typical northern river in terms of its seasonal dynamics. Water temperature data were collected at the Klondike River monitoring site during 2010–12. Daily average temperatures ranged from 0° to 13°C for water and from –47° to 21°C for air. Between freeze-up in the fall and breakup in the spring, water temperature stays fairly constant at ~0°C. After ice breakup, water temperature rises to reach a maximum around mid-summer. Water temperature then follows a decreasing trend until freeze-up. Water temperature can vary by more than a few degrees within a single day, which is why hourly water temperatures show more variability than daily data. Water temperature is also much less variable than air temperature because water heats and cools more slowly. There is a lag of about a week between water and air temperatures during the breakup period. Flow rate is lowest during winter months when the river is iced over, and peak flows occur as a result of upstream and localized ice jams, snowmelt, and rainfall events.

The Klondike River is an example of how flow may affect water temperature on a seasonal basis. Flow and water level at this site are quite low in comparison to the other three monitoring locations in this study. Peak annual flows ranged from 200 to 400 m³/s, and flow was less than 50 m³/s in the late fall and winter months. Water level ranged from 0.5 to 2.5 m (data not shown). The lag between air and water temperatures changes seasonally. For example, Figure 2 shows that from spring to mid-summer, daily air temperatures are on average 5°C warmer than water temperatures, whereas from late summer to fall, mean daily water and air temperatures are nearly identical. The increased response of water temperature to air temperature in the fall may be due to the shallow water level and reduced flow.

Observations of water temperature, air temperature, and flow from the Great Bear River monitoring station are presented in Figure 3. This data set covers four years (2002–03 and 2012–13) of water temperature measurements taken at three-hour intervals. The three-hour data were fairly noisy up until the gap during August and September 2012 and less noisy afterwards, which may suggest replacement of the temperature sensor or change in monitoring location or depth. Long-term daily flow and water level measurements are also available for this site. These measurements can be considered accurate for the most part, except for the winter months when anomalous spikes are present.

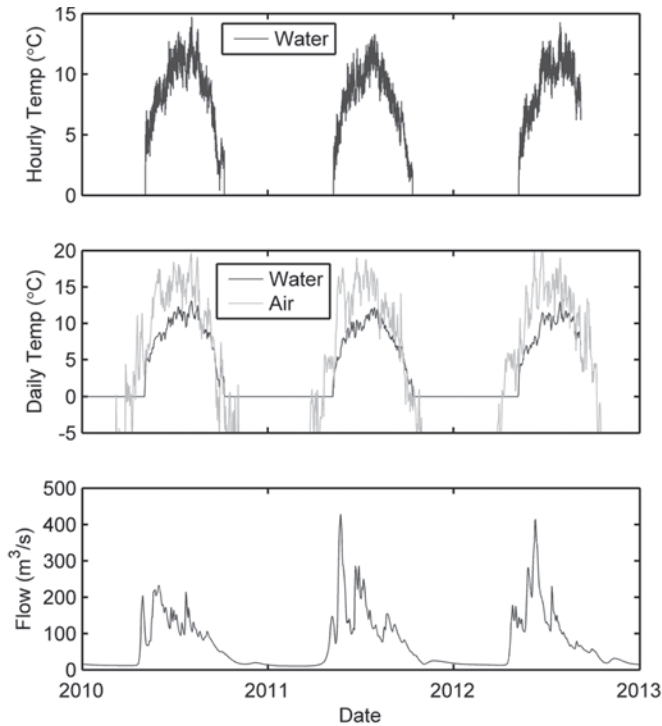


FIG. 2. Klondike River (09EA003) hourly water temperature, average daily air and water temperatures, and flow during 2010–12.

The Great Bear River monitoring site is unique among the monitoring sites examined in this study because it is only 3 km downstream from an extremely large lake: Great Bear Lake (area of $\sim 31\,000\text{ km}^2$), which has a strong influence on the river's water temperature and flow dynamics. This river differs in many features from the Klondike River. Firstly, flow and water level are fairly constant throughout the year. Maximum flow was $700\text{ m}^3/\text{s}$, while minimum flow was only $525\text{ m}^3/\text{s}$. This is the case because the water level of the lake may change by only 20–30 cm during a single year (Johnson, 1975). Secondly, water temperature lags behind air temperature by about a month (Fig. 3). This is unusual for rivers and is caused, in this case, by the heat storage of the Great Bear Lake. At this monitoring location, the Great Bear River is late in breaking up in the spring and freezing up in the fall. Although air temperature is well below freezing in November, the river does not freeze until the temperature of the lake is reduced. Because Great Bear Lake is so large, this process takes considerable time.

Also of interest is a drop in water temperature of a few degrees near the end of June, which is seen in both the daily and three-hour data (Fig. 3). This drop is evident for all years in the record, but is strongest for 2002 and 2003. At this time of the year, the prevailing wind is from the east, heading towards the mouth of the river. The cause of the temperature drop may not be lake overturn, but rather the lake ice that is flowing down the river at this period. Lake ice begins to melt in May, but it is not until mid-July that the lake is completely ice-free (Johnson, 1975; Rouse et al., 2008; Kang et al., 2012). The arm of the lake with the

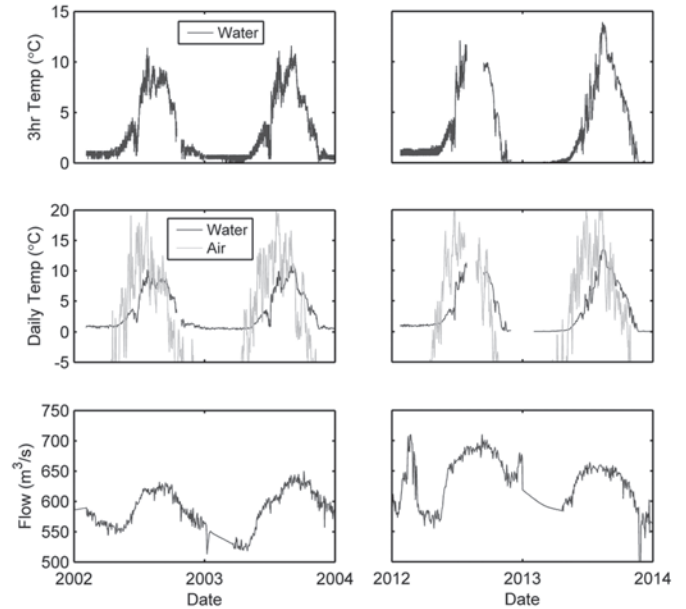


FIG. 3. Great Bear River (10JC003) three-hourly water temperature, average daily air and water temperatures, and flow during 2002, 2003, 2012, and 2013.

mouth of Great Bear River, Keith Arm, becomes ice-free in late June to early July (Woo et al., 2007). This timing is consistent with the water temperature drop. However, it is only a hypothesis that lake ice causes this temperature drop, and more data and research are needed to fully understand this phenomenon.

Low-Frequency Long-Term Data Sets

The observations for Liard River at Upper Crossing over the period 1991–2013 are shown in Figure 4. During this time, water temperature ranged from 0° to 17°C . Air temperature generally ranged from -20° to 20°C , with a record minimum of -38°C and maximum of 25°C . For the entire record, peak annual flows ranged from 1000 to $3000\text{ m}^3/\text{s}$, while winter discharge was about $100\text{ m}^3/\text{s}$. Water level ranged from 2–8 m (data not shown). The data from this site are typical for the PYLTM program. The water temperature measurements taken every two weeks follow mean daily air temperature well, and they appear to capture annual water temperature dynamics adequately. The long-term records are useful to show interannual variation and change of water and air temperatures. To reveal details of the air and water temperature relationship, a close-up look at the record for 2009–11 is given in Figure 5. Air and water temperatures are seen to have a larger lag on the rising limb than on the falling limb, which is similar to what is seen for the Klondike River. Seasonal differences in flow and water depth may be responsible for this pattern.

The records for the Yukon River at Carmacks cover the years 1981–96. During this period, water temperature ranged from 0° to 19°C . Air temperature generally varied from -25° to 20°C , with a minimum of -52°C and a maximum of 36°C (Fig. 6). A zoomed-in plot of a few years'

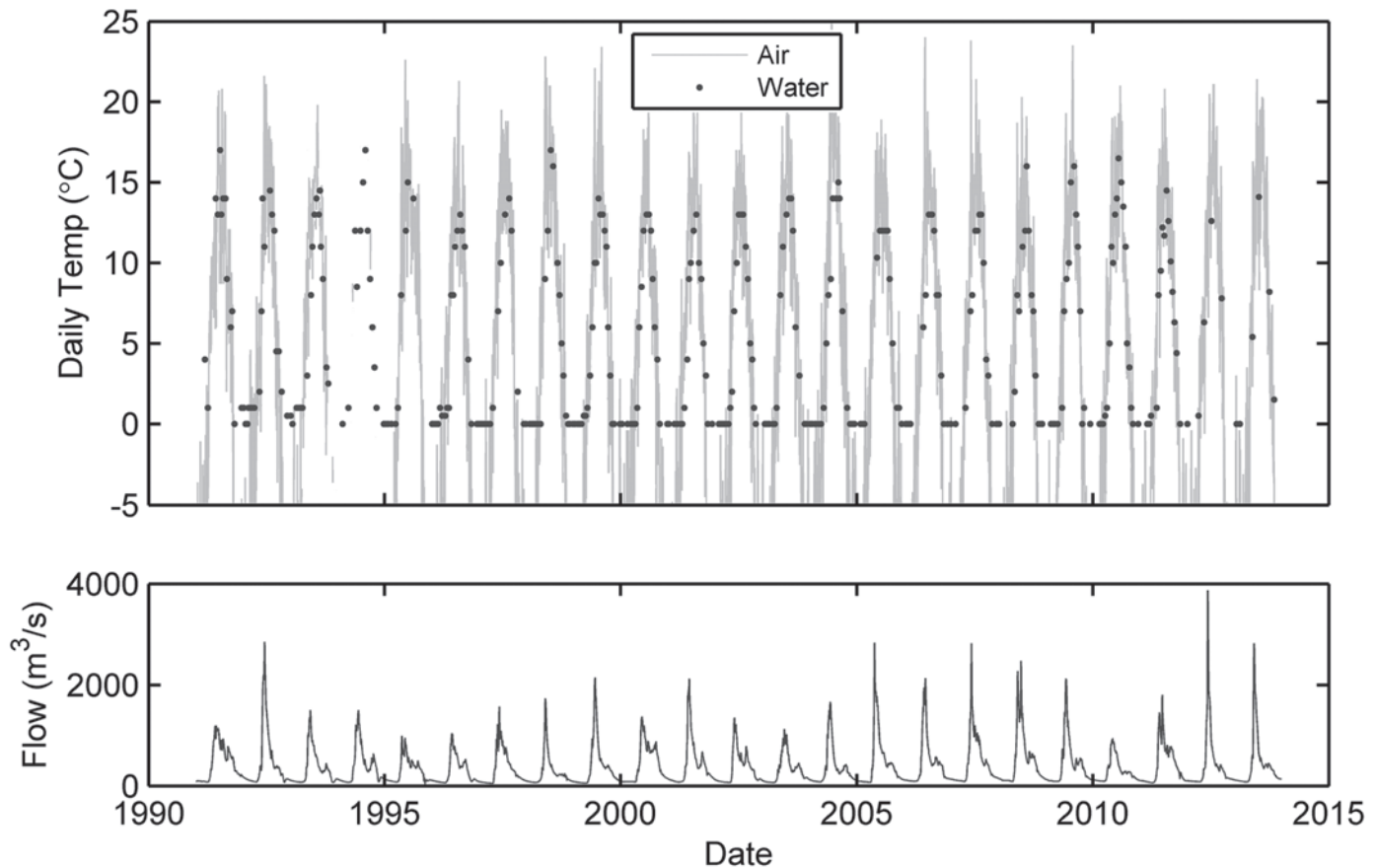


FIG. 4. The Liard River (10AA001) bi-weekly water and air temperatures and average daily flow during 1990–2013.

data (1987–89) is shown in Figure 7. The air temperature record has quite a few missing data points. On the rising limb, air and water temperatures are similar, with very little lag, whereas the falling limb shows a significant lag between water and air temperatures. Annual peak flows ranged from 1000 to 3000 m^3/s , a range similar to that of the Liard River. Minimum flow over the entire record was 230 m^3/s . Because larger lags are shown in the fall under low flow conditions, it appears that discharge at this site may not have a strong effect on the water temperature and air temperature correlations.

Model Analysis

The linear association between air and water temperatures for different lag times has been plotted in Figure 8. The Klondike and Great Bear River show two very different patterns. The correlation between water and air temperatures quickly decreases as lags longer than 1 d are considered for the Klondike River. The Great Bear River has the opposite pattern: the correlation starts low, but increases with longer lags. The optimal lag of 40 d for the Great Bear River site is consistent with Figure 3, which shows a large persistent lag for the entire open water season. The data for the Klondike River show differences in lag that are dependent on season, with an average lag of 1 d. For the Yukon and Liard Rivers, the optimal lag times

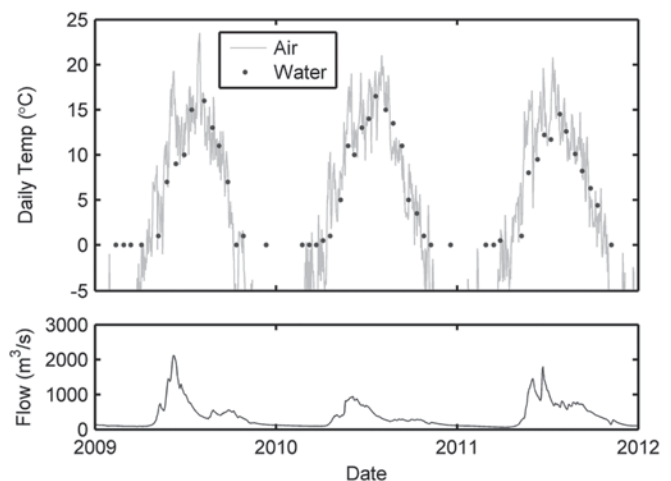


FIG. 5. The Liard River (10AA001) air and water temperatures and flow measurements during 2009–11.

are 14 d and 1 d, respectively. For these low-frequency, long-term data sets, the relationship between correlation and lag time is seen to be very noisy (Fig. 8). The Klondike and Great Bear monitoring sites, which are the high-frequency short-term data sets, show a smooth relationship. The differences are likely due to sampling frequency. In particular, low-frequency long-term data sets have fewer data points available to be used in determining optimal

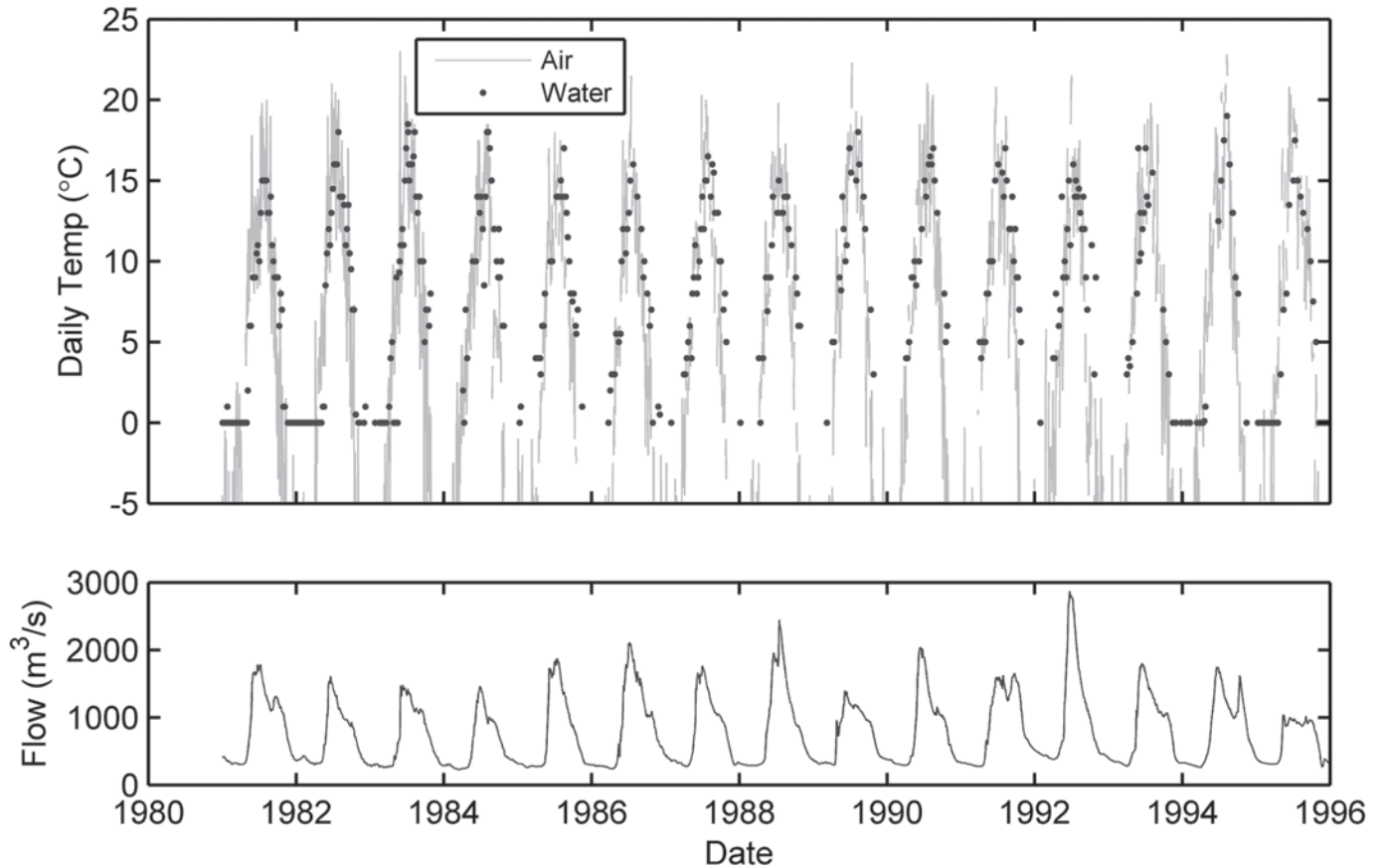


FIG. 6. Yukon River at Carmacks (09AH001) bi-weekly water temperature, daily air temperature, and daily flow during 1981–96.

lag, and the instantaneous measurements were not always collected at the same time each day.

Scatterplots of water temperature versus air temperature are shown in Figure 9. Water temperature measurements from the two PYLTM sites fall along distinct lines, indicating a resolution of 1°C . The high-frequency data sets, although over a short time period, still provide more water temperature measurements than those from the long-term, low-frequency measurements of the PYLTM study. The relationship between water temperature and air temperature follows a linear trend at three of the four monitoring sites examined. The Great Bear River shows a curved trend. Low water temperatures in May and June represent the period when the Great Bear River is ice-free, but the lake remains frozen. When water temperature for this period is compared to air temperature with a 40 d time lag, poor correlation is seen (Fig. 9); the relationship is flat for air temperatures below 0°C . Correlation for the Great Bear River is stronger during the other open water months, when air temperature is above 0°C .

The water temperature models were tested on the four monitoring stations. The results are shown in Table 3. The performance metrics were calculated for the open water season only. The air2stream model (Toffolon and Piccolroaz, 2015) generally gave a superior fit compared to the s-shape and linear regression models. We also examined the effect of including discharge data in the

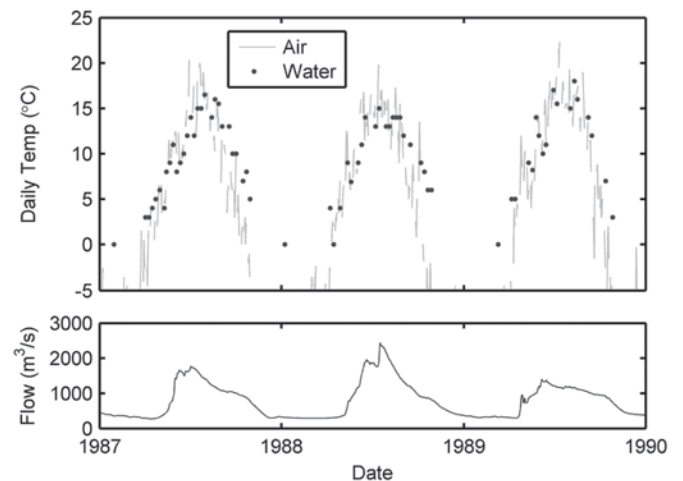


FIG. 7. Yukon River at Carmacks (09AH001) air and water temperatures and discharge during 1987–90.

water temperature models. Results indicated that adding discharge data improved water temperature simulation; however, the improvement was often small (difference in RMSE $< 0.15^{\circ}\text{C}$). We conclude that air temperature data alone may be sufficient. The water temperature estimates that improved the most with inclusion of discharge data were those of the Klondike River site. This result is expected because the correlation between water and air

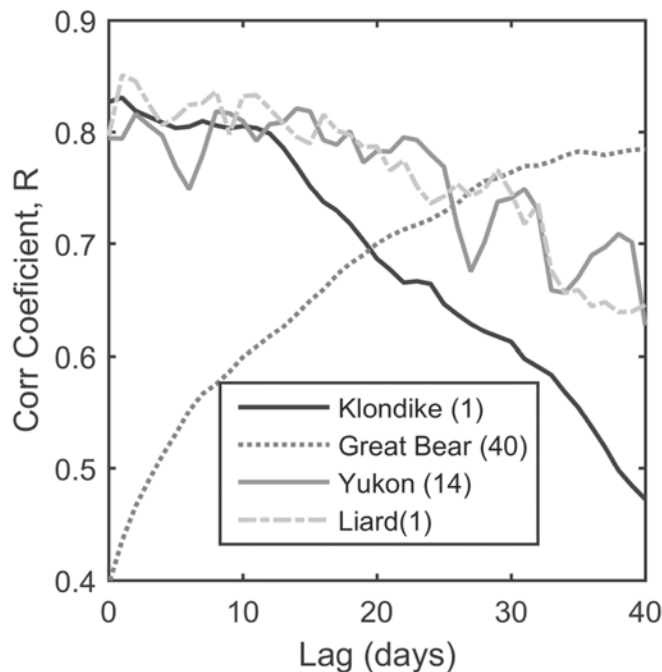


FIG. 8. Linear correlation between air and water temperature during open water season. The optimal lag time is given in parentheses.

temperature changes was seasonally affected by changes in discharge (Fig. 2).

The Klondike River water temperature observations were also the best fit to the temperature models (RMSE = 1.13°C; NSE = 0.91). The Great Bear River had the second best performance metrics (RMSE = 1.37°C; NSE = 0.81), followed by the Liard River (RMSE = 1.69°C; NSE = 0.84) and the Yukon River (RMSE = 2.10°C; NSE = 0.82). The differences in performance among the sites may be due to a number of factors. Important considerations are the length of the monitoring period and the water temperature sampling regime. The Klondike River and Great Bear River monitoring stations produced high-frequency, short-term datasets containing three to four years of water temperature observations. Longer time periods may show larger variations in river flow, as well as in air and water temperatures. Sampling regimes for the Klondike River and Great Bear River were 1 h and 3 h, respectively. The Liard River and Yukon River locations produced low-frequency, long-term data sets, making an instantaneous measurement once every two weeks for 15–20 years. An average of the sub-daily data likely provides a more representative daily average water temperature, as opposed to the instantaneous measurements from the PYLTM study. The metrics were calculated only for the open water season. However, it is important to note that the linear regression model cannot be used to predict water temperature in the winter. In particular, only the s-shape and air2stream models are able to predict a winter water temperature of 0°C.

In this study, water temperature was modeled from air temperature and flow data. Accuracy of water temperature estimates may also be improved by considering seasonally

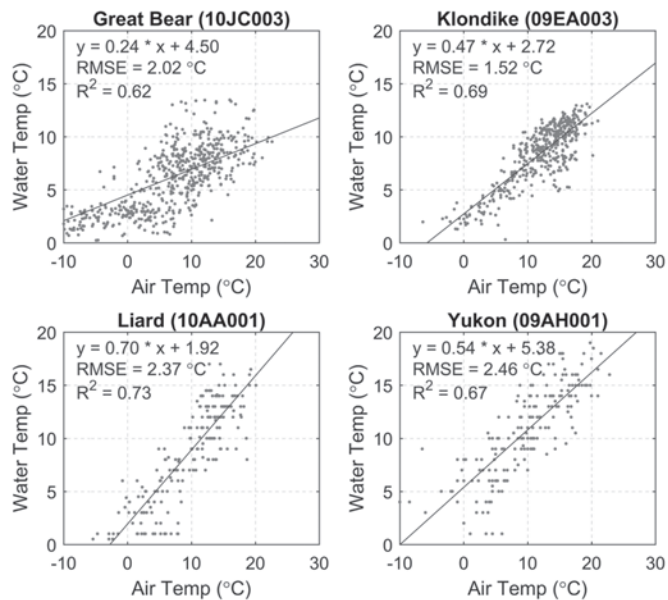


FIG. 9. Linear relationship between air and water temperatures at the optimal lag for the four monitoring stations.

based relationships. It can be seen from the Klondike River data (Fig. 2) that under lower discharge rates during late summer and fall, water temperature is similar to air temperature. The relationship between water temperature and air temperatures shows seasonal hysteresis. This phenomenon is most visible in the Great Bear River data, although also evident for the PYLTM monitoring sites.

Comparison of Monthly Water Temperatures

The mean monthly air and water temperatures for the four monitoring sites are shown in Figure 10. For the two PYLTM sites, the average number of measurements used to calculate the mean for each month was 17 (range: 11–22). For the high-frequency, short-term data sets, in contrast, ~90 measurements were used. Monthly air temperature peaks in July. Water temperature also usually peaks in July, but mean air temperatures are generally similar in July and August. A few conclusions can be drawn from the figure. At the monthly timescale, water and air temperatures follow a similar seasonal pattern, which suggests that air temperature exerts a strong direct or indirect control over water temperature. Secondly, the larger optimal lags for the Yukon (09AH001) and Great Bear (10JC003) Rivers are evident on a monthly scale. Lastly, for the monitored sites on the Yukon (09AH001) and Liard (10AA001) Rivers, a relatively small difference is seen between monthly air and water temperatures compared to the other two sites. It is possible that this result is due to water temperature sampling frequency. Water temperature samples for these two PYLTM sites were taken at an average of 2 pm local standard time, with a standard deviation of 3–4 h. The majority of these samples may therefore represent water temperatures warmer than the daily mean.

TABLE 3. Performance metrics for the different water temperature models: RMSE in °C with NSE in parentheses.

	Klondike 09EA003	Great Bear 10JC003	Liard 10AA001	Yukon 09AH001
1: Linear (Ta)	1.52 (0.69)	2.02 (0.62)	2.38 (0.73)	2.46 (0.67)
2: Linear (Ta & Q)	1.12 (0.83)	1.99 (0.63)	2.30 (0.74)	2.45 (0.68)
3: S-shape (Ta)	1.47 (0.71)	1.89 (0.66)	2.20 (0.76)	2.28 (0.72)
4: S-shape (Ta & Q)	1.26 (0.79)	1.74 (0.68)	2.15 (0.78)	2.25 (0.73)
5: air2stream 5-par (Ta)	1.13 (0.91)	1.37 (0.81)	1.69 (0.84)	2.10 (0.82)
6: air2stream 8-par (Ta & Q)	1.13 (0.89)	1.18 (0.86)	1.64 (0.83)	2.06 (0.83)

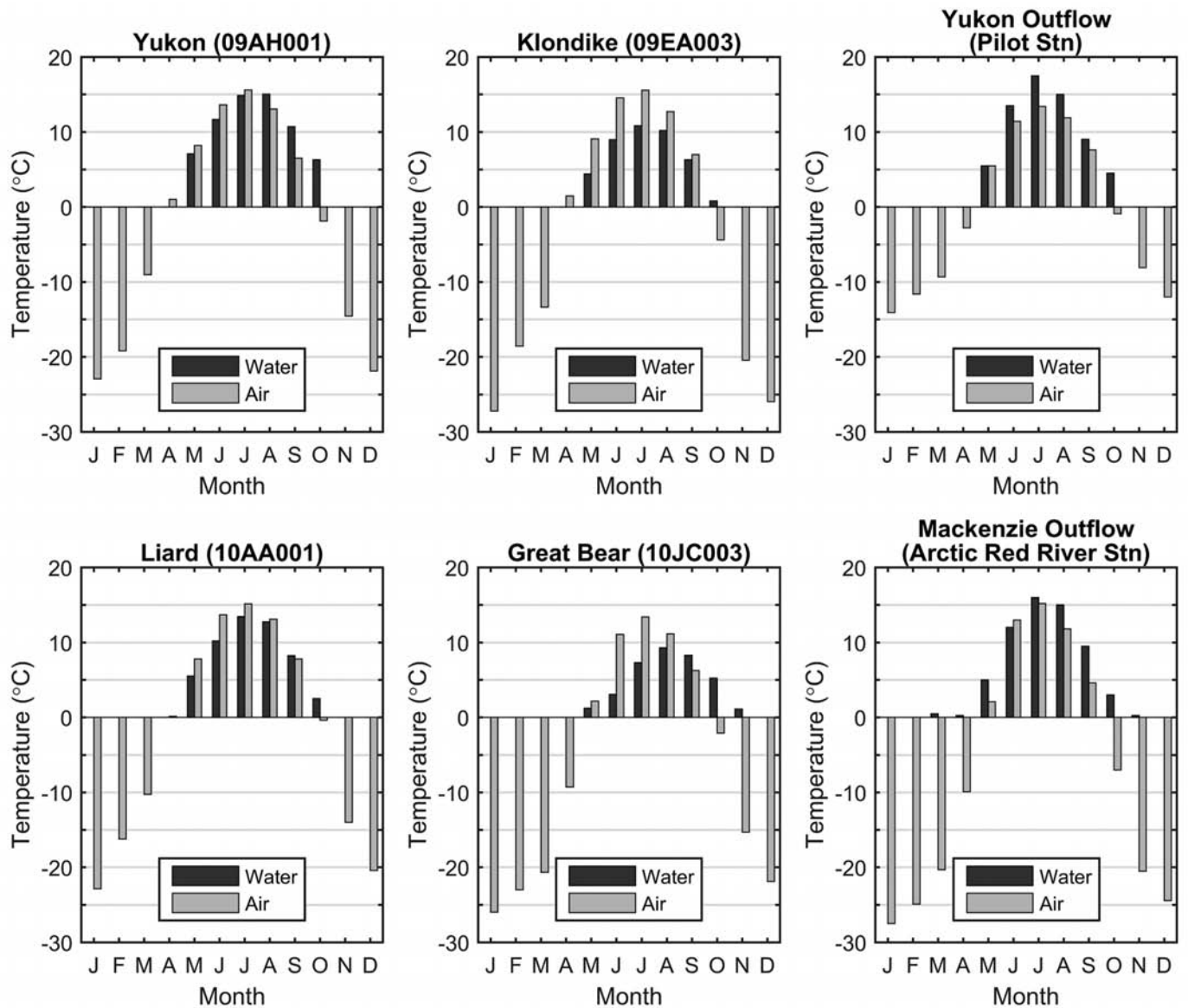


FIG. 10. Comparison of mean monthly air and water temperatures for the monitoring sites and outlet stations in the Yukon (top) and Mackenzie (bottom) River basins. Stations are arranged from most upstream (left) to most downstream (right). Outlet station data are from Yang et al. (2014).

Comparison of the data sets indicates that spatial variability in air and water temperatures is perhaps due mainly to the differences in sampling periods and regimes. For example, the mean July air temperature at the Klondike River is the same as at the Yukon River and higher than at the Liard River, even though the Klondike River station is at a higher latitude. The data sets cover different and

almost non-overlapping time periods. The Klondike River data cover the years 2010–12, while the Yukon River at Carmacks and the Liard River have observations for 1980–1996 and 1991–2013, respectively.

Mean monthly water temperatures for the outlets of the Mackenzie and Yukon basins are presented in Figure 10. The monthly water temperatures were developed from a

long-term data record with low temporal resolution (Yang et al., 2014). The mean July water temperatures of the Yukon River at the Pilot station and the Mackenzie River at the Arctic Red River station were about 17°C and 16°C, respectively (Yang et al., 2014). At the Pilot station, mean monthly water temperature during the open water season is generally a few degrees higher than local mean monthly air temperature; the Arctic Red River station exhibits similar characteristics. This pattern differs from that of the other four monitoring stations, where mean water temperature is generally lower than local air temperature during the open water season (Fig. 10). It is important to note that the discharge at the four monitoring stations is considered low with respect to the total discharge from the Yukon and Mackenzie basins. For example, at the Pilot and Arctic Red River stations, the average June flow rates are 16 000 m³/s and 20 000 m³/s, respectively (Yang et al., 2014). Of the four monitoring stations analyzed in this study, the Yukon River at Carmacks had the highest flow, with a June average of 1500 m³/s, which accounts for less than 10% of the outflow at the Pilot station. Discharge is strongly related to the size of the contributing area. The Pilot and Arctic Red River stations have large contributing areas, and all water from the Yukon and Mackenzie basins exits through these two channels, whereas the four monitoring locations examined in this study have small contributing areas. In cases of big rivers and high discharge, such as those near the outlets of large basins, local air temperature may not be a good predictor for water temperatures. The use of air and water temperatures of upstream tributaries may be a potential consideration for estimating water temperatures at the Pilot station or Arctic Red River station.

The water temperatures at the Pilot and Arctic Red River stations are significantly warmer than those at the upstream stations. In contrast, Liu et al. (2005), who examined the spatial variability of water temperature over the Lena River basin in Siberia, found water temperature at the outlet of the Lena River to be several degrees cooler than in the upstream sub-basins (Liu et al., 2005). Water temperature data in Russia, where the pattern of water temperature decreasing with latitude towards the basin outlet was observed, are long-term data and more consistent in terms of monitoring duration and frequency than data from the sites examined in this study. The quality and frequency of water temperature measurements across the Yukon and Mackenzie watersheds have been inconsistent, which may have led to the different results from this study. In addition, water temperatures over the Mackenzie and Yukon basins are monitored by several different agencies for various purposes and we therefore lack the benefits of a unified network. In particular, the time of the measurement, frequency, and monitoring duration are not consistent amongst sites. Measurement depth and position from shore are also likely not consistent and may contribute to the variation in results.

CONCLUSION

Water temperature data are lacking across the Mackenzie and Yukon River basins, particularly long-term records with high temporal frequency. This study examined the water temperature regimes at four monitored locations within the upper Yukon and central-lower Mackenzie regions. Two of the monitoring sites (Klondike River and Great Bear River) had high-frequency, short-term data: sub-daily water temperature records for a few years. The Klondike River had a water temperature regime typical of low-flow northern rivers and demonstrated how seasonal flow patterns may affect air temperature–water temperature correlations. The water temperature regime of the Great Bear River monitoring location was strongly influenced by the heat storage of Great Bear Lake, representing an example of strong upstream (lake) control. Water temperature measurements taken at the Liard River and the Yukon River at Carmacks during the PYLTM program were low-frequency, long-term records: bi-weekly measurements over decades. The data at these sites generally captured the annual water temperature cycle and appeared to match air temperature well. However, it was found that the instantaneous water temperature measurements may not represent the daily average.

The characteristics of the two different data sets strongly influenced data analysis and model performance. We investigated the association between water and air temperatures for each monitoring site. Uncertainty in the correlation between air and water temperatures and lag time was seen for the low-frequency, long-term data sets, but not for the high-frequency, short-term data sets. We compared the water temperature regimes of the sites by examining differences in mean monthly values. Because the sites were monitored in different years, it is not easy to develop clear conclusions about the spatial variability of water temperature among the sites. We examined the performance of several water temperature models using air temperature and flow data as inputs. Model performance was slightly improved by including discharge. The best fits were found for the high-frequency, short-term data sets. The air2stream model, a physically structured hybrid model with calibrated parameters, performed better than the statistical regression models.

Water temperature is very important to many applications and relatively easy to measure. Unfortunately water temperature has not been systematically observed at the northern operational and research networks in Canada and the United States. In the Mackenzie and Yukon Rivers, water temperature data were traditionally taken in conjunction with irregular water chemistry and sediment samples. Water temperature directly affects many aspects of basin hydrology and ecology. As climate warms over the high latitudes, there is an urgent need to improve water temperature observations in the northern regions of Canada.

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