



# Yukon River Water Isotope Data

Interpretation of Canadian Indigenous  
Observation Network Results



**Northern Climate ExChange**  
YUKON RESEARCH CENTRE • Yukon College



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Whitehorse, Yukon  
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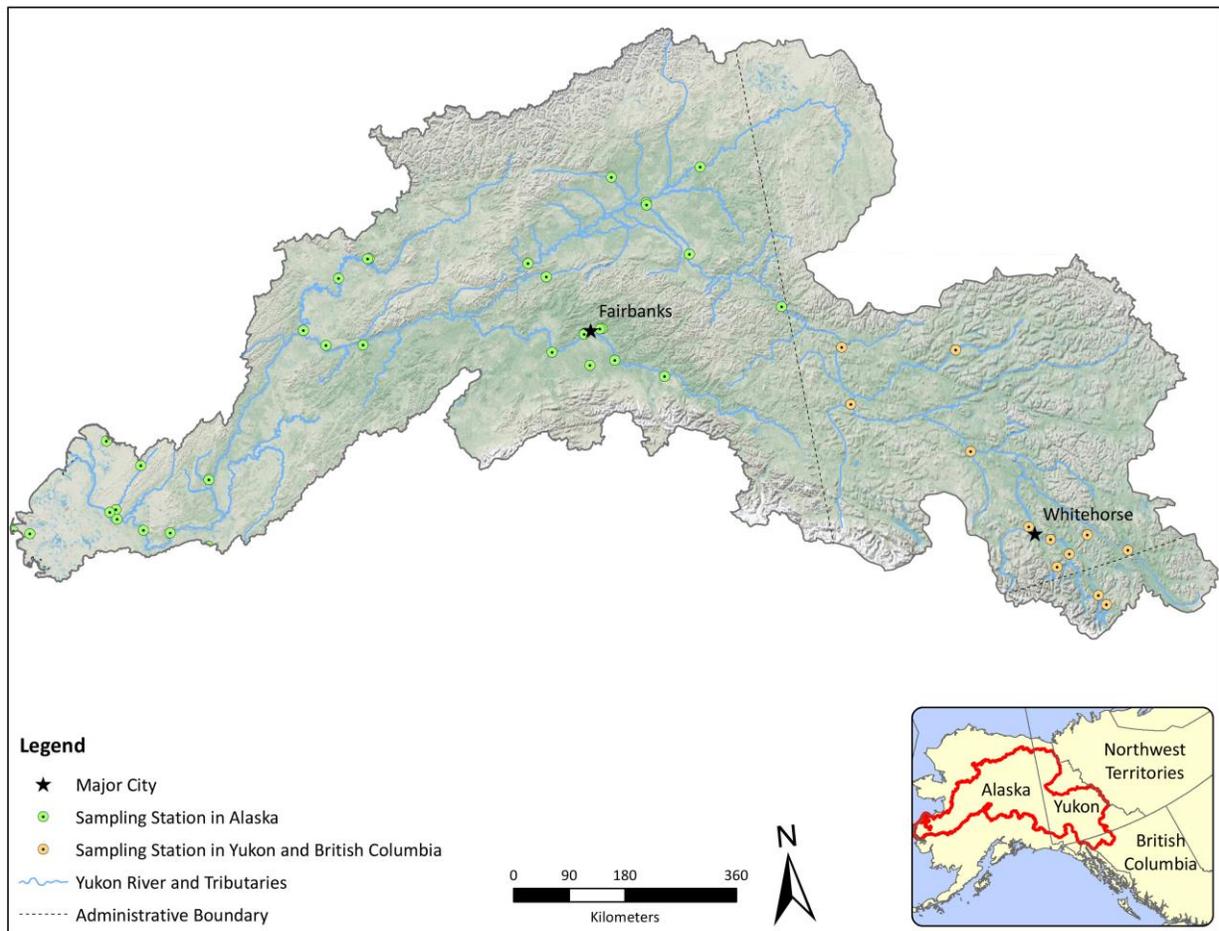
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**LIST OF ACRONYMS AND INITIALISMS**

|                |   |
|----------------|---|
| $\delta^*$     | Limiting isotopic composition (i.e., composition of the last drop of water in an evaporating water body)    |
| $\delta_p$     | Isotopic composition of annual precipitation  |
| $\delta_{ps}$  | Isotopic composition of summer precipitation  |
| $\delta_{SSL}$ | Isotopic composition of a water body at isotopic and hydrologic steady state under given climate conditions |
| GMWL           | Global meteoric water line  |
| ION            | Indigenous Observation Network  |
| LEL            | Local evaporation line  |
| NCE            | Northern Climate Exchange   |
| VSMOW          | Vienna Standard Mean Ocean Water  |
| YRC            | Yukon Research Centre   |
| YRITWC         | Yukon River Intertribal Watershed Council   |

## PROJECT INTRODUCTION

This project examines a robust set of water isotope data collected within the Yukon River watershed. The data was collected by the Yukon River Intertribal Watershed Council (YRITWC)'s Indigenous Observation Network (ION) of community-based monitors over the past several years, at sampling nodes along the Yukon River (see Figure 1 for ION sampling site locations throughout the Yukon River watershed). Here, the YRITWC has partnered with the Northern Climate Exchange (NCE; part of the Yukon Research Centre at Yukon College) to work towards interpretation of the isotope data collected from Canadian stations.



**Figure 1.** Location of Indigenous Observation Network Yukon River monitoring sites within the Yukon River watershed.

The YRITWC has been charged by its signatory Tribes and First Nations with coordinating the collection, analysis and amalgamation of water quality and quantity data for the Yukon River, for the purposes of protection and preservation of the Yukon River watershed. The YRITWC's signatories are particularly concerned about climate change impacts on fish habitat in the Yukon River, and thus the monitoring program the YRITWC coordinates through its Indigenous Observation Network aims to assess water quality within the framework of the Canadian Council of Ministers of the Environment's Water Quality Guidelines for the Protection of Aquatic Life.

This project, which focuses on interpretation of the water isotope component of YRITWC's dataset, represents an important step forward in returning information to the communities in which it was collected, and to the monitors who were involved in its collection. It contributes towards the process of integrating YRITWC's data in watershed planning, resource management, and adaptation-related decision-making.

It is important to note that this project focuses mainly on sample results collected from Canadian sites, which span the Yukon River headwaters to the Alaska border. Some samples at the mouth of the Yukon River in Alaska will also be examined, but most of this report will focus on Canadian sites.

## **USING WATER ISOTOPE TRACERS FOR HYDROLOGY RESEARCH**

Water isotope tracers are increasingly being used in hydrology research as a tool to assess water movement through the hydrological cycle. In many cases, collecting a small sample of water can be a simpler, more cost-effective approach to assessing hydrology than traditional hydrological monitoring methods. On a site by site basis, water isotope tracers allow researchers to begin to assess the relative roles of different inputs (like rainfall, snowmelt and groundwater) and outputs (like evaporation) to local hydrology. Water isotope tracers can be used to tracer water origins, for hydrograph separation, and as the basis for comparing hydrological variability between sites or over time.

For this project, water isotope tracers can be used to assess key components of Yukon River hydrology, and how these components vary both over space and over time within the watershed. YRITWC's integration of water isotope tracers as part of their suite of sampled parameters is a progressive approach to its monitoring program.

The analysis and interpretation of water isotope tracers is rooted in the composition and structure of the water molecule. The oxygen and hydrogen elements that make up the water molecule naturally have different isotopic species – that is, there are different “species” of oxygen and hydrogen molecules that have the same number of protons in the atom, but a different number of neutrons. All oxygen and hydrogen molecules behave the same way chemically, as a result of having the same number of protons, but the different numbers of neutrons between species give the elements different atomic masses. Oxygen has three isotopic species - oxygen-16 ( $^{16}\text{O}$ ), oxygen-17 ( $^{17}\text{O}$ , which is relatively rare) and oxygen-18 ( $^{18}\text{O}$ ), while hydrogen has two naturally occurring isotopic species, protium ( $^1\text{H}$ ) and deuterium ( $^2\text{H}$ ). (Tritium, or  $^3\text{H}$ , is an unstable isotopic species of hydrogen that is naturally very rare, but is produced via nuclear reactions, and has its own unique role in tracing water origin and age. Tritium is not considered as part of this project.) With the exception of  $^3\text{H}$ , the isotopic species of oxygen and hydrogen are stable (i.e., they do not decay over time, like  $^{14}\text{C}$ ) and mass conservative (i.e., no new molecules can be created or destroyed over time). This means that their behavior is relatively predictable, and can be modelled and applied, in this case to the study of hydrological processes.

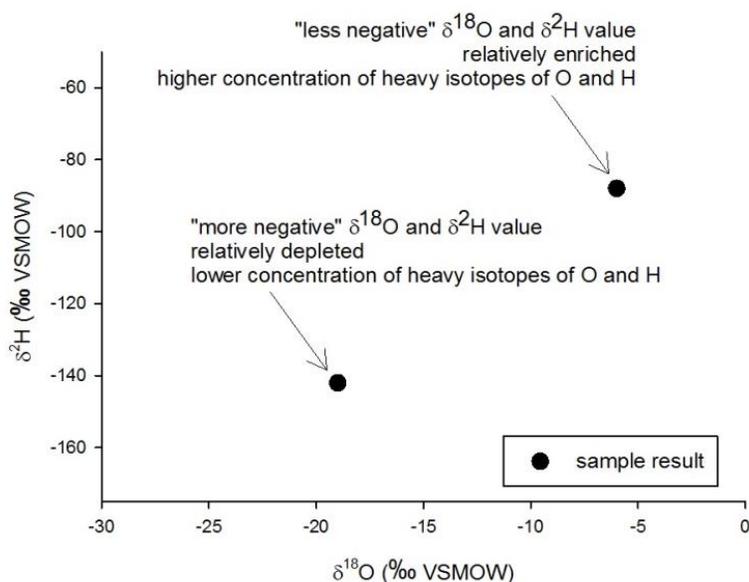
The use of water isotope tracers becomes very useful in the study of hydrology because a molecule of water made of lighter isotopic species of oxygen and hydrogen, like  $^{16}\text{O}$  or  $^1\text{H}$ , will be lighter overall than a water molecule made of the heavier species like  $^{18}\text{O}$  or  $^2\text{H}$ . In turn, the mass differences of different water molecules, or isotopic species of water, means they move through the hydrological cycle in different ways - heavier water molecules are the first to fall as rain or snow, while the lighter molecules are the first to evaporate. By measuring the ratio of light to heavy water isotope tracers in a water sample and a standard, and by examining results in the context of some additional constraining factors (discussed below), researchers can use water isotope tracers to understand site-specific and basin-wide hydrological processes.

### How Results Are Interpreted

Water isotope results are expressed as delta ( $\delta$ ) values, in parts per thousand (‰, or per mil), reflecting the ratio of  $^{18}\text{O}/^{16}\text{O}$  or  $^2\text{H}/^1\text{H}$  in a water sample versus a globally accepted standard (Vienna Standard Mean Ocean Water, or VSMOW). A negative value means that the sample has less of the heavy isotope than the standard, while a positive value means the sample has more of the heavy isotope relative to the standard. In studies in cold regions, results are always negative, meaning water samples always have less of the heavier isotope than the standard.

Results are often discussed in terms of relative enrichment or depletion. A sample that is relatively depleted compared to another sample is “more negative” – that is, the sample has less of the heavy isotope than relatively more enriched or “less negative” value. This language makes the interpretation of water isotope tracers somewhat confusing!

However, interpretation can be simplified by examining sample results on a  $\delta$ - $\delta$  plot. These plots show  $\delta^{18}\text{O}$  (the oxygen isotope result) along the x-axis and  $\delta^2\text{H}$  (the hydrogen isotope result) along the y-axis. Results of the isotopic analysis of water samples can be plotted on these plots, also called  $\delta$ - $\delta$  space, and examined relative to each other, which simplifies the mental math required to interpret “less negative” and “more negative” results. Figure 2 shows an example of a  $\delta$ - $\delta$  plot illustrating these principles.



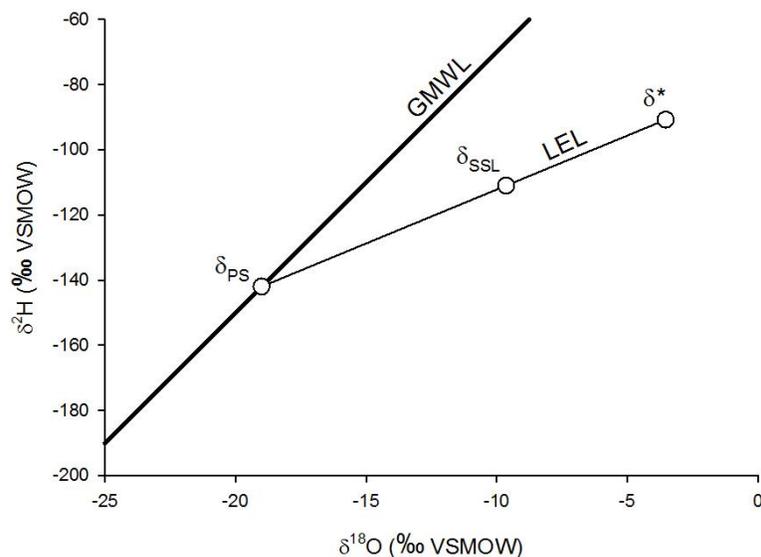
**Figure 2.** Sample  $\delta$ - $\delta$  plot showing two hypothetical sample results. Annotations illustrate the language used to describe the composition of one sample relative to the other.

Researchers often build a framework within  $\delta$ - $\delta$  space that facilitates interpretation of results. This framework provides researchers with the basis for examining relative contributions of one sample against other key parameters, like the composition of rainfall or the composition of a lake at isotopic and hydrologic steady state. The backbone of the isotopic framework is the Global Meteoric Water Line (GMWL). This line shows the relationship between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in precipitation arising from the global ocean source, measured in samples collected from stations around the world (Craig, 1961), and its equation is  $\delta^2\text{H} = 8 * \delta^{18}\text{O} + 10$ . However, because isotopic compositions of water samples change during rainfall and evaporation, for example, the composition of a water sample from surface water like a river will not usually fall along the GMWL. Instead, local water samples typically fall along a Local

Evaporation Line (LEL), which has a slope that is defined by local climate conditions and reflects the role evaporation, among other factors, plays in controlling water balances.

For this study, the slope of the LEL has been calculated using local climate conditions (i.e., 30-yr climate normal data measured from Environment Canada’s meteorological monitoring station at Whitehorse Airport (Environment Canada, 2014)). Two points of reference are typically shown on the LEL. These are the isotopic composition of a water body at hydrological and isotopic steady state (i.e., the ratio of evaporation to inflow is equal ( $E/I = 1$ )), which is shown on  $\delta$ - $\delta$  plots as  $\delta_{SSL}$ , and the limiting isotopic composition, or the modelled composition of the last drop of water under given climate conditions before a water body completely evaporates. This parameter is typically shown as  $\delta^*$ , and it bounds the enriched end of the LEL. The depleted end of the LEL is bound by its intersection with the GMWL, and this point represents the approximate composition of local precipitation. It is often referred to as  $\delta_l$  ( $l =$  input), but here, we refer to this point as  $\delta_{ps}$ , where PS = summer precipitation, because this value is the same as values published for local summer precipitation (Gibson and Edwards, 2002).

An example  $\delta$ - $\delta$  plot, constructed using data relevant to this study, is shown below in Figure 3.



**Figure 3.** Example of an isotopic framework in  $\delta$ - $\delta$  space. GMWL = Global Meteoric Water Line; LEL = local evaporation line;  $\delta_{ps}$  = approximate isotopic composition of summer precipitation;  $\delta_{SSL}$  = isotopic composition of a lake at isotopic and hydrological steady state, and  $\delta^*$  = limiting isotopic composition. The framework is constructed based on 30-yr climate normal data measured at the Whitehorse Airport meteorological monitoring station (Environment Canada, 2014).

## SAMPLE COLLECTION AND ANALYSIS

Water samples were collected from nodes along the Yukon River by ION technicians. Sampling site names, coordinates and elevations for Canadian sites are included in Table 1, while Figure 5 shows locations of Canadian sampling sites. Water samples were collected by boat, from the main channel, flow or most central point at each sampling location. Where a boat was not available for sample collection, samples were collected just off shore, along a straight reach of the river as far as possible from eddies or features disrupting natural flow. Samples were collected from  $\sim 10$  cm below the surface of the water in a holding jar. For water isotope analysis, water from the holding jar was filtered through

a 0.45 µm GMF filter and then subsampled into 10 mL glass vials, which were tightly capped and sent for analysis.

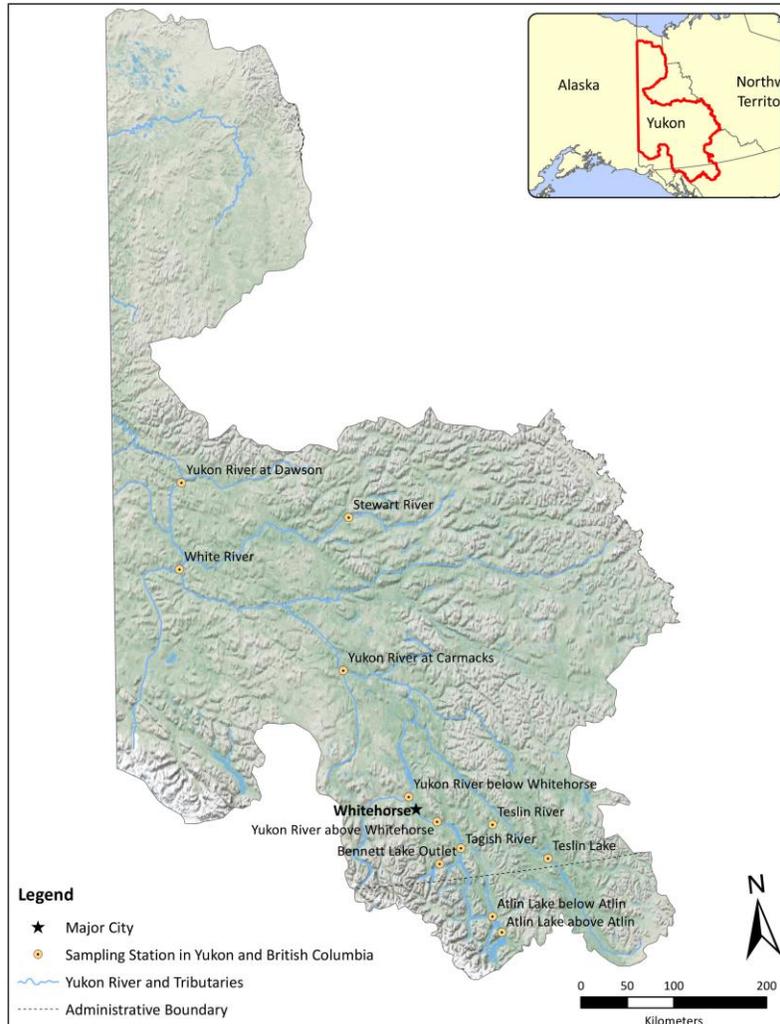
Typically, samples were collected by ION monitors several times during the thaw season – in early spring, during the summer months, and in late summer/early fall before freeze-up. Sampling frequency varies between sites. It is important to note that at the time this report was prepared, the USGS laboratory analyzing the sample results had quite a backlog of samples to analyze. As of the time of writing, no samples collected after early 2010 had been analyzed, although sampling by ION monitors continued after this period.

**Table 1. ION monitoring sites in the Canadian portion of the Yukon River watershed.**

| YRITWC    |                              | Latitude | Longitude | Elevation | Sample |            |          |
|-----------|------------------------------|----------|-----------|-----------|--------|------------|----------|
| Site name | Water body name              | dec deg  | dec deg   | masl      | count  | Start date | End date |
| atysq1a   | Atlin Lake above Atlin       | 59.438   | -133.670  | 671       | 5      | 08-07-07   | 10-03-12 |
| atysq1b   | Atlin Lake below Atlin       | 59.599   | -133.815  | 671       | 7      | 08-06-23   | 10-03-12 |
| teyzw1a   | Teslin Lake                  | 60.087   | -132.601  | 688       | 3      | 08-06-12   | 10-05-25 |
| teyzw1b   | Teslin River                 | 60.482   | -133.592  | 681       | 16     | 08-07-10   | 10-03-11 |
| becfa1a   | Bennett Lake outlet          | 60.163   | -134.715  | 671       | 10     | 08-06-10   | 10-05-24 |
| tacfa1b   | Tagish River                 | 60.293   | -134.262  | 653       | 14     | 08-06-10   | 10-05-24 |
| yuyxy1a   | Yukon River above Whitehorse | 60.574   | -134.670  | 652       | 15     | 08-06-04   | 10-05-25 |
| yuyxy1b   | Yukon River below Whitehorse | 60.839   | -135.180  | 633       | 12     | 07-03-23   | 10-05-25 |
| yucex1a   | Yukon River at Carmacks      | 62.118   | -136.263  | 652       | 13     | 08-06-03   | 09-09-06 |
| whyda1a   | White River                  | 63.192   | -139.592  | 366       | 4      | 08-07-03   | 09-07-30 |
| styma1a   | Stewart River                | 63.587   | -135.860  | 549       | 13     | 08-06-24   | 09-09-06 |
| yuyda1a   | Yukon River at Dawson        | 64.028   | -139.478  | 320       | 24     | 06-05-30   | 10-07-12 |

Samples were analyzed for  $^{16}\text{O}/^{18}\text{O}$  and  $^1\text{H}/^2\text{H}$  ratios by the United States Geological Survey National Research Program laboratories in Boulder, CO. Results are reported as  $\delta$  values, expressing deviations per mil (‰) between the sample being analyzed and the V-SMOW standard on a scale normalized to Standard Light Arctic Precipitation ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H} = -55.5\text{‰}$ ,  $-428\text{‰}$ ; Coplen, 1996). The type of isotope ratio mass spectrometer and the analytical uncertainty of the instrument are unknown at this time, although typical uncertainty values are approximately  $\pm 0.2\text{‰}$  for  $\delta^{18}\text{O}$  and  $\pm 2\text{‰}$  for  $\delta^2\text{H}$ .

Climate data was obtained from Environment Canada meteorological monitoring stations located in the Yukon River watershed. Thirty-year climate normal data was obtained from the Whitehorse Airport station ( $60^\circ 42' 34.2''$  N,  $135^\circ 04' 07.8''$  W). Evaporation-flux-weighted values used in isotopic frameworks were derived from calculated potential evapotranspiration using methods described by Malmstrom (1969) and Dingman (1993). Isotopic framework parameters were calculated following methods described by Brock et al. (2007).



**Figure 4.** Location of ION sampling sites in the Canadian portion of the Yukon River watershed.

### THE YUKON RIVER WATERSHED IN CANADA

The Yukon River is the third longest river in North America (see Figure 1 for watershed overview). Rising in the Coast Mountains of northern British Columbia, the river travels almost 3200 km to its mouth at the Bering Sea. The entire Yukon River watershed drains an area approximately 840 000 km<sup>2</sup>, approximately 324 000 km<sup>2</sup> of which is situated in British Columbia or the Yukon. Average discharge for the river at its mouth is approximately 195 km<sup>3</sup> per year.

There is general agreement that the Llewellyn Glacier, part of the Juneau Icefields in the Coast Mountains, is the headwater source for the Yukon River. (Some consider Lindeman Lake to be a potential alternative headwater source.) Regardless of the primary source, the Yukon River proper begins at the outlet of Marsh Lake, above the headwater region known at the Southern Lakes area. This portion of the Yukon River watershed is hydrologically quite interesting. It is composed of several large, sinuous lakes, many of which have low connecting gradients and interact quite freely during certain periods of the year. For example, the water level of Marsh Lake can influence water levels on Bennett and Tagish lakes, through backwater effects that occur when Marsh Lake levels are high. However, other lakes in the Southern Lakes area are connected by rivers with steep hydrological gradients (e.g., Atlin,

Tutshi and Fantail lakes) and are therefore not influenced by backwater events from Marsh Lake (Yukon Energy, date unknown). These headwater lakes are important because, as sample results described below demonstrate, they attenuate winter snowmelt and summer precipitation signals, and act to somewhat moderate the isotopic composition of downstream discharge.

The headwaters of the Yukon River are regulated by Yukon Energy Corporation for energy generation at the Whitehorse dam. Marsh Lake is regulated by a control structure that is open in the summer, but closed through the winter season to maintain regular flows during the winter season, when energy demands are high. The lowest water levels in Marsh Lake are usually achieved in late April/early May, which maximum levels are usually reached in mid-August/early September. Typically, gates at Marsh Lake are open between May 15<sup>th</sup> and August 15<sup>th</sup> (Yukon Energy Corporation, date unknown).

After the Whitehorse dam, the Yukon River continues its course generally northwest towards the Alaska border. Major downstream tributaries include the Teslin, Pelly, White and Stewart rivers. (Samples from the Teslin, White and Stewart rivers are included as part of this report.) The White River, which is glacier-fed, introduces high loads of suspended sediment to the Yukon River, which remains noticeably more turbid after the confluence with the White River. Additional details about tributary rivers and their watersheds are included later in the report.

## **SAMPLE RESULTS AND OVERVIEW**

Sample results analyzed in this report are included in full in Appendix A.

To take a first look at YRITWC's dataset, all data were superimposed on an isotopic framework in  $\delta$ - $\delta$  space built using Whitehorse 30-yr climate normal data, as described above.

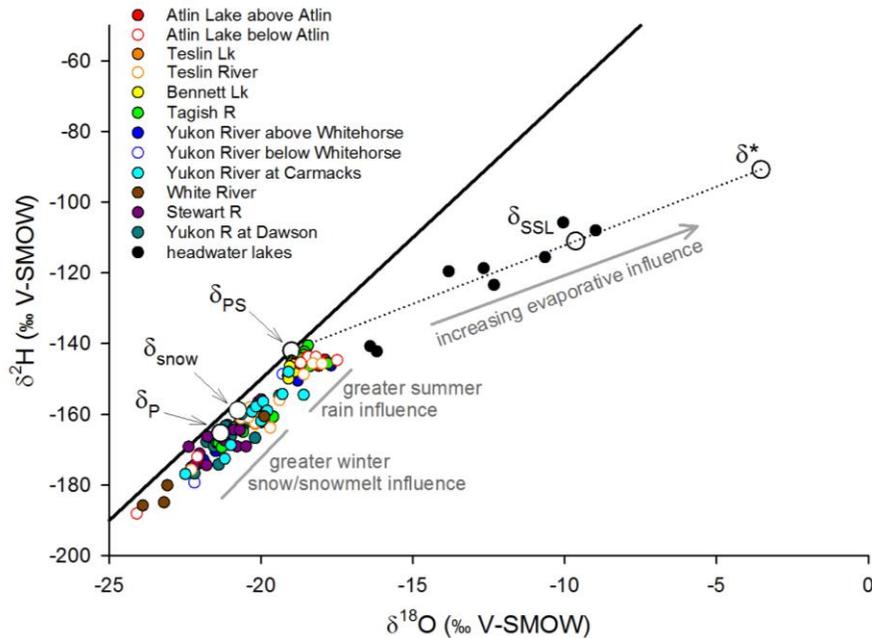
To check the validity of the isotopic framework built using climate normal data, several samples collected from lakes in the Yukon River headwaters via another NCE project are plotted on *Figure 5*. Field observations made at the time of sampling suggest these lakes were likely to undergo evaporation (i.e., samples were collected from lakes perched above drainage networks or surrounded by marsh, indicating minimal direct river influence). Indeed, these lakes plot along the LEL, suggesting the modelled trajectory of evaporative enrichment for the region is suitable. Because the intersection of the LEL and the GMWL is also an indicator of the approximate composition of local precipitation, it also supports the summer precipitation value published for the region (Gibson and Edwards, 2002).

As would be expected for samples collected from major fast-flowing rivers and large lakes with direct river influence, samples collected from the Yukon River and its major lakes all plot close to the GMWL. Evaporative enrichment in large rivers, especially in cold regions, is not expected, and indeed is not observed here – none of the sample results plot along the LEL.

Instead, sample results fall in two relatively distinct clusters parallel to the GMWL. These two clusters of samples roughly group around  $\delta_p$  and  $\delta_{ps}$ , respectively. This distinction indicates that one grouping of samples is largely influenced by the input of water with an isotopic composition comparable to that of amount-weighted annual precipitation, and one group is influenced by water with a composition comparable to that of amount-weighted summer precipitation. In other words, the more depleted samples are more heavily influenced by snowmelt runoff, while the other is more heavily influenced by summer rainfall.

Interestingly, samples do not seem to be split into these two groupings by geography, but rather by sampling year. Generally, samples collected in 2008 plot more closely to  $\delta_{ps}$ , while samples collected in 2009 plot more closely to  $\delta_p$ . This will be explored further in the sections below.

NCE researchers were able to collect samples of snow from the headwaters of the Yukon River during sampling campaigns for another project. Samples were collected from the Llewellyn Glacier, which is the primary source of water for the Yukon River, as well as from persistent high alpine snowpacks and other glacier study sites in the headwater region. Sample results appear to plot in close alignment with the amount-weighted annual precipitation value reported by the Global Network of Isotopes in Precipitation (IAEA/WMO, 2015), indicating consistency with locally measured values.



**Figure 5.** Water isotope results from ION sampling stations between the Yukon River headwaters and the Alaska border. Results are plotted on a framework constructed using 30-yr climate normal data from Environment Canada's Whitehorse station (Environment Canada, 2014). See Figure 3 for abbreviations.

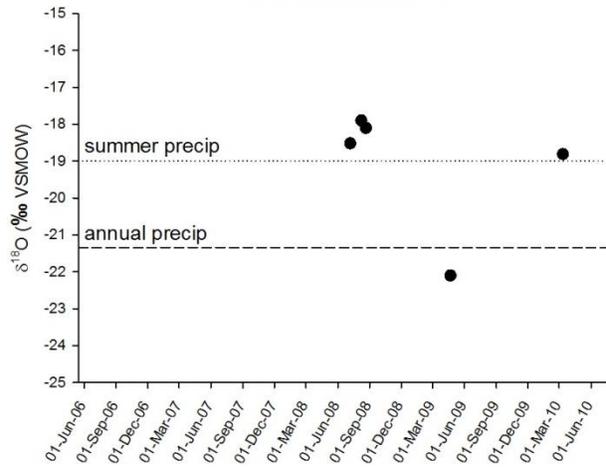
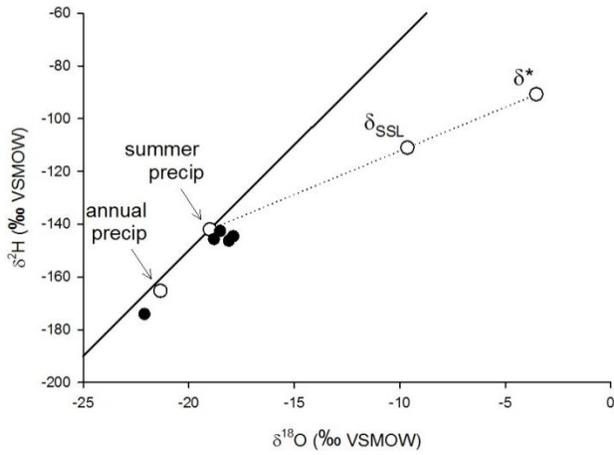
### Sample results by site

In order to examine trends in isotopic composition along the Yukon River, sample results from each of the ION monitoring sites were examined. Sites order follows roughly from the headwaters to the Alaska border. While trends in results are quite consistent between many sites, interesting trends on a site-by-site basis can still be inferred.

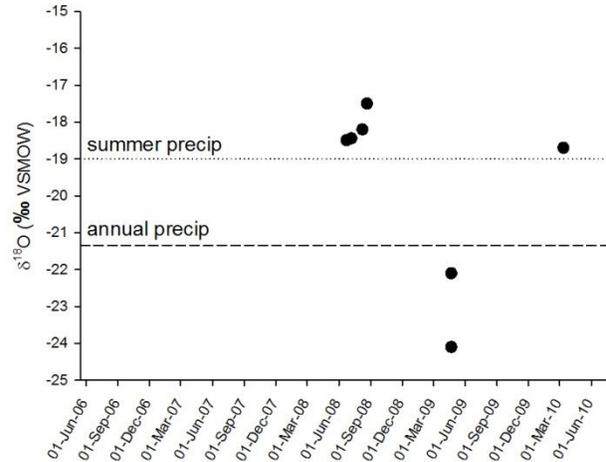
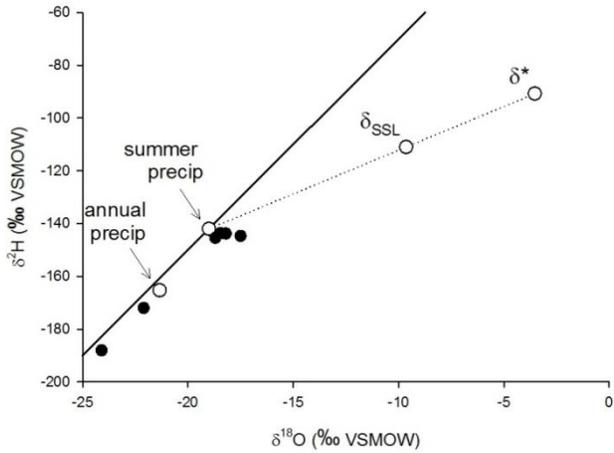
#### Atlin Lake above and below Atlin

Atlin Lake is the closest ION sampling point to the glacier at the headwaters of the Yukon River, and therefore the water composition of Atlin Lake can be considered to represent the initial isotopic composition of the Yukon River. ION monitors collect samples from Atlin Lake both above and below the community of Atlin. Results are shown in Figure 6a and Figure 6b. Most sample results plot closely around the intersection of the GMWL and the LEL, near  $\delta_{PS}$ , although Figure 6a and b indicates that these samples were collected in 2008. Samples collected in 2009 are comparably quite depleted; they plot close to, or beyond,  $\delta_P$ . However, these samples were collected above and below Atlin on April 22, 2009, collected on June 6, 2009, that is not consistent with other Bennett Lake outlet results ( $\delta^{18}O = -20.9\text{‰}$ ). It is possible that this sample result is an outlier; however, it may also be a valid result that is influenced by the same broader driver that is causing variability at other sampling sites in 2009.

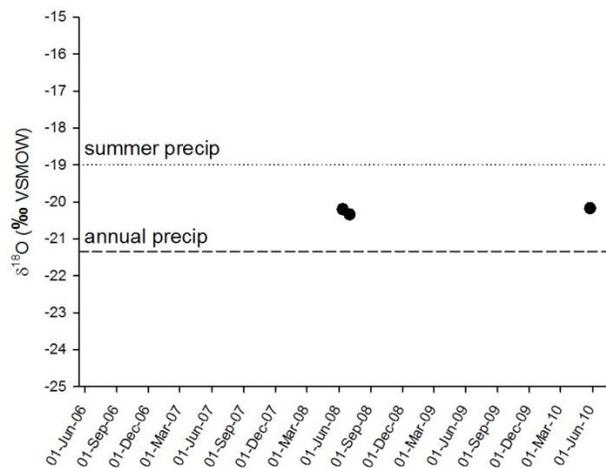
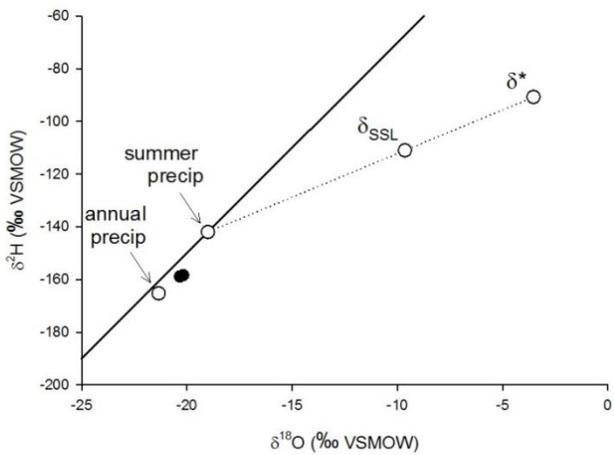
a) Atlin Lake above Atlin



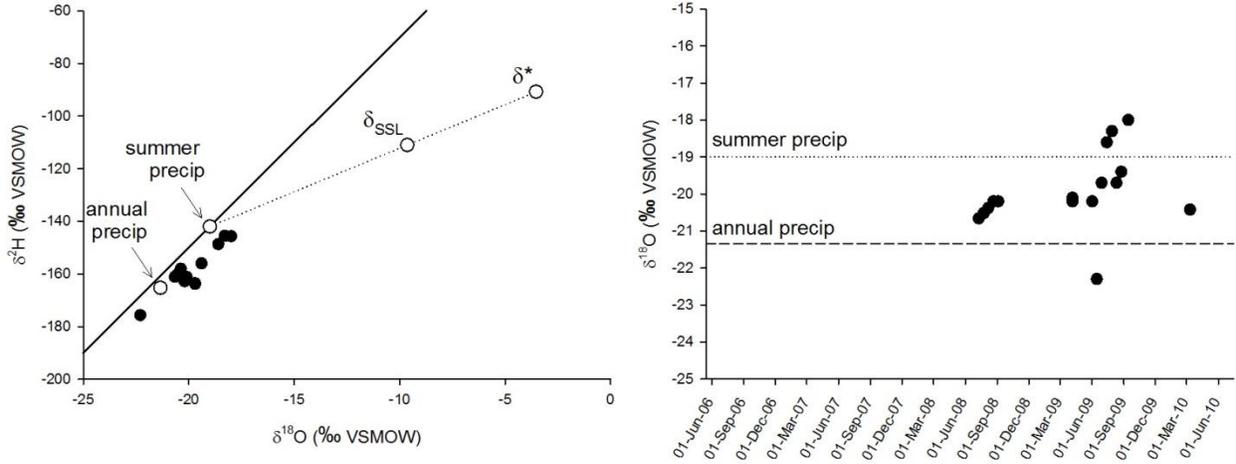
b) Atlin Lake below Atlin



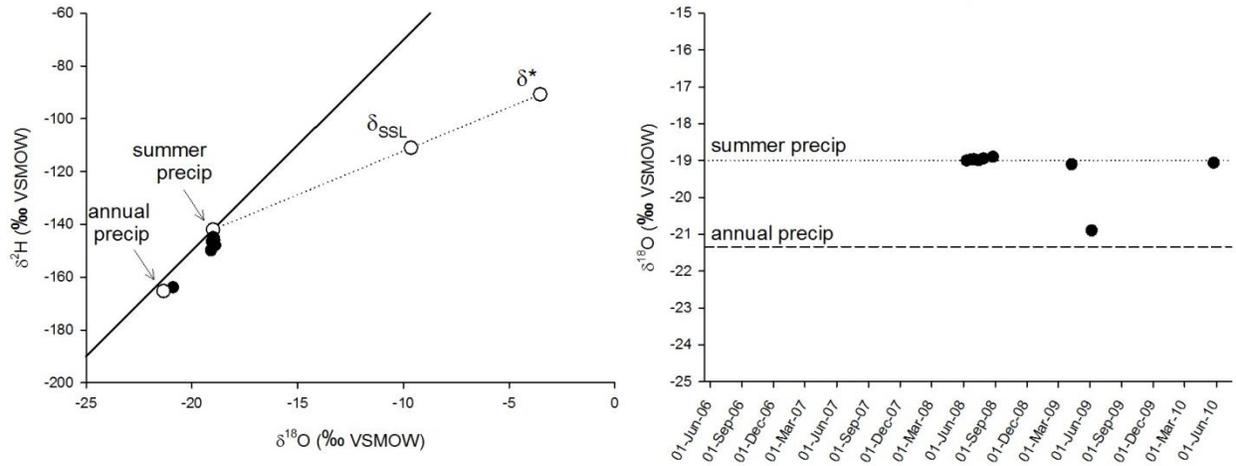
c) Teslin Lake



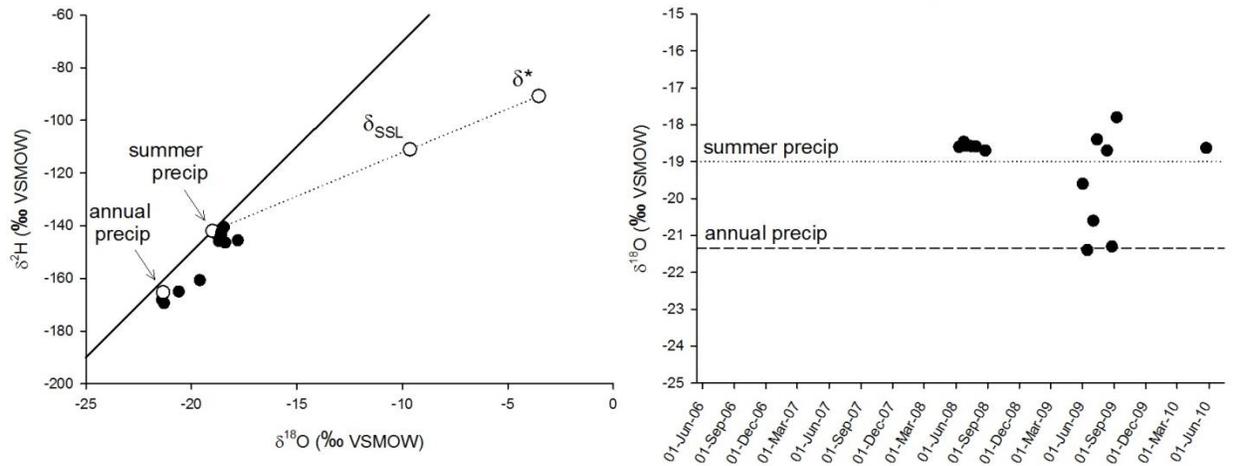
d) Teslin River



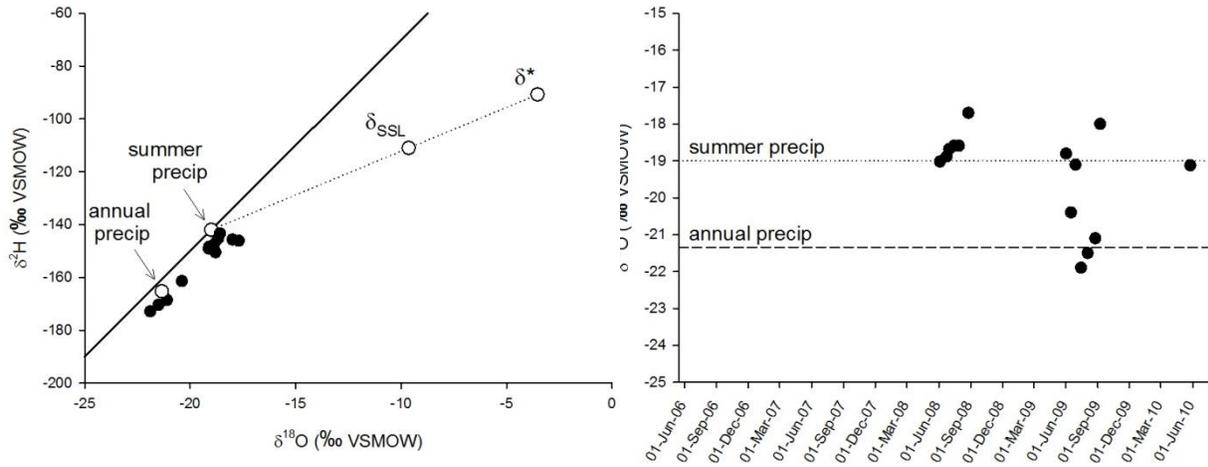
e) Bennett Lake outlet



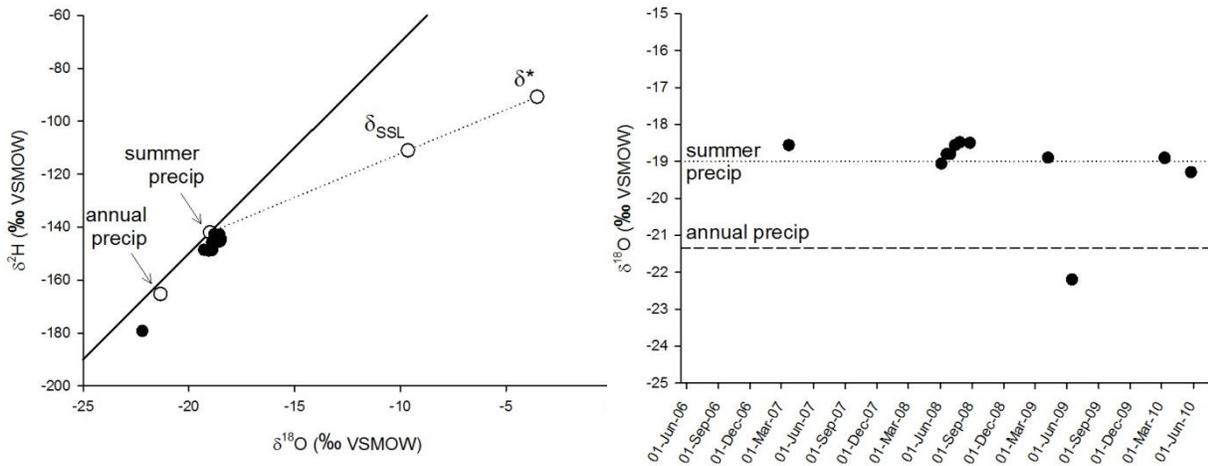
f) Tagish River



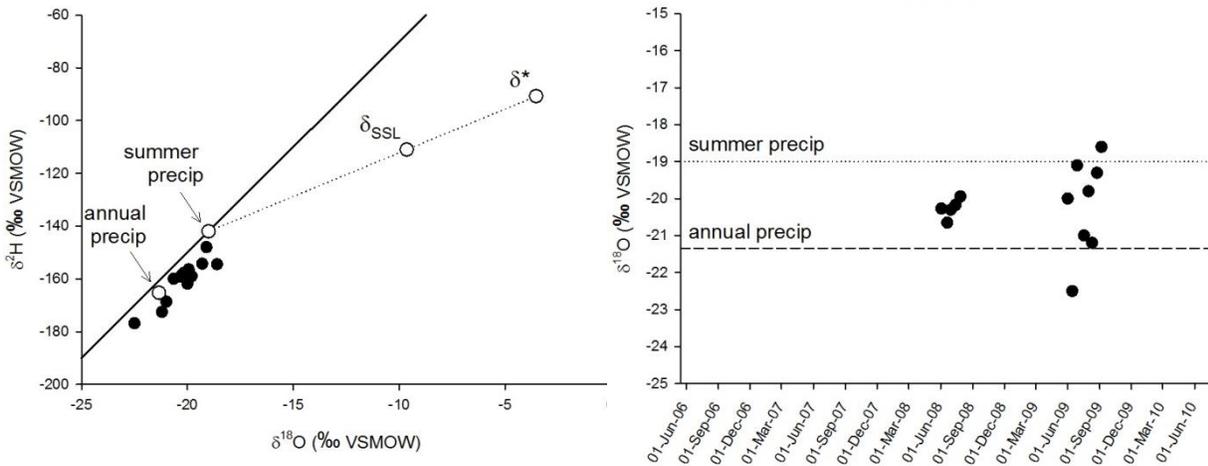
g) Yukon River above Whitehorse



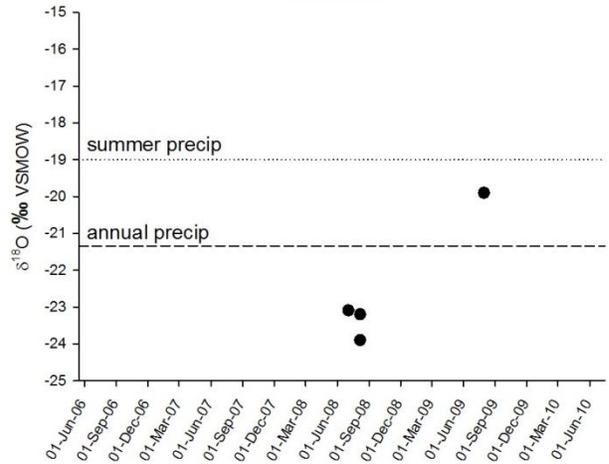
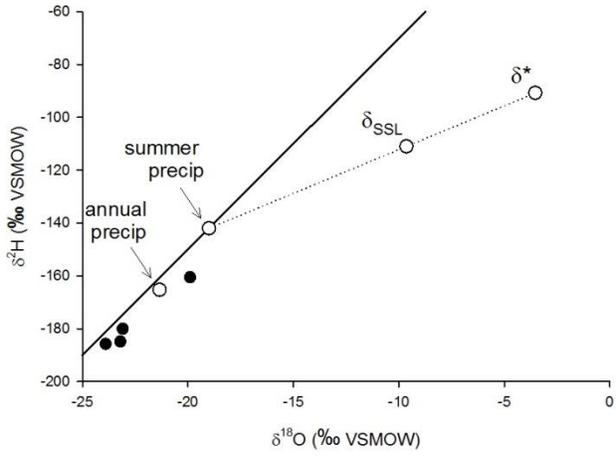
h) Yukon River below Whitehorse



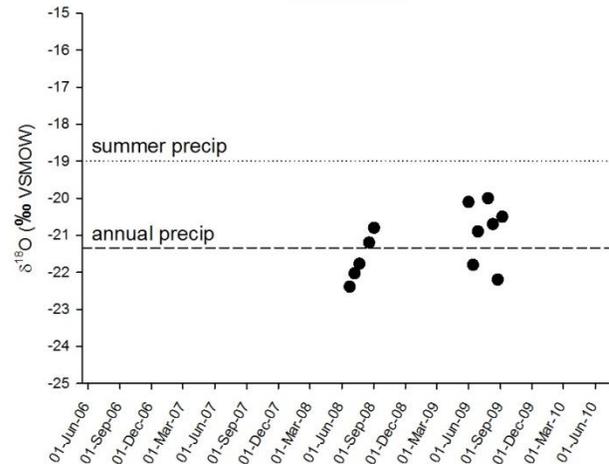
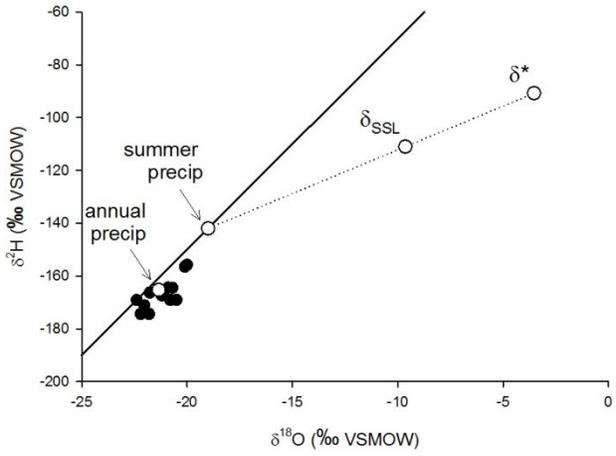
i) Yukon River at Carmacks



j) White River



k) Stewart River



l) Yukon River at Dawson

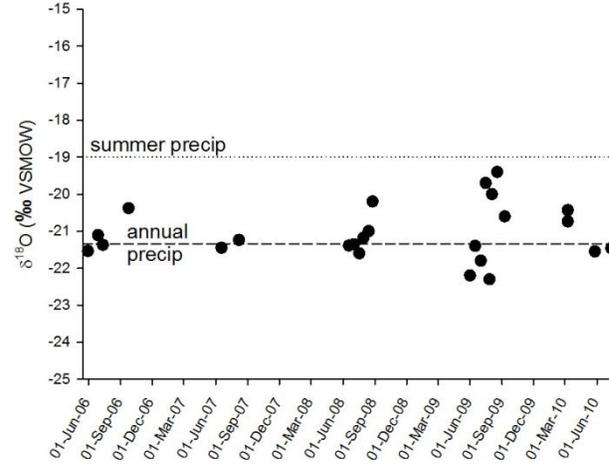
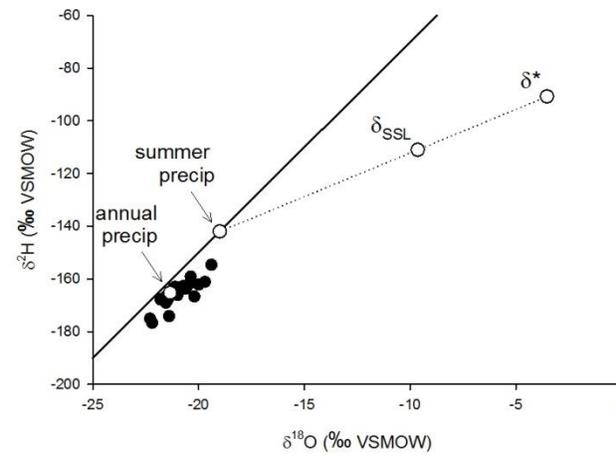


Figure 6.  $\delta$ - $\delta$  plots and time series diagrams for all ION sampling sites in Yukon.

### Teslin Lake and Teslin River

Very few samples were collected from Teslin Lake, but all results are very consistent (average  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$  = -20.2‰, -158‰; Figure 6c,d) and suggest a mix between summer and annual precipitation composition. Samples collected from the Teslin River in 2008 have a similar composition (seasonal average  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$  = -20.4‰, -160‰), although results from 2009 are quite variable, as with other sample sites in this dataset. The single sample collected from both Teslin Lake and the Teslin River in 2010 has a composition comparable to results from 2008 samples.

### Bennett Lake

Results from the Bennett Lake outlet cluster around the composition of summer precipitation (Figure 6e), suggesting this site attenuates summer rainfall and that this is a controlling factor in the lake's water balance. There is a single sample, collected on June 6, 2009, that is not consistent with other Bennett Lake outlet results ( $\delta^{18}\text{O}$  = -20.9‰). It is possible that this sample result is an outlier; however, it may also be a valid result that is influenced by the same broader driver that is causing variability at other sampling sites in 2009.

### Tagish River

The Tagish River flows from Tagish Lake into Marsh Lake. Results are shown in Figure 6f. In 2008, sample results were approximately 0.5‰ more enriched in  $\delta^{18}\text{O}$  than those from Bennett Lake, indicating slight evaporative enrichment of water as it moves through the Southern Lakes system. As with Bennett Lake, 2008 sample results are remarkably consistent. In contrast, 2009 sample results are highly variable, fluctuating between -21.4‰ and -17.8‰ in  $\delta^{18}\text{O}$ . The single sample result analyzed for 2010 suggests a return to 2008 conditions, although more sample results are required to know this is definitively the case.

### Yukon River

The Yukon River itself is sampled by ION technicians at several points – above Whitehorse (near the outlet of Marsh Lake), below Whitehorse (near the confluence with the Takhini River), at Carmacks and at Dawson. Interpretation of sample results is described collectively here, because comparable trends at all four sites are noted.

In 2008, sample results above and below Whitehorse (Figure 6g, h) plot around the isotopic composition of summer precipitation ( $\delta_{\text{PS}}$ ), while sample results from the Yukon River at Dawson plot close to the isotopic composition of mean annual precipitation ( $\delta_{\text{P}}$ ). Results from the Yukon River at Carmacks (Figure 6i) plot between the two. This pattern of progressive downstream depletion is consistent with results from other major northern rivers (e.g., Yi et al., 2010), reflecting latitudinal depletion of precipitation.

However, progressive enrichment over the 2008 thaw season is evident at each site. This indicates that a minimal degree of evaporative enrichment is occurring at each site over the course of the season, and/or that runoff to the river over the course of the summer is also becoming more enriched (e.g., due to summer rainfall).

In contrast, sample results from 2009 are extremely variable at all Yukon River sites, as with most other ION sites. Results at all sites range from more depleted than  $\delta_{\text{P}}$  to close to or more enriched than  $\delta_{\text{PS}}$ , with considerable within-season variability. (This variability is not as evident at the sampling site below Whitehorse, because only two samples were collected at this site in 2009.)

While no results are available for the Yukon River at Carmacks in 2010, the few samples collected from the Yukon River above and below Whitehorse, and from Dawson, indicate that water isotopic

compositions are more comparable to those collected in 2008 than 2009. In other words, sample results appear to be similar to 2008 compositions; for the Yukon River above and below Whitehorse, results are close to  $\delta_{pS}$ , while at Dawson, results are close to  $\delta_p$ . As with Bennett Lake and the Tagish River, these results indicate a return to pre-2009 conditions.

The Yukon River at Dawson (Figure 6l) has the longest data record of all Canadian ION stations. While fewer samples were collected in 2006 and 2007 than in 2008 and 2009, it is still possible to generalize hydrological conditions at this site in 2006 and 2007. As with 2008, results for the two preceding years cluster closely around  $\delta_p$ . However, it is important to consider here that the value for  $\delta_p$  comes from a data record measured at Whitehorse, over 700 km upstream of Dawson. Because there is typically progressive depletion in precipitation with latitude (which, as described above, is also evident in this dataset), it is possible that the Whitehorse  $\delta_p$  (annual precipitation) value is more similar to an actual  $\delta_{pS}$  (summer precipitation) value for Dawson. In other words, Dawson results clustering around  $\delta_p$  do not necessarily indicate that input waters to the Yukon River around Dawson have shifted from  $\delta_{pS}$  to  $\delta_p$ ; instead, Dawson's  $\delta_{pS}$  is probably close to Whitehorse's  $\delta_p$ . (Additional sampling of precipitation, which is outlined in more detail in the "Recommendations" section, could help determine whether this theory is viable.)

The other important aspect that the 2006 and 2007 samples for the Yukon River at Dawson indicate is that results from the 2009 season are not reflective of typical conditions. 2006, 2007, 2008 and 2010 all have relatively consistent results that do not show the same wide range of variability inherent in 2009 results. This suggests that, at least in terms of the duration of the Dawson record, 2009 was quite an unusual year. The analysis of samples from multiple sites post 2009 will help confirm this hypothesis.

#### White River

The White River is a 320 km tributary of the Yukon River that rises from the Russell Glacier in the Saint Elias Mountains of Alaska and meets the Yukon River just upstream of the Stewart River. The White River is notable for its high suspended sediment loads; it reduces the clarity of the Yukon River after its confluence.

Four samples were collected from the White River by ION monitors – three in 2008 (although two were collected on the same day) and one in 2009. Results are shown in Figure 6j. The 2008 samples are isotopically quite depleted compared with other samples in this dataset, with  $\delta^{18}\text{O}$  values of -23.1 to -23.9‰. In contrast, the single result for 2009 has a  $\delta^{18}\text{O}$  value of -19.9‰. As with Teslin Lake and the Teslin River, the relative depletion at this site may be the results of different sourcewaters for the White River in comparison to the Yukon River. The Saint Elias Mountain headwaters may have a slightly different moisture source than the Cassiar or Coast mountains that serve as the headwaters for the Yukon and Teslin, underscoring the important role headwater discharge plays on downstream river composition, as well as the variability inherent in the heterogeneous terrain of the region.

#### Stewart River

The Stewart River rises in the Selwyn Mountains, near the Yukon-Northwest Territories border. It is 530 km long, and discharges to the Yukon River ~110 km south of Dawson. Its headwaters are the most westerly of the major tributaries examined here. The Stewart River watershed is ~51 000 km<sup>2</sup> (Water Survey of Canada, 2015), and historic flooding by the Stewart River at the Town of Mayo has occurred on several occasions. Now, the town is protected by a dyke and has developed a community flood response plan.

Results for the Stewart River are shown in Figure 6k. As with the Yukon River, the Stewart River exhibits uniform enrichment in  $\delta^{18}\text{O}$  over the course of 2008, and notable variability in 2009. However, results

from both years cluster more closely around  $\delta_p$  than those from other sites (particularly in 2009). As with results from the Yukon River at Dawson, it may be that the composition of summer precipitation in the Stewart River headwaters is more depleted than that of Whitehorse, and as a result is more closely aligned with  $\delta_p$  than with  $\delta_{ps}$ .

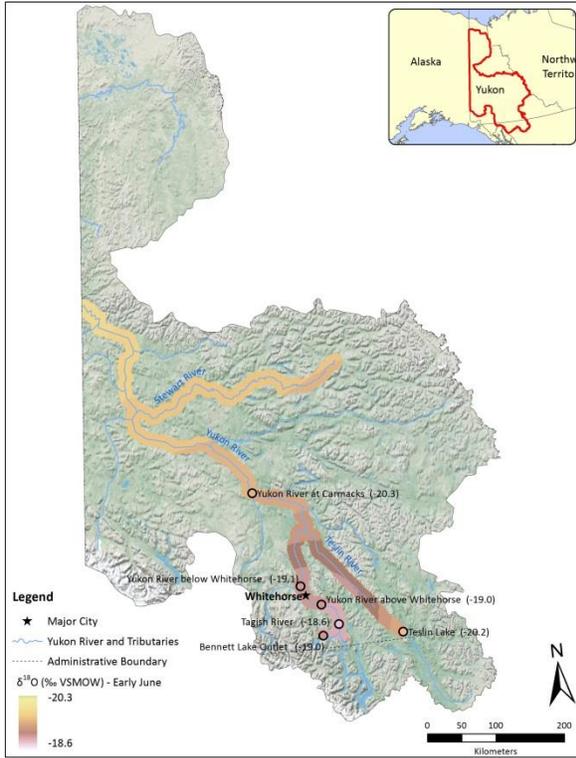
### ***Spatial variability in 2008 data***

Because the data collected during the 2008 monitoring year demonstrates quite predictable behavior isotopically, additional analysis and processing of this data has been completed, to demonstrate how data for subsequent years can be treated.

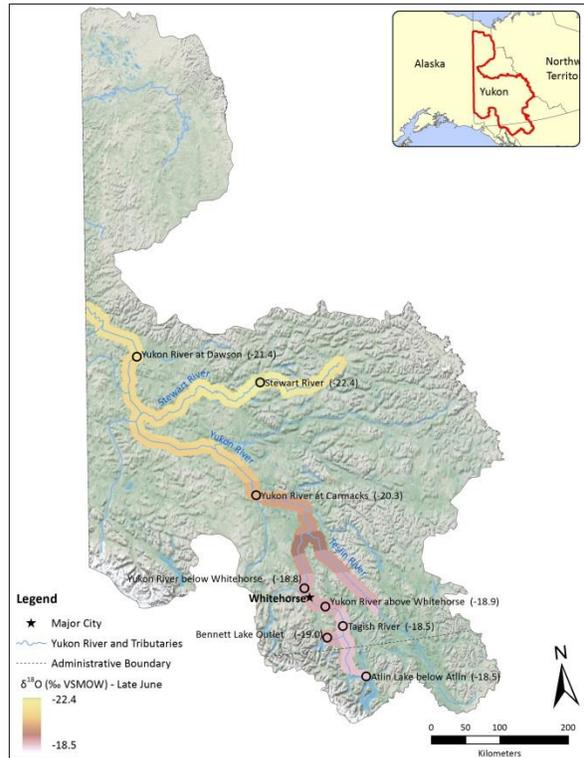
First, we developed maps that integrate spatial interpolation of sample results, to display isotopic characteristics in the watershed over both space and time. To do this, results from 2008 were grouped by time period into early June, late June, early July, late July, and early August data sets. Not all sampling points had results for each time period grouping, so not all sampling points are displayed on each map. Then, results from each sampling site were plotted in ArcGIS, and interpolation of values between sampling points was conducted using a Kriging interpolation process. Results are shown in Figure 7. While the results shown here are displayed in other formats elsewhere in this report, displaying them spatially on a map allows the user to more easily digest variation between sites and over time. For example, the maps demonstrate very clearly the depletion in river composition in all time periods between headwaters and mouth, indicated by the gradient from the enriched pink/brown colours in the headwaters to the yellow colours of the downstream reaches. Additionally, it demonstrates the influence of depleted input waters downstream, evidenced by the greens of the White River sampling point in the early August figure (Figure 7c,e). The value in these spatial interpolations will become especially useful when seasonal comparisons between multiple years can be made, and when presenting results to non-technical audiences.

Secondly, data are shown based on distance from the Llewellyn Glacier at the headwaters of the Yukon River. Figure 8 shows all sampling data collected in 2008 from each sampling site versus distance from the headwaters, as well as river gradient. As with the timeseries plots shown in Figure 6, this plot depicts the trend from enrichment to depletion with distance downstream, and also distinguishes sections of the river – in particular, a) the shallow headwaters and upper reaches, which have more isotopically enriched values generally, and b) the steeper mid and downstream reaches of the river, which have more isotopically depleted values, generally. Again, such plots serve as useful tools for depicting complex data, and will be valuable for plotting subsequent years of sampling data and examining trends spatially.

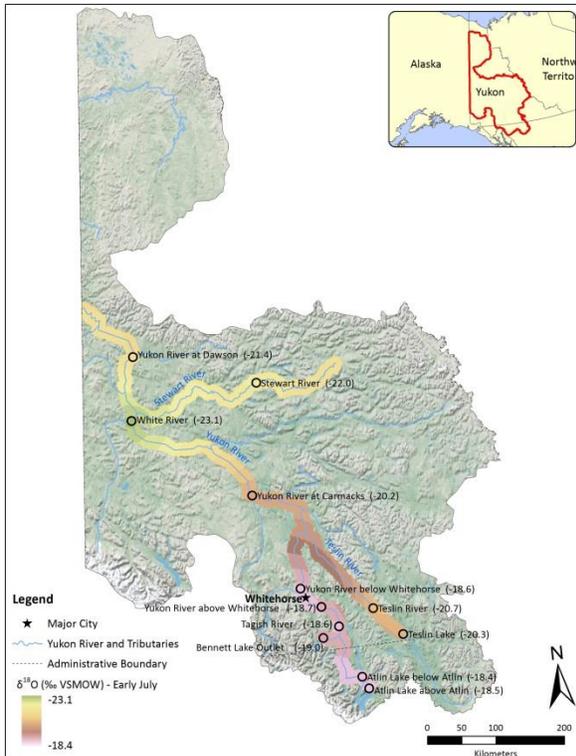
a) Early June



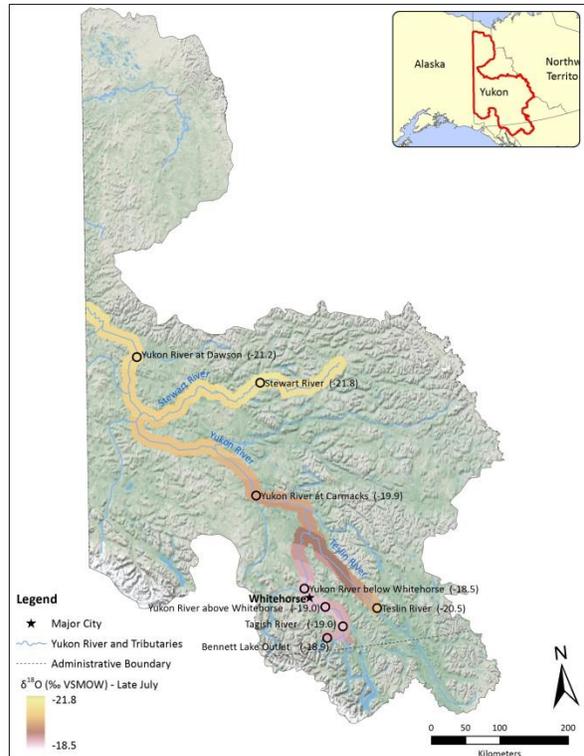
b) Late June



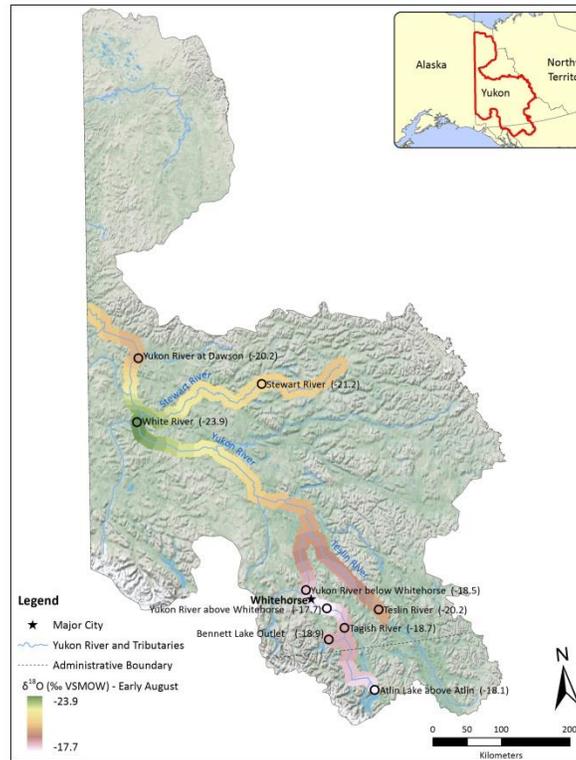
c) Early July



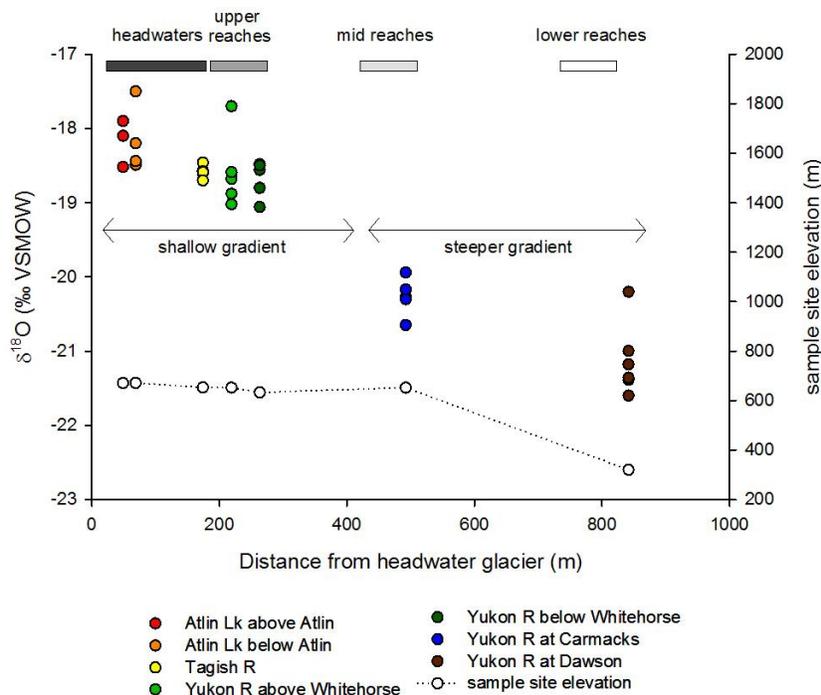
d) Late July



## e) Early August



**Figure 7.** Interpolation of  $d18\text{O}$  composition of the Yukon River based on sample results from ION sampling sites (done using a Kriging interpolation method). Sample results have been grouped by seasonal time period, as a) early June, b) late June, c) early July, d) late July, and e) early August. Not all sites have samples for each period.



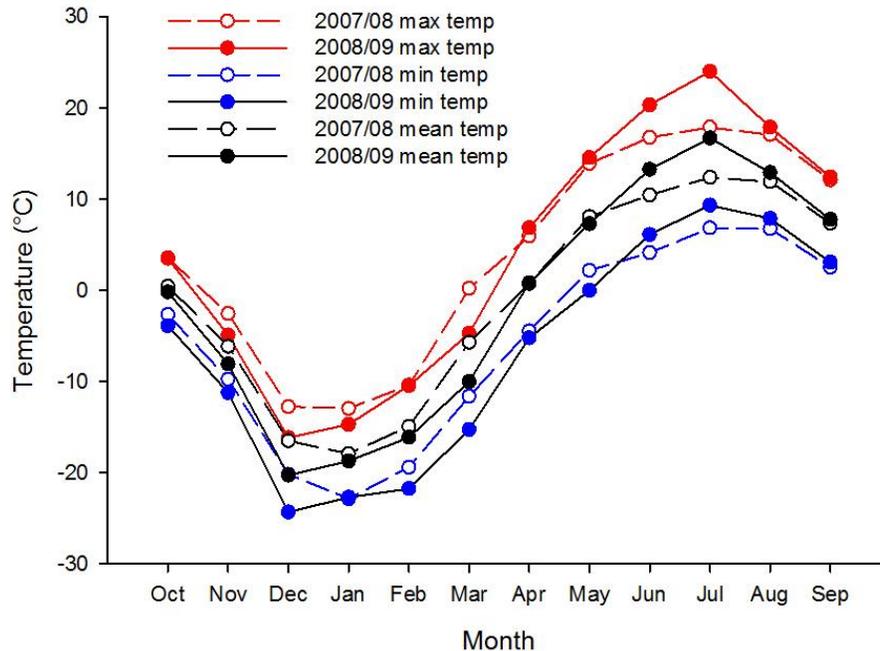
**Figure 8.**  $\delta^{18}\text{O}$  results from all samples collected from Canadian ION sites in 2008 (coloured circles), grouped by site and plotted against distance from the terminus of the Llewellyn Glacier at the headwaters of the Yukon River. Open circles show elevation at each of the sample sites and thereby represent the gradient of the Yukon River from the headwaters to the Dawson sample site.

### 2008 vs. 2009 Climate

As demonstrated in the plots in Figure 6, data for all sites shows quite a lot of variability in 2009 compared with 2008. Because the variability is apparent at all sites, it is unlikely that it can be attributed to poor sampling technique, mis-labelling, post-sampling evaporative losses, machine malfunction or other data processing stages.

To attempt to identify processes that may account for some of this variability, climate data for both years is examined here. In this section, climate data is shown by hydrological year. In this case, the hydrological year used is October 1 – September 30. This is because the precipitation that falls during the winter does not melt and contribute to the hydrology of an area until the following spring. Therefore, the 2008 summer sampling season falls within the October 1, 2007 – September 30, 2008 hydrological year, while 2009 sample results fall within the October 1, 2008 – September 30, 2009 hydrological year. Climate data included here was obtained from the Whitehorse Airport meteorological monitoring station (Environment Canada, 2015).

First, temperature data between the two years is examined. Figure 9 shows minimum, maximum and mean annual air temperatures for the 2007/08 and 2008/09 hydrological years. Generally, mean temperatures are quite similar both years. Fall 2008/09 is slightly cooler than 2007/08 ( $-9.5^{\circ}\text{C}$  vs.  $-7.4^{\circ}\text{C}$ ; Table 2), while summer temperatures are a few degrees warmer ( $12.5^{\circ}\text{C}$  vs.  $10.6^{\circ}\text{C}$ ; Table 2). Spring temperatures, during the ice-melt season, are virtually identical. Winter temperatures are cooler in 2008/09 (Table 2); however, this is during the ice-on period and likely has little influence on regional hydrology.



**Figure 9.** Minimum, maximum and mean air temperatures for the 2007/08 and 2008/09 hydrological years (Environment Canada, 2015).

**Table 2.** Average mean air temperature by season for the 2007/08 and 2008/09 hydrological years (Environment Canada, 2015).

| Season | Months        | Mean temperature (°C) |         |
|--------|---------------|-----------------------|---------|
|        |               | 2007/08               | 2008/09 |
| Fall   | Oct, Nov, Dec | -7.4                  | -9.5    |
| Winter | Jan, Feb, Mar | -12.8                 | -14.9   |
| Spring | Apr, May, Jun | 6.4                   | 7.1     |
| Summer | Jul, Aug, Sep | 10.6                  | 12.5    |

Higher summer temperatures during the 2008 summer season may contribute to increased evaporative enrichment; however, it does not account entirely for the range of variability in the dataset. If evaporative enrichment were the only process taking place, it would lead to progressive enrichment in  $\delta^{18}\text{O}$  values, rather than values that fluctuate from more enriched to more depleted (e.g., Figure 6g).

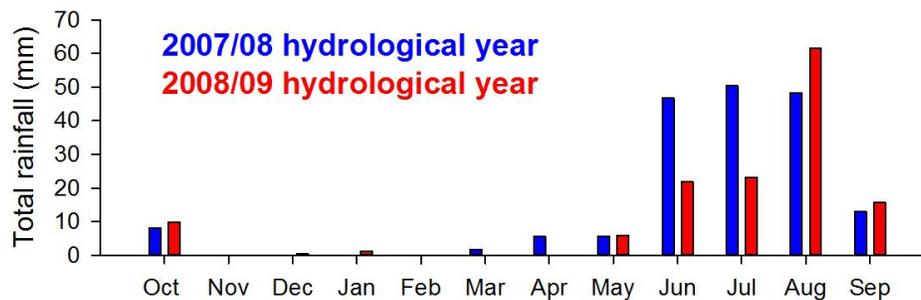
Precipitation variability could also account for some of the variability seen in the 2009 dataset. Heavy summer rainfall can introduce isotopically depleted waters to a region. Rainfall in August 2009 was greater than that of 2008 (61.6 mm vs. 48.3 mm; Figure 10a); however, June and July precipitation were both double 2009 amounts (46.8 and 50.4 mm vs. 21.8 and 23.2 mm for June and July 2008 and 2009, respectively).

To examine the relationship between rainfall and water isotope results from river samples more closely, Figure 11 shows precipitation versus  $\delta^{18}\text{O}$  for three key Yukon River sampling sites along the mainstem of the river – the Yukon River above Whitehorse, at Carmacks, and at Dawson. If major summer rainfalls

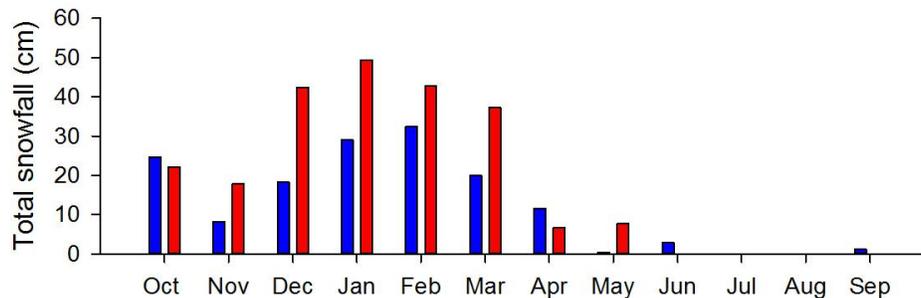
were having a significant influence on water isotope results, we would expect to see depletion in sample results in response to rainfall. However, 2008 results do not show this to be the case. For example, on August 24, 2008, 12.8 mm of rain fell, and water isotope results collected from the Yukon River at Whitehorse and Dawson show slight continued seasonal enrichment.

Winter snowfall was also greater in the 2008/09 hydrological year than in 2007/08 for all months but October, when snowfall was slightly less (Figure 10b). Total snowfall between October and May was 144.4 cm for 2007/08, compared with 226.0 cm for 2008/09. A deeper snowpack can introduce larger pulses of isotopically depleted water to a receiving body upon melt than a smaller snowpack, which can influence early season isotopic composition (although would not likely account for the late-season variability exhibited in this dataset).

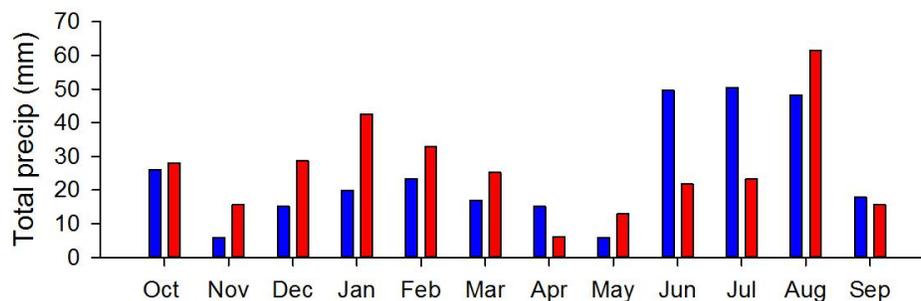
a) Total rainfall



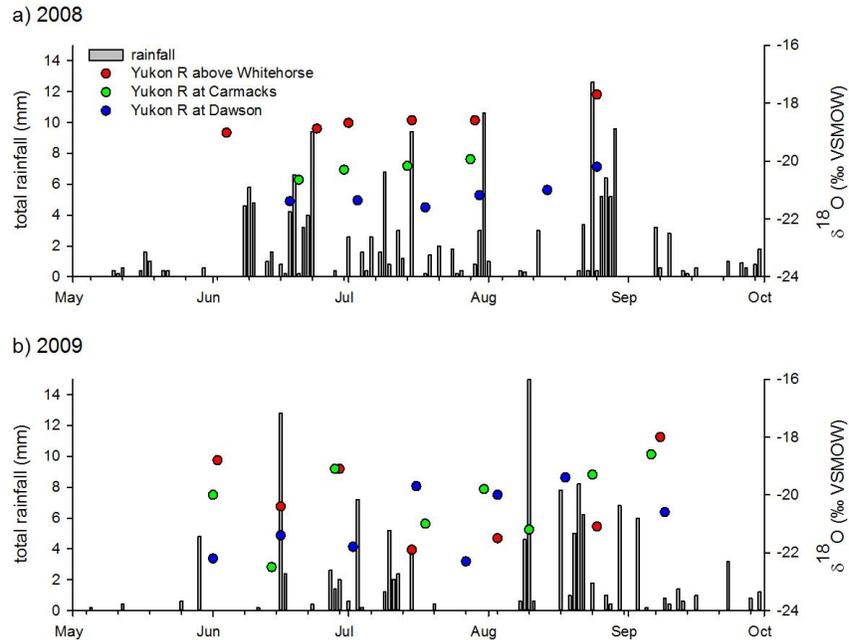
b) Total snowfall



c) Total precipitation

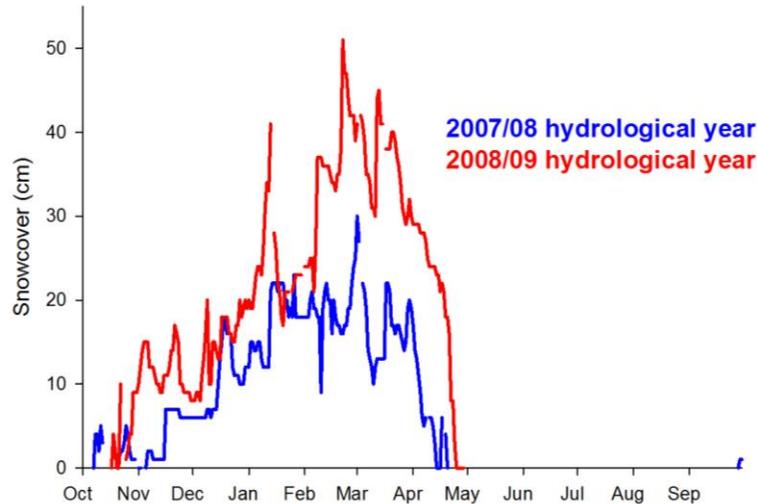


**Figure 10.** Total rainfall, total snowfall, and total precipitation for the 2007/08 (blue) and 2008/09 (red) hydrological years. To calculate total precipitation, snowfall amounts were converted to snow water equivalent and summed with total rainfall (Environment Canada, 2015).



**Figure 11.** Total rainfall (mm) versus  $\delta^{18}\text{O}$  results for the Yukon River above Whitehorse, at Carmacks and at Dawson, for a) 2008 and b) 2009. Total rainfall data comes from Environment Canada (2015).

Snowcover can also be a useful indicator of early-season hydrological conditions, as snowmelt influence can exert controls over later-season hydrology. Evidently, snowpack was deeper during winter 2009 than 2008 (Figure 12); in fact, at points during the season, snowpack in 2009 was almost double that of 2008. Notably, snowcover declines in late winter (presumably due to snowpack melt) appears to initiate around the same time in both years, although the higher snowcover amounts in 2009 would have resulted in greater snowmelt pulses to receiving water bodies. However, results from June water sampling campaigns do not appear to show significant influence from a high late-spring 2009 snowmelt pulse; Table 3 shows early spring lakewater results from Yukon River sampling sites are quite similar year-to-year. It is unlikely that lower elevation winter snowcover contributed to the variability in summer lakewater results. However, it is important to note that the data examined here is collected from the Whitehorse Airport station, and may not reflect snowpack conditions in the mountain and glacier headwaters of the Yukon River.

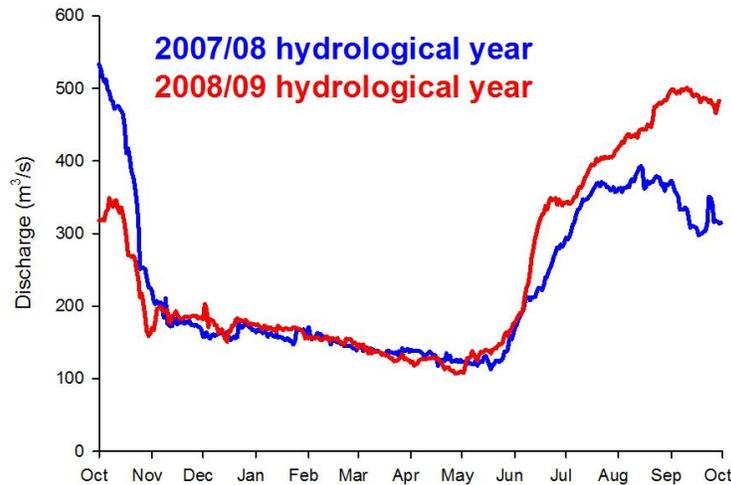


**Figure 12.** Snowcover during winter of the 2007/08 (blue) and 2008/09 (red) hydrological years (Environment Canada, 2015).

**Table 3.**  $\delta^{18}\text{O}$  results for June samplings from select Yukon River sites for 2008 and 2009.

| Site                         | 2008          |                              | 2009          |                             |
|------------------------------|---------------|------------------------------|---------------|-----------------------------|
|                              | Sampling date | $\delta^{18}\text{O}$ result | Sampling date | $\delta^{2}\text{H}$ result |
| Yukon River above Whitehorse | 04-Jun        | -19.0                        | 02-Jun        | -18.8                       |
|                              | 24-Jun        | -18.9                        | 16-Jun        | -20.4                       |
| Yukon River at Carmacks      | 03-Jun        | -20.3                        | 01-Jun        | -20                         |
|                              | 20-Jun        | -20.7                        | 14-Jun        | -22.5                       |
|                              | 30-Jun        | -20.3                        | 28-Jun        | -19.1                       |
| Yukon River at Dawson        | 18-Jun        | -21.4                        | 01-Jun        | -22.2                       |
|                              |               |                              | 16-Jun        | -21.4                       |

Finally, we examine river discharge to identify differences between the 2007/08 and 2008/09 hydrological years (Figure 13; Water Survey of Canada, 2015). During both years, winter discharge is low. At this time, groundwater inputs are the key source of flow to the river, and flow is minimal (Janowicz, 2008). However, discharge during late spring and early summer 2009 exceeds that of 2008, and discharge during summer 2009 is higher throughout the season than in 2008. It is possible that this increased discharge, which could represent greater headwater snowmelt or glacial runoff conditions. (Starting in 2013, the YRC established a network of five meteorological monitoring stations at three headwater glaciers in the Yukon River basin. This data can be used to compare results of ION samplings in 2012 and subsequent years, to examine the link between downstream isotopic composition and headwater snowpack and glacial discharge.)



**Figure 13.** Discharge for the Yukon River at Whitehorse, for the 2007/08 (blue) and 2008/09 (red) hydrological years (Water Survey of Canada, 2015).

The winter conditions and high discharge volumes shown above resulted in a dramatic spring breakup of the Yukon River in 2009. Reports from Yukon Government’s Water Resources Branch (e.g., Janowicz, 2009) and news media (e.g., NBC News, 2009) document a high flood year on the Yukon River, including evacuations at Henderson’s Corner near Dawson and major flood damage in Eagle, Alaska. The Water Resources Branch reports that at Dawson, breakup was initiated by significant snowmelt inputs that produced a rapid rise in water level (Janowicz, 2009). Additionally, the Water Resources Branch flooding summary describes the Yukon River breakup as a dynamic event:

The degree days of thaw ... was relatively low, suggesting the ice to be strong and competent. The relatively thick ice associated with the preceding colder than normal winter combined with an above normal snowpack and a seven day period of above normal temperatures contributed to the dynamic nature of the breakup event (Janowicz, 2009).

A notable spring flood could produce a broad degree of variability in water isotope data, and later season (e.g., July and August) inputs of higher-than-normal high alpine snowpacks could result in variability in results from samples collected river during that period. However, none of this clearly explains the degree of variability inherent in the 2009 ION sample set. A combination of factors identified here, including 2009’s warmer summer temperatures, higher late summer rainfall, deeper winter snowpacks, greater snowmelt pulse, and higher summer discharge amounts, may contribute to this variability. Analysis of samples collected in 2010 and later, done in the context of regional climate parameters and incorporating some of the YRC’s new headwater climate, snowpack and glacier data, may shed additional light on why sample results were more variable in 2009, particularly if 2010 or later showed similar climate conditions or a similar range of variability.

## RECOMMENDATIONS

Based on the preliminary interpretation of the data presented in this report, several recommendations can be made. These are listed here, and researchers from the NCE are happy to discuss any recommendation in more detail with YRITWC staff.

1. Analyze samples collected after early 2010. USGS laboratories currently have a backlog of samples to analyze; analysis of results would allow researchers to examine trends in site-by-site hydrology post 2009. Importantly, new sample results would contribute to the investigation of longer-term trends in river isotope hydrology. For example, analysis to samples collected in 2014 would give a site like the Yukon River at Dawson an eight-year data record. Such a record would allow researchers to begin to investigate temporal trends in hydrology, and potentially link them to changes in, e.g., temperature or snowpack during this time.
2. New sample results should be integrated in the  $\delta$ - $\delta$  and time series plots presented in this report. NCE researchers may be able to support YRITWC staff in doing this, and NCE is happy to provide all the templates for analysis to the YRITWC if/when they would like to employ them for future data analysis.
3. Expand sampling activities to include water sources at ION monitoring sites. These could include tap water and precipitation samples. Sampling these additional parameters would help constrain the isotopic frameworks within which samples are analyzed, shed light on hydrological processes throughout the watershed, and provide valuable new, updated data regarding isotopic compositions of moisture sources in a region that is broadly under-sampled.
  - a. *Tap water*: ION technicians could collect samples of tap water from dwellings close to monitoring sites. If tap water is sourced from a deep well, it can serve as a simple method of sampling groundwater composition. While groundwater contributions to Yukon River flow are typically assumed to be minimal (Janowicz, 2008), having samples of groundwater composition might allow researchers to enhance our understanding of the role of groundwater in the Yukon River watershed. If nothing else, groundwater samples may have the same composition as the Yukon River, which simply indicates hydrological connectivity and does not impair research findings.
  - b. *Rain*: Rainfall samples for isotopic analysis can be difficult to collect, because the technician needs to collect enough water to fill a sample jar completely without allowing for evaporation. During heavy rain events, this can be achieved simply by placing a sampling container below, e.g., a drainspout, and capping it as soon as it is full. For lighter rain events, alternative low-cost sampling apparatuses like the ball-in-funnel collector have shown to be effective and reliable in field settings (Prechsl et al., 2014).
  - c. *Snow*: Snow samples could be collected easily by ION technicians in plastic bags, melted, and subsampled in analysis bottles. Snow could be collected from major snow events, periodically through the winter, and/or by snow core (e.g., the entire column of snow is collected near the end of winter, thawed, mixed and subsampled). As with the tap water and rain samples, having an isotopic composition of snow at different monitoring locations would be incredibly valuable for parsing inputs to the Yukon River in subwatersheds along its reaches.
4. From an isotopic perspective, collecting water samples above and below Atlin and Whitehorse is unnecessary. There are no major tributaries to Atlin Lake and the Yukon River, respectively, between the “above” and “below” sampling locations that would cause a notable change in

isotopic composition at the two points. It is possible that collecting water samples from these sites is necessary for the analysis of other parameters; however, it is likely not necessary to analyze water isotope samples from above “above” and “below” sites for Atlin and Whitehorse.

5. Examine sample results in the context of additional YRITWC parameters. The YRITWC has an extensive set of additional parameters it samples for and analyzes, including parameters related to physical properties (e.g., temperature, pH, conductance, dissolved oxygen, etc.) and water chemistry (e.g., concentrations of parameters like nitrates, sulphates and calcium, hardness, dissolved organic and inorganic carbon, etc.). YRITWC has already done some analysis of these additional parameters; integrating this analysis with the water isotope tracer results may reveal new insights about local and watershed-scale hydrology.
6. Compare the hydrographs and water isotope results of the Yukon River at Whitehorse and the Stewart River. Results may provide the basis for comparing discharge and water balance/general hydrology in a regulated (Yukon River at Whitehorse) versus unregulated (Stewart River) catchment.
7. Once data from multiple years is analyzed, consider trends exhibited in sample results in response to changes in climate. Trends in results over several years can be compared with measured climate parameters (e.g., temperature) to identify trajectories of change. Then, projections of climate trends under various scenarios can be used to predict potential future evolution of Yukon River hydrology. This will become particularly important with regards to decisions about long-term water management, for example. Examples of climate scenarios for the Yukon are included in Appendix B.

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## APPENDIX A – WATER ISOTOPE RESULTS

| Water body name | Sample date | $\delta^{18}\text{O}$ (‰ VSMOW) | $\delta^2\text{H}$ (‰ VSMOW) | Water body name   | Sample date | $\delta^{18}\text{O}$ (‰ VSMOW) | $\delta^2\text{H}$ (‰ VSMOW) |
|-----------------|-------------|---------------------------------|------------------------------|-------------------|-------------|---------------------------------|------------------------------|
| Atlin Lake      | 08-07-07    | -18.5                           | -143                         | Tagish River      | 08-06-10    | -18.6                           | -144                         |
| above Atlin     | 08-08-08    | -17.9                           | -145                         |                   | 08-07-01    | -18.6                           | -145                         |
|                 | 08-08-21    | -18.1                           | -146                         |                   | 08-06-24    | -18.5                           | -141                         |
|                 | 09-04-22    | -22.1                           | -174                         |                   | 08-07-15    | -18.6                           | -142                         |
|                 | 10-03-12    | -18.8                           | -146                         |                   | 08-07-29    | -18.6                           | -143                         |
| Atlin Lake      | 08-06-23    | -18.5                           | -144                         |                   | 08-08-25    | -18.7                           | -146                         |
| below Atlin     | 08-07-07    | -18.4                           | -144                         |                   | 09-06-02    | -19.6                           | -161                         |
|                 | 08-08-08    | -18.2                           | -144                         |                   | 09-06-15    | -21.4                           | -168                         |
|                 | 08-08-21    | -17.5                           | -145                         |                   | 09-07-13    | -18.4                           | -146                         |
|                 | 09-04-22    | -22.1                           | -172                         |                   | 09-07-02    | -20.6                           | -165                         |
|                 | 09-04-22    | -24.1                           | -188                         |                   | 09-08-11    | -18.7                           | -146                         |
|                 | 10-03-12    | -18.7                           | -145                         |                   | 09-08-25    | -21.3                           | -169                         |
| Teslin Lake     | 08-06-12    | -20.2                           | -159                         |                   | 09-09-08    | -17.8                           | -146                         |
|                 | 08-07-02    | -20.3                           | -159                         |                   | 10-05-24    | -18.6                           | -144                         |
|                 | 10-05-25    | -20.2                           | -158                         | Yukon River above | 08-06-04    | -19.0                           | -148                         |
| Teslin River    | 08-07-10    | -20.7                           | -161                         | Whitehorse        | 08-06-24    | -18.9                           | -148                         |
|                 | 08-07-24    | -20.5                           | -160                         |                   | 08-07-01    | -18.7                           | -145                         |
|                 | 08-08-06    | -20.4                           | -158                         |                   | 08-07-15    | -18.6                           | -143                         |
|                 | 08-09-04    | -20.2                           | -163                         |                   | 08-07-29    | -18.6                           | -143                         |
|                 | 08-08-21    | -20.2                           | -162                         |                   | 08-08-25    | -17.7                           | -146                         |
|                 | 09-04-06    | -20.1                           | -161                         |                   | 09-06-02    | -18.8                           | -151                         |
|                 | 09-04-06    | -20.2                           | -161                         |                   | 09-06-16    | -20.4                           | -161                         |
|                 | 09-06-02    | -20.2                           | -162                         |                   | 09-07-15    | -21.9                           | -173                         |
|                 | 09-06-15    | -22.3                           | -176                         |                   | 09-06-29    | -19.1                           | -148                         |
|                 | 09-07-14    | -18.6                           | -149                         |                   | 09-08-03    | -21.5                           | -170                         |
|                 | 09-06-29    | -19.7                           | -164                         |                   | 09-08-11    | -14.9                           | -116                         |
|                 | 09-07-29    | -18.3                           | -146                         |                   | 09-08-25    | -21.1                           | -169                         |
|                 | 09-08-11    | -19.7                           | -164                         |                   | 09-09-08    | -18.0                           | -146                         |
|                 | 09-08-25    | -19.4                           | -156                         |                   | 10-05-25    | -19.1                           | -149                         |
|                 | 09-09-14    | -18.0                           | -146                         | Yukon River below | 07-03-23    | -18.6                           | -143                         |
|                 | 10-03-11    | -20.4                           | -161                         | Whitehorse        | 08-06-04    | -19.1                           | -149                         |
| Bennett Lake    | 08-06-10    | -19.0                           | -145                         |                   | 08-06-20    | -18.8                           | -143                         |
| outlet          | 08-06-24    | -19.0                           | -145                         |                   | 08-06-30    | -18.8                           | -146                         |
|                 | 08-07-01    | -19.0                           | -146                         |                   | 08-07-14    | -18.6                           | -146                         |
|                 | 08-07-15    | -19.0                           | -146                         |                   | 08-07-28    | -18.5                           | -145                         |
|                 | 08-07-29    | -18.9                           | -146                         |                   | 08-08-26    | -18.5                           | -145                         |
|                 | 08-08-25    | -18.9                           | -148                         |                   | 09-04-08    | -18.9                           | -149                         |
|                 | 09-04-09    | -19.1                           | -150                         |                   | 09-06-16    | -22.2                           | -179                         |
|                 | 09-06-06    | -20.9                           | -164                         |                   | 10-03-10    | -18.9                           | -146                         |
|                 | 09-06-15    | -15.9                           | -120                         |                   | 10-03-10    | -18.9                           | -146                         |
|                 | 10-05-24    | -19.1                           | -146                         |                   | 10-05-25    | -19.3                           | -149                         |

YUKON RIVER WATER ISOTOPE DATA

| Water body name | Sample date | $\delta^{18}\text{O}$ (‰ VSMOW) | $\delta^2\text{H}$ (‰ VSMOW) | Water body name | Sample date | $\delta^{18}\text{O}$ (‰ VSMOW) | $\delta^2\text{H}$ (‰ VSMOW) |
|-----------------|-------------|---------------------------------|------------------------------|-----------------|-------------|---------------------------------|------------------------------|
| Yukon River     | 08-06-03    | -20.3                           | -159                         | Yukon River     | 06-05-30    | -21.5                           | -167                         |
| at Carmacks     | 08-06-20    | -20.7                           | -160                         | at Dawson       | 06-06-28    | -21.1                           | -163                         |
|                 | 08-06-30    | -20.3                           | -159                         |                 | 06-07-12    | -21.4                           | -165                         |
|                 | 08-07-14    | -20.2                           | -158                         |                 | 06-09-24    | -20.4                           | -159                         |
|                 | 08-07-28    | -19.9                           | -156                         |                 | 07-06-18    | -21.5                           | -166                         |
|                 | 09-06-01    | -20.0                           | -162                         |                 | 07-08-07    | -21.2                           | -165                         |
|                 | 09-06-14    | -22.5                           | -177                         |                 | 08-06-18    | -21.4                           | -167                         |
|                 | 09-06-28    | -19.1                           | -148                         |                 | 08-07-03    | -21.4                           | -165                         |
|                 | 09-07-18    | -21.0                           | -169                         |                 | 08-07-18    | -21.6                           | -168                         |
|                 | 09-07-31    | -19.8                           | -159                         |                 | 08-07-30    | -21.2                           | -163                         |
|                 | 09-08-10    | -21.2                           | -173                         |                 | 08-08-14    | -21.0                           | -166                         |
|                 | 09-08-24    | -19.3                           | -154                         |                 | 08-08-25    | -20.2                           | -167                         |
|                 | 09-09-06    | -18.6                           | -155                         |                 | 09-06-01    | -22.2                           | -177                         |
| White River     | 08-07-03    | -23.1                           | -180                         |                 | 09-06-16    | -21.4                           | -174                         |
|                 | 08-08-06    | -23.9                           | -186                         |                 | 09-07-02    | -21.8                           | -168                         |
|                 | 08-08-06    | -23.2                           | -185                         |                 | 09-07-16    | -19.7                           | -161                         |
|                 | 09-07-30    | -19.9                           | -161                         |                 | 09-08-03    | -20.0                           | -162                         |
| Stewart River   | 08-06-24    | -22.4                           | -169                         |                 | 09-07-27    | -22.3                           | -175                         |
|                 | 08-07-08    | -22.0                           | -171                         |                 | 09-08-18    | -19.4                           | -155                         |
|                 | 08-07-22    | -21.8                           | -166                         |                 | 09-09-09    | -20.6                           | -164                         |
|                 | 08-08-19    | -21.2                           | -167                         |                 | 10-03-09    | -20.7                           | -163                         |
|                 | 08-09-02    | -20.8                           | -169                         |                 | 10-03-09    | -20.4                           | -162                         |
|                 | 09-06-01    | -20.1                           | -157                         |                 | 10-05-26    | -21.6                           | -169                         |
|                 | 09-06-14    | -21.8                           | -174                         |                 | 10-07-12    | -21.5                           | -168                         |
|                 | 09-06-28    | -20.9                           | -164                         |                 |             |                                 |                              |
|                 | 09-07-19    | -11.8                           | -100                         |                 |             |                                 |                              |
|                 | 09-07-27    | -20.0                           | -156                         |                 |             |                                 |                              |
|                 | 09-08-10    | -20.7                           | -165                         |                 |             |                                 |                              |
|                 | 09-08-24    | -22.2                           | -174                         |                 |             |                                 |                              |
|                 | 09-09-06    | -20.5                           | -169                         |                 |             |                                 |                              |

## APPENDIX B – AIR TEMPERATURE PROJECTIONS FOR YUKON

Projections of changes in mean annual air temperature (MAAT) that were prepared for the NCE and are presented here are based on annual air temperature modelling, and were enhanced to reflect heterogeneity in the local landscape (specifically, mountainous terrain). This represents a significant increase in the understanding of MAAT. This approach incorporated specific topographical features in the study region (e.g., mountains) and knowledge about related area-specific surface lapse rates (SLRs) at fine resolution (30 x 30 m). To develop these enhanced air temperature models and predictions, current MAAT modeling was conducted. Work drew on data from clusters of previously established air temperature monitoring stations in Yukon. Each monitoring station consisted of a radiation shield mounted at 1.5-1.6 m on a metal pole. An Onset Hobo Pro data-logger (accuracy  $\pm 0.2^{\circ}\text{C}$ ), equipped with an external thermistor, was used to monitor air temperature inside the screen. In order to predict MAAT across the region, a 3<sup>rd</sup> order polynomial trend surface of annual SLR values below treeline was generated (Lewkowicz and Bonnaventure, 2011). This surface was then combined with a 4<sup>th</sup> order polynomial trend surface of treeline elevations, which was separately developed from sampling topographic maps and Google Earth images to limit the application of the SLR values to terrain below treeline. Above this level, it was assumed that standard environmental lapse rates of  $-6.5^{\circ}\text{C}/\text{km}$  prevail. In addition, a 3<sup>rd</sup> order polynomial trend surface of projected sea level temperature was generated from the long-term records of 18 climate stations in the region (Environment Canada, 2013), which had been reduced to sea level (e.g., Eitzmuller et al., 2007) by applying the projected SLR value for each station based on its continentality (Lewkowicz and Bonnaventure, 2011). The projected sea level temperature surface was then readjusted using a digital elevation model at 30 x 30 m resolution, the SLR grid for elevations up to treeline, and the standard environmental lapse rate from treeline upwards. The result was a gridded model of MAAT for the region based on elevation with the measured variability in SLR taken into account but not including aspect or localized topographic effects on cold-air pooling.

The basis for developing projections of MAAT incorporating the SLRs (also called perturbed MAAT models) involved using statistically downscaled GCM data obtained from the Scenarios Network for Arctic and Alaska Planning at the University of Alaska Fairbanks (SNAP, 2012; [www.snap.uaf.edu](http://www.snap.uaf.edu)). The SNAP dataset contains multiple GCM scenarios for mean annual air temperatures, as well as modelled average temperature surfaces for past climate normals (e.g., 1980-2009). The data used to obtain the perturbed MAAT models included the 2 km-resolution projection surfaces provided by SNAP for the IPCC scenarios of A1B, A2 and B1. These particular scenarios were chosen for this application because they represent the most commonly used scenarios in GCM modelling and represent a broad range of potential climate conditions. Each of the three scenarios shown in this Appendix represents the following sets of conditions:

### ***The B1 scenario – low to moderate degrees of climate change***

- rapid economic growth (as in A1B), but with rapid changes towards a service and information economy
- population rising to 9 billion in 2050 and then declining as in A1 (see Nebojša et al., 2000)
- reductions in material intensity and the introduction of clean and resource-efficient technologies
- an emphasis on global solutions to economic, social and environmental stability

### ***The A1B scenario – medium to high degrees of climate change***

- rapid economic growth

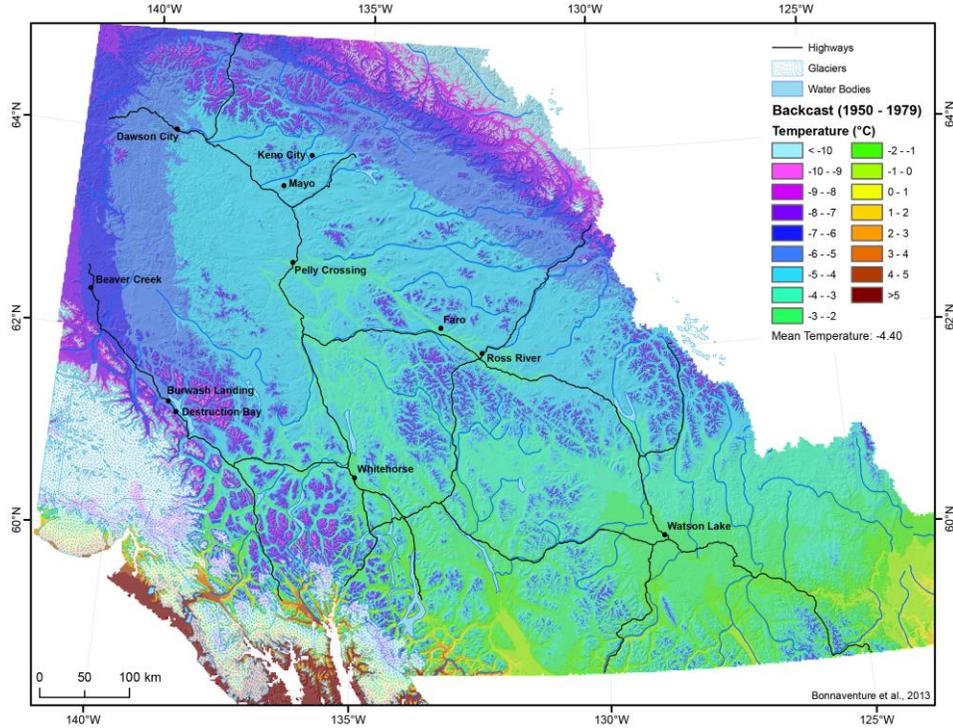
- a global population that reaches 9 billion in 2050 and then gradually declines
- the quick spread of new and efficient technologies
- a convergent world, i.e., income and way of life converge between regions
- extensive social and cultural interactions worldwide
- a balanced emphasis on all energy sources

***The A2 scenario –high degree of climate change***

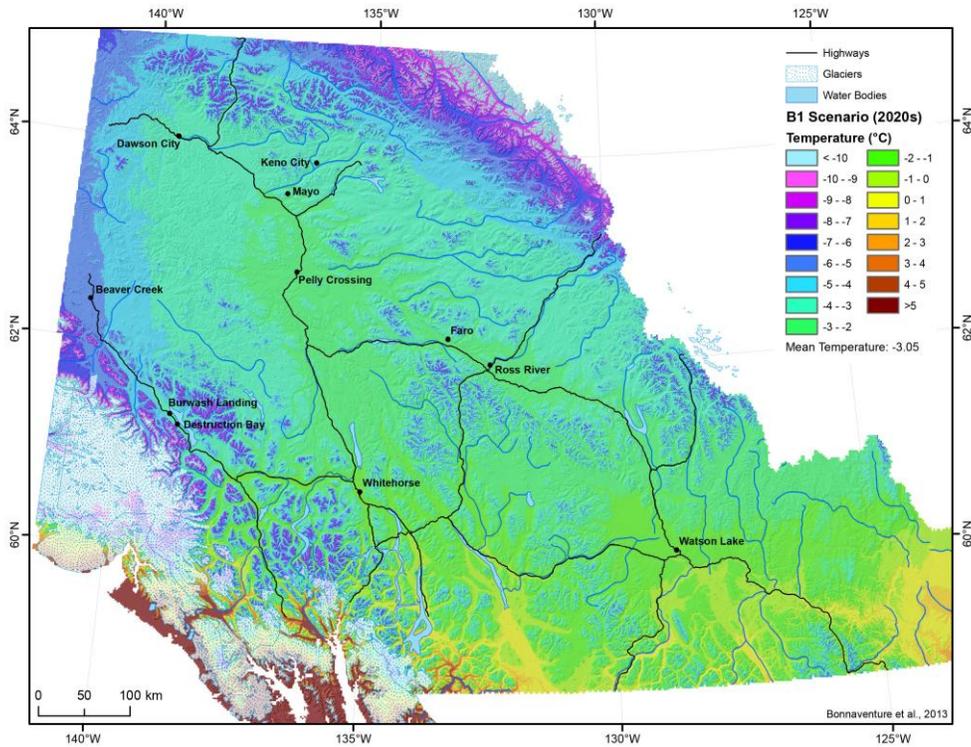
- a world of independently operating, self-reliant nations
- continuously increasing population
- regionally oriented economic development
- slower and more fragmented technological changes and improvements to per-capita income

To develop each scenario, SNAP drew on data from five separate models, thereby ensuring the greatest range of predictions within each scenario. Perturbed MAAT models were developed by examining difference (and thus change) between what the SNAP model predicted for the current climate (i.e., the 1980-2009 climate normal) and each of the three scenarios for the years 2020, 2050 and 2080. In addition, a backcasted model was also produced which examined the difference between current climate (1980-2009) and the climate normal from 1950-1979. Hence, modelling efforts examined the predicted difference between each time slice for each scenario and adjusted the previously created MAAT model accordingly. In order to incorporate the data from the 2 x 2 km grid cells for each SNAP model, the cell size was resampled to 30 x 30 m. This effectively provided a broad geographic basis for sample change at a territorial scale (macroclimate), which could then be topographically corrected to site specific SLRs in the Burwash and Destruction Bay study area. The differences between the predicted SNAP models were then added (forecasting) or subtracted (backcasting) to the current MAAT model using raster calculator in ArcGIS<sup>®</sup> 10.1 (ESRI, USA). The results of these models provide significantly more information about the variable nature of spatial climate in geographically mountainous areas than the raw GCM data itself, which typically displays high levels of inaccuracies in the mountainous regions of Yukon.

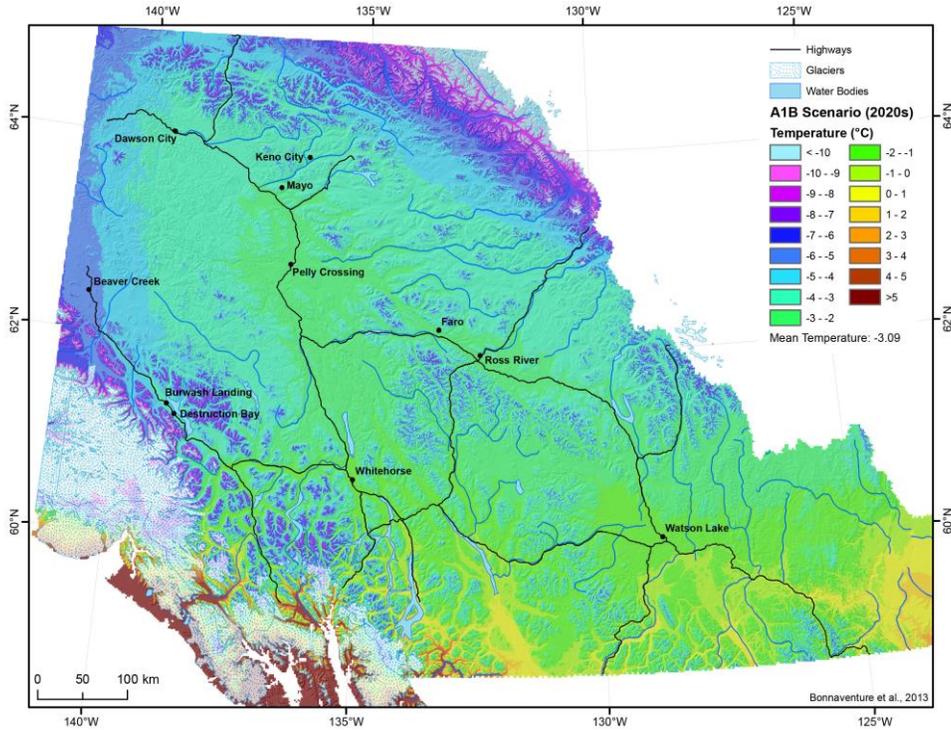
Based on the methods described above, MAAT projections for the Yukon are shown in Figures B1-B10, below. Note that additional climate projections, based on data provided by SNAP (2012), are available by contacting the NCE. Projections are available for mean annual and seasonal temperature and precipitation, as well as freeze and thaw dates and growing degree days, for the A1B and B1 scenarios, for the 2020s and 2050s, as well as the 1960-1990 time period.



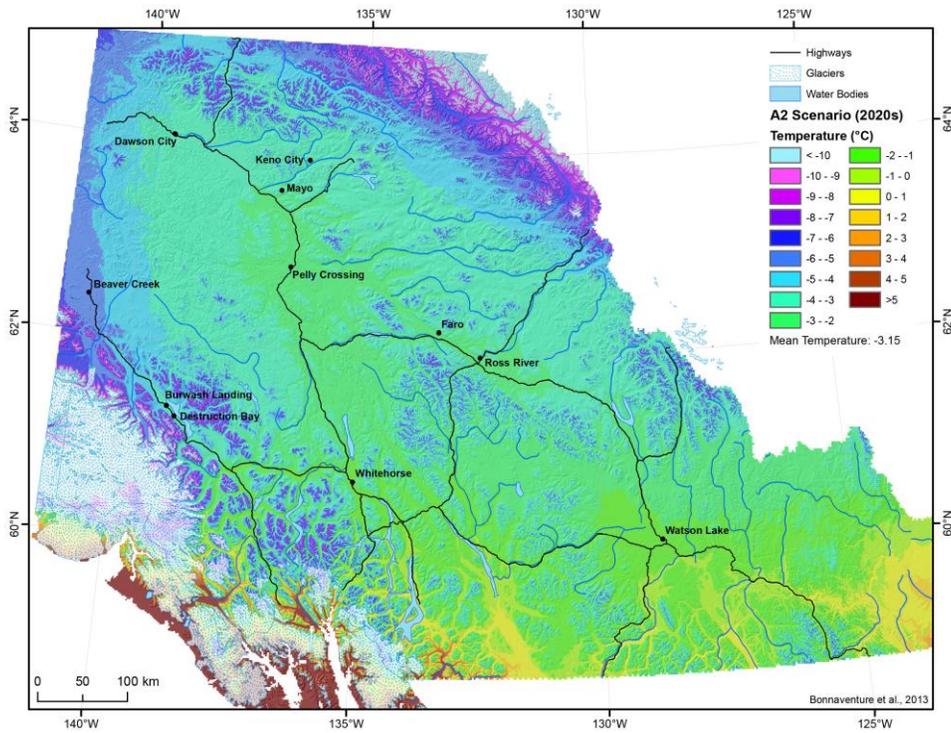
**Appendix B1.** Mean annual air temperature for southern Yukon, backcasted for the 1950-1979 period.



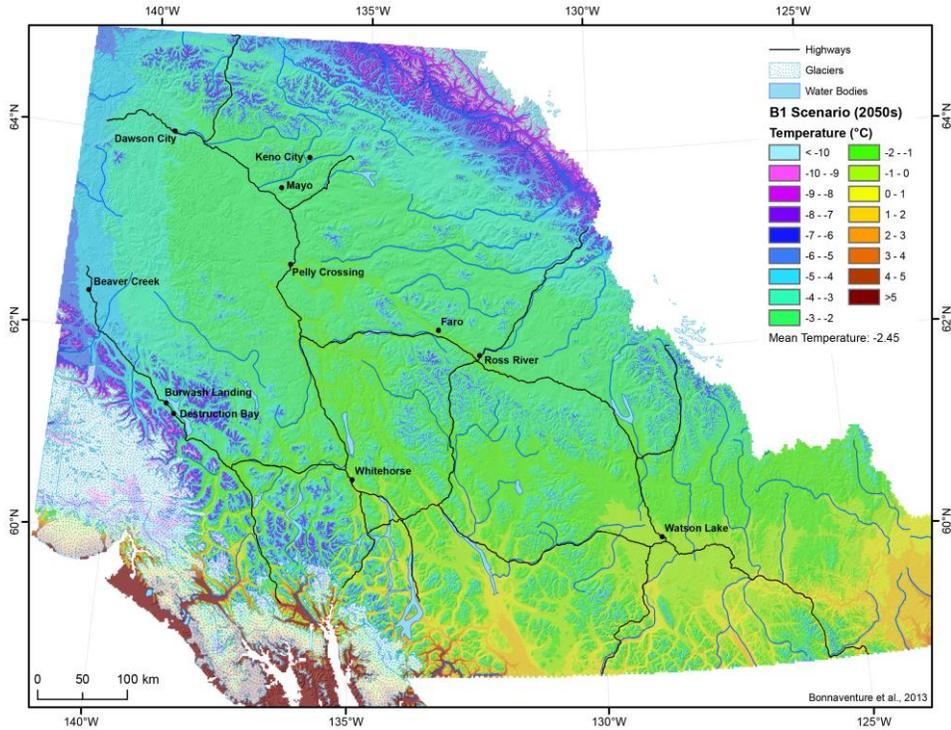
**Appendix B2.** Mean annual air tempelature for southern Yukon for 2020, projected using the B1 scenario.



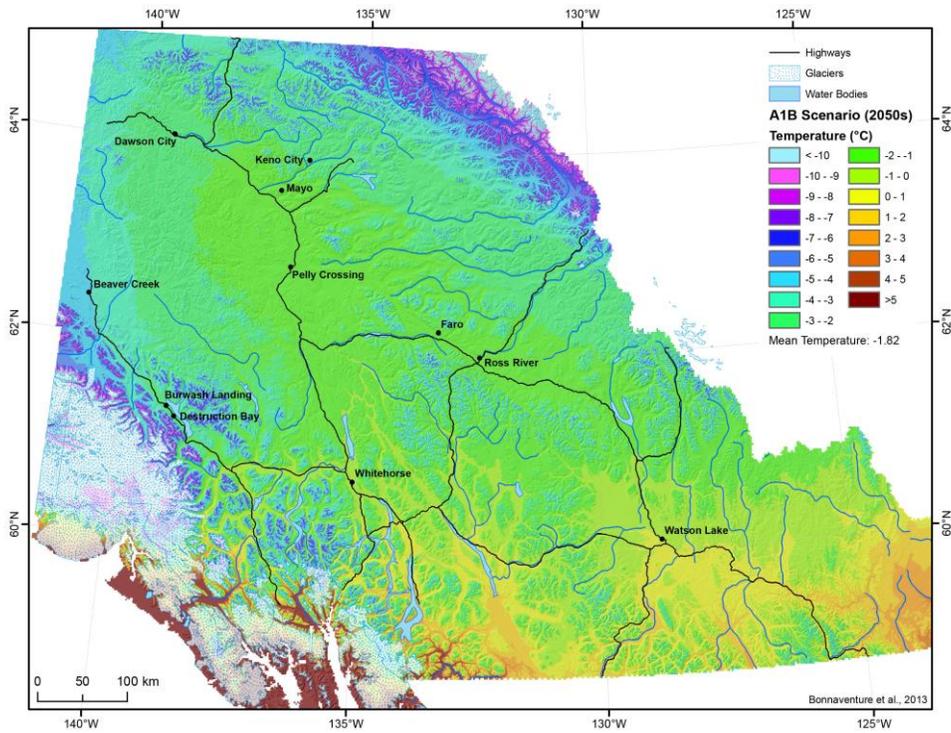
**Appendix B3.** Mean annual air temperature for southern Yukon for 2020, projected using the A1B scenario.



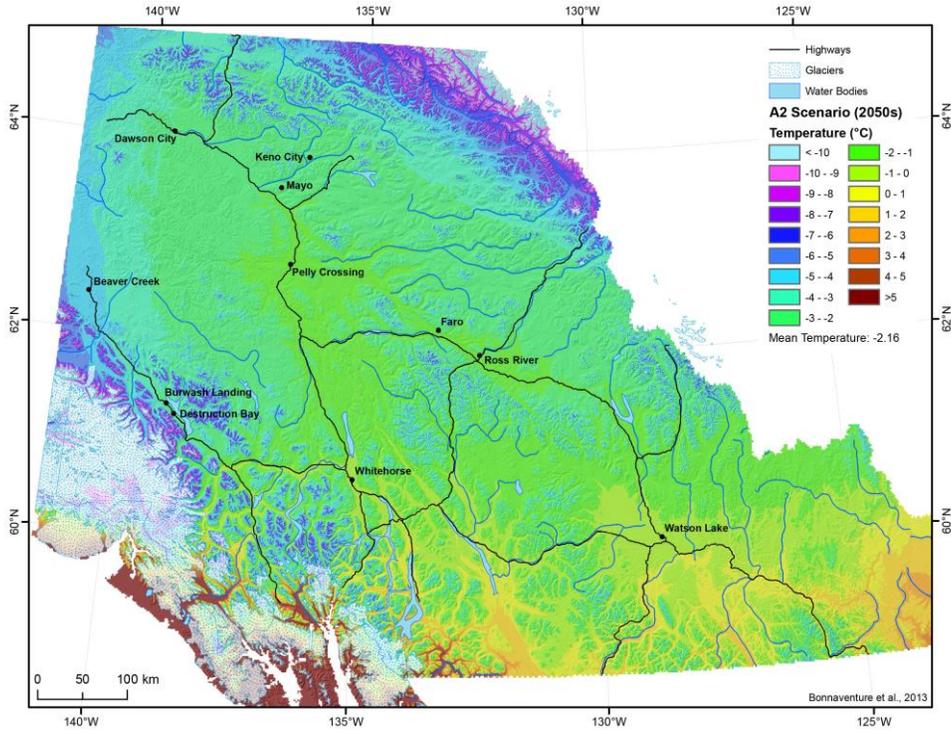
**Appendix B4.** Mean annual air temperature for southern Yukon for 2020, projected using the A2 scenario.



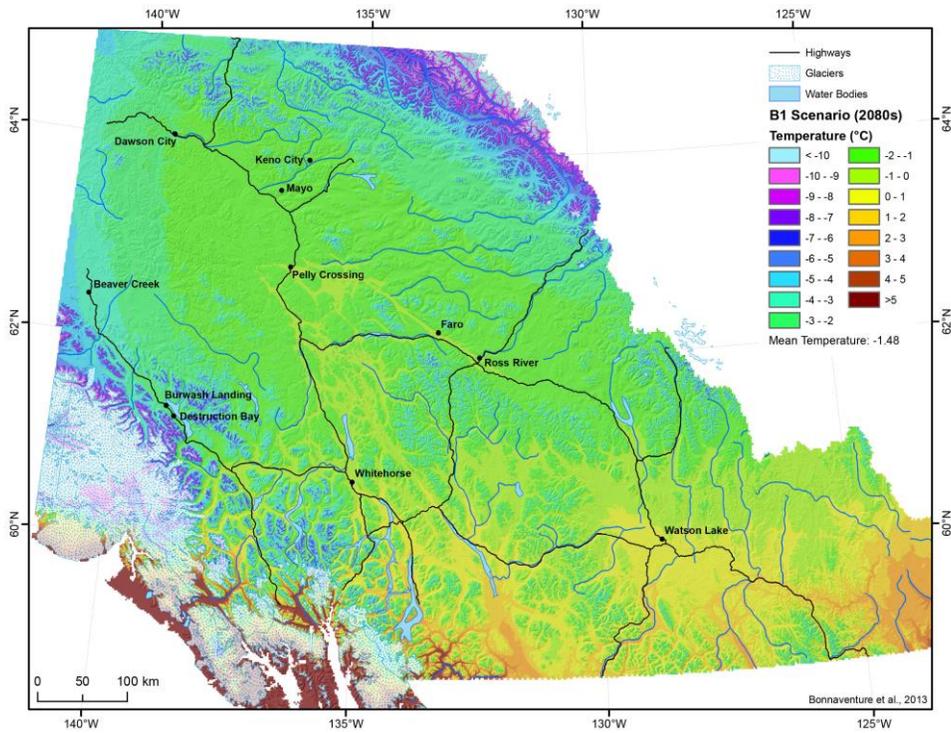
**Appendix B5.** Mean annual air temperature for southern Yukon for 2050, projected using the B1 scenario.



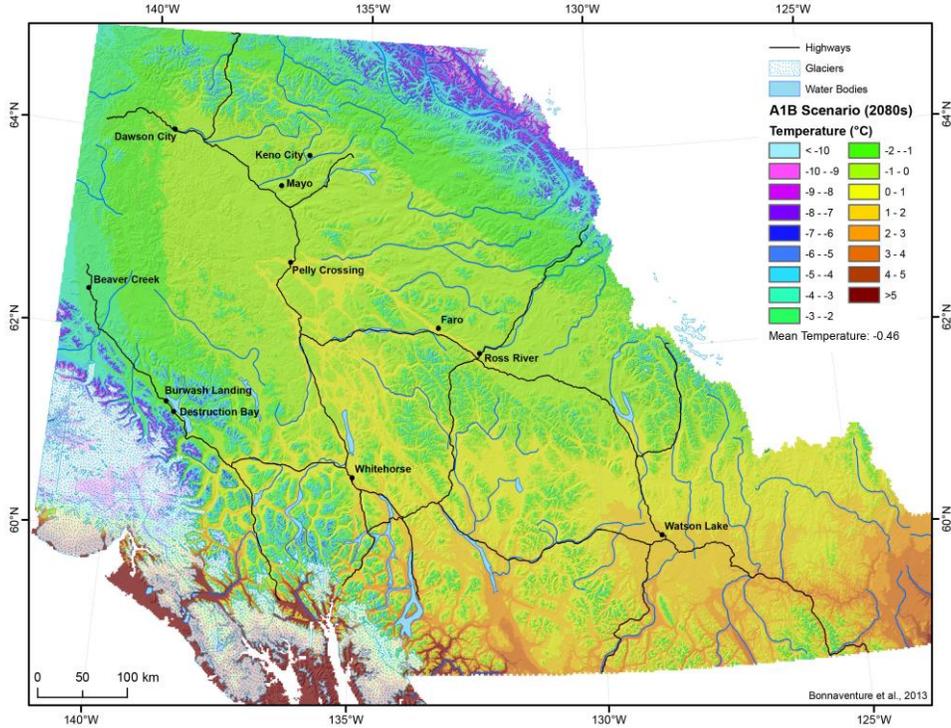
**Appendix B6.** Mean annual air temperature for southern Yukon for 2050, projected using the A1B scenario.



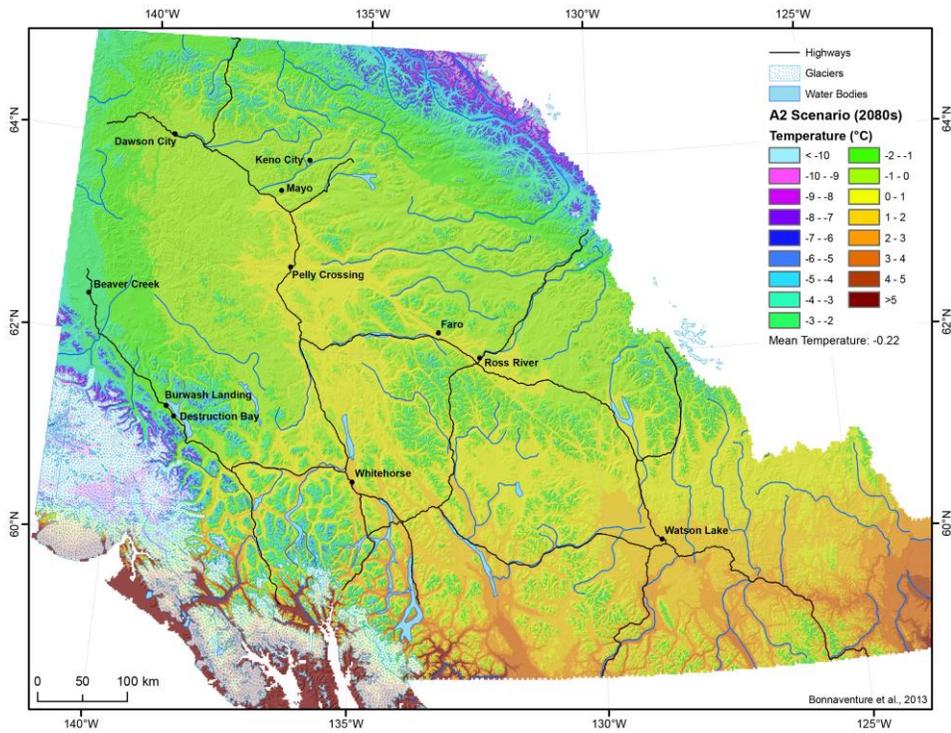
**Appendix B7.** Mean annual air temperature for southern Yukon for 2050, projected using the A2 scenario.



**Appendix B8.** Mean annual air temperature for southern Yukon for 2080, projected using the B1 scenario.



**Appendix B9.** Mean annual air temperature for southern Yukon for 2080, projected using the A1B scenario.



**Appendix B10.** Mean annual air temperature for southern Yukon for 2080, projected using the A2 scenario.