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Coordination and Sustainability of River Observing Activities in the Arctic

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ABSTRACT. To understand and respond to changes in the world's northern regions, we need a coordinated system of long-term Arctic observations. River networks naturally integrate across landscapes and link the terrestrial and ocean domains. Changes in river discharge reflect changes in the terrestrial water balance, whereas changes in water chemistry are linked to changes in biogeochemical processes and water flow paths. Sustained measurements of river water discharge and water chemistry are therefore essential components of an Arctic observing network. As we strive to establish and sustain long-term observations in the Arctic, these two measurements must be coupled. Although river discharge and chemistry measurements are already coupled to some extent within national boundaries, this is not done in a consistent and coordinated fashion across the pan-Arctic domain. As a consequence, data quality and availability vary widely among regions. International coordination of river discharge and chemistry measurements in the Arctic would be greatly facilitated by formal commitments to maintain a set of core sites and associated measurements that are mutually agreed upon among pan-Arctic nations. Involvement of the agencies currently operating river discharge gauges around the Arctic and establishment of an overarching coordination entity to implement shared protocols, track data quality, and manage data streams would be essential in this endeavor. Focused studies addressing scale-dependent relationships between watershed characteristics and water chemistry, in-stream processes, and estuarine and coastal dynamics are also needed to support interpretation and application of Arctic river observing data as they relate to land and ocean change.

Key words: Arctic; river; discharge; chemistry; observing network; monitoring

RÉSUMÉ. Pour comprendre les changements qui s'opèrent dans les régions nordiques du monde et y réagir, nous devons nous doter d'un système coordonné d'observation à long terme dans l'Arctique. Les réseaux fluviaux s'intègrent naturellement dans les paysages et relient le domaine terrestre au domaine océanique. Les changements qui s'exercent dans les réseaux fluviaux sont le reflet des changements dans l'équilibre hydrique terrestre, tandis que les changements qui s'exercent sur l'hydrochimie sont liés aux changements caractérisant les processus biogéochimiques et les parcours d'écoulement de l'eau. Par conséquent, un réseau d'observation arctique devrait essentiellement être assorti de mesures durables d'évacuation des eaux fluviales et d'hydrochimie. Au moment où nous nous efforçons d'établir et de soutenir des observations à long terme dans l'Arctique, ces deux types de mesures doivent être suivies en parallèle. Bien que les mesures de l'évacuation fluviale et les mesures chimiques soient déjà, dans une certaine mesure, suivies en parallèle à l'intérieur des frontières nationales, cela ne se fait pas de manière uniforme et coordonnée à la grandeur du domaine panarctique, et en conséquence, la qualité et la disponibilité des données varient beaucoup d'une région à l'autre. La coordination internationale des mesures d'évacuation fluviale et chimiques dans l'Arctique serait grandement facilitée par l'existence d'engagements officiels visant à maintenir une série d'emplacements fondamentaux et de mesures connexes fixées par entente mutuelle au sein des nations panarctiques. La participation des agences qui gèrent les manomètres d'évacuation fluviale dans l'Arctique et l'établissement d'une entité de coordination générale mettant en œuvre des protocoles partagés, vérifiant la qualité des données et gérant les flux de données seraient également essentiels. Des études ciblées portant sur les relations influencées par l'échelle entre les caractéristiques du bassin hydrographique et l'hydrochimie, sur les processus s'opérant à l'intérieur des cours d'eau et sur la dynamique des estuaires et des rives s'avèrent également nécessaires pour étayer l'interprétation et l'application des données d'observation fluviale de l'Arctique en matière de changement terrestre et océanique.

Mots clés : Arctique; fluvial; débit; chimie; réseau d'observation; surveillance

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INTRODUCTION

River water discharge varies as a function of precipitation, evaporation, and storage within a drainage basin. At the same time, the chemistry of river water is strongly influenced by biogeochemical sources and processes as water flows through the landscape. Thus, rivers serve as sentinels of water balance and biogeochemical changes occurring across broad spatial scales. This function is vitally important in Arctic and sub-Arctic regions, where widespread changes in hydrology (Rawlins et al., 2010), vegetation (Beck and Goetz, 2011), permafrost (Oelke et al., 2004), and industrial development (Kumpula et al., 2011) are taking place and greater changes are anticipated for the future.

Records of river discharge have already proven extremely valuable for examining variability over a wide range of spatial and temporal scales in the Arctic (Peterson et al., 2002; Yang et al., 2002, 2003, 2007; Déry and Wood, 2005; Déry et al., 2005, 2009; McClelland et al., 2006; Shiklomanov and Lammers, 2009; Overeem and Syvitski, 2010; Rawlins et al., 2010; Lesack et al., 2013). River discharge is currently increasing around much of the pan-Arctic watershed, with a strong upward trend in annual values beginning in the 1960s on the Eurasian side of the Arctic (Peterson et al., 2002) and in the late 1980s on the North American side (Déry et al., 2009). However, the temporal patterns in river discharge are strongly dependent on the window of time under consideration (Holmes et al., 2013). This makes longer datasets particularly valuable for identifying trends that may be linked to climate change.

In contrast to river discharge data, long-term datasets on river water chemistry in the Arctic are relatively rare, and we do not yet have sufficient information to assess change on a pan-Arctic scale. Analyzing how riverine chemistry varies across broad spatial scales has significantly advanced our understanding of how processes such as the release of organic matter and the progression of weathering may be affected by factors such as changing permafrost extent (Frey and Smith, 2005; Frey et al., 2007; Frey and McClelland, 2009; Tank et al., 2012a). However, these cross-watershed comparisons do not lessen the need for long-term chemistry datasets to examine change over time.

Arctic river observing is important not only for assessing widespread changes on land, but also for understanding how changes in river export may influence the ocean system. We know that current-day variability in the land-to-ocean transport of biogeochemical constituents in the Arctic has a significant impact on processes such as primary production (Tank et al., 2012b), bacterial dynamics (Vallières et al., 2008; Anderson et al., 2009), and aragonite saturation (Mathis et al., 2011). Therefore, we also expect that future changes in river water chemistry will produce changes in the biogeochemical state of the Arctic Ocean. This is particularly true for coastal waters, but larger-scale impacts are also of interest because the Arctic Ocean is relatively small compared to the land area that drains into it (McClelland et al., 2012). The strong riverine signal within the Arctic Ocean allows basic riverine chemistry to trace water movements within the larger Arctic Ocean basin (Cooper et al., 2005; Fichot et al., 2013).

In this paper, we address three major themes defined for the 2013 Arctic Observing Summit in Vancouver, British Columbia: 1) Status of the current observing system, 2) Observing system design and coordination, and 3) Mechanisms for coordination of support, implementation, and operation of a sustained Arctic observing system. The first theme is addressed in the sections "Past and ongoing efforts to monitor river discharge" and "Past and ongoing efforts to monitor water chemistry." The second and third themes are addressed in the section "Linking river discharge and water chemistry measurements." We highlight short-term research requirements to support interpretation of changes measured at river observing sites in the "Complementary research" section and summarize recommendations related to themes 2 and 3 in the final section.

PAST AND ONGOING EFFORTS TO MONITOR RIVER DISCHARGE

River discharge within the pan-Arctic watershed is characterized by marked seasonality, with low flow during the winter, peak flow during the spring, and intermediate flow during the summer and fall (McClelland et al., 2012). The transition from low flow to peak flow occurs over days to weeks, with the onset of the spring freshet varying from year to year as a function of temperature. Patterns of summer discharge differ substantially among regions, reflecting differences in summer precipitation regimes and basin retention characteristics (McClelland et al., 2012). For example, discharge to the Barents, Kara, and Laptev Seas tends to decrease rapidly after peaking in the spring, whereas discharge decreases much more gradually in the Hudson Bay region.

Major efforts to monitor river discharge within the pan-Arctic drainage area (20.5×10^6 km^2, excluding Greenland, the Canadian Arctic Archipelago, and other islands) began in the 1930s. However, the spatial distribution and number of active discharge monitoring stations has varied significantly over time (Shiklomanov et al., 2002). In Russia, the number of stations increased steadily from 1935 to ~1980, whereas in North America, the number of stations did not begin to increase substantially until the 1950s and peaked in ~1985. The number of active discharge monitoring stations in Russia and North America declined substantially from the 1980s to 2000 and has remained relatively steady since that time. At present, Russia, Canada, and the United States have 1066, 1305, and 32 active river discharge monitoring stations, respectively, within the pan-Arctic watershed (Fig. 1). These stations are maintained by Roshydromet (Federal Service for Hydrometeorology and Environmental Monitoring in Russia), the Water Survey of Canada, and the U.S. Geological Survey (USGS). Note, however, that these numbers are based on information from these agencies, and

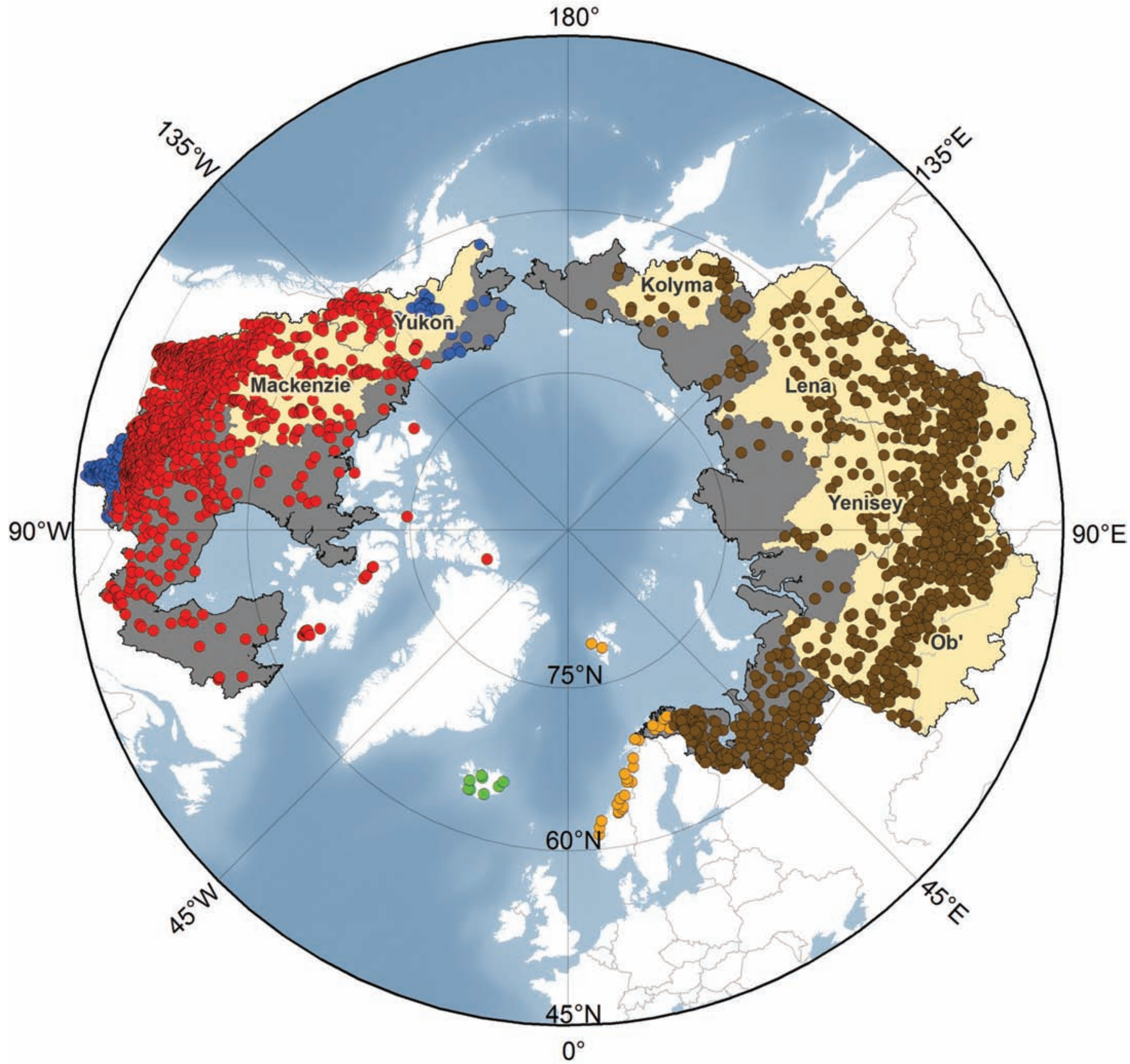

FIG. 1. Map of the pan-Arctic drainage area (20.5 × 10^6 km^2) showing active river discharge monitoring stations in Russia (brown), Canada (red), the United States (blue), Scandinavia (yellow), and Iceland (green). Watersheds of the six largest rivers within the pan-Arctic drainage area are also highlighted.

not all of the gauges counted as "active" are continuously operational. For example, river discharge was not measured at 80 (approximately 8%) of the officially operating stations in Russia during 2011, and 63 active stations had significant data gaps in that year. Thus, according to information reported by regional Roshydromet offices and compiled in the State Hydrological Institute, the functional number of gauges providing information about river discharge across the Russian Arctic in 2011 was only about 920. The number for Canada is also misleading, since many of the active gauges (~30%) are operated only in summer.

While a large majority of active river discharge monitoring stations are located in the southern half of the pan-Arctic watershed, monitoring stations at downstream locations on the Yenisey, Ob', Lena, Kolyma, Mackenzie, and Yukon Rivers capture discharge from 53% of the pan-Arctic watershed. Thus, downstream gauges located on the major Arctic rivers are particularly important for tracking widespread changes in watershed hydrology and freshwater inputs to the ocean. River discharge is routinely estimated from water stage using regression relationships (rating curves) between measured stage and discharge that have been developed over many years. However, it is important to add new data to the rating curves over time to maintain reliable estimates of river discharge. When the rating curves are not updated regularly, uncertainty in the discharge estimates gradually increases (Shiklomanov et al., 2006). Unfortunately, the quality of discharge data for downstream gauges on the major Russian Arctic rivers is decreasing because the rating curves for these rivers are not being adequately updated. For example, rating curves for open water conditions on the Yenisey at Igarka and the Lena at Kusur have not been updated since 2003, and the rating curve for open water conditions on the Kolyma at Kolymskoye has not been updated since 1998. Given the particular importance of these gauges for tracking pan-Arctic river discharge, updates to the rating curves for these stations need to be made a high priority.

Gauging stations on smaller rivers account for an additional ~25% of drainage from the pan-Arctic watershed. The remaining (ungauged) area is dominated by small drainage basins near the land-ocean interface. Although these basins contribute little to overall river discharge within the pan-Arctic watershed, they may be very important with respect to understanding climate change impacts in the Arctic. The relevance of monitoring river discharge and water chemistry at a variety of scales and geographic locations is discussed in later sections of this document.

PAST AND ONGOING EFFORTS TO MONITOR WATER CHEMISTRY

Russia

Water temperature, thickness of ice and snow, turbidity, and sediment concentrations are measured along with river stage at many of the Russian river discharge monitoring sites mentioned above. For example, 327 sites currently measure sediment concentrations within the Russian Arctic drainage basin. Roshydromet also maintains a Water Quality Monitoring Network (WQMN) that was established in the 1970s and 1980s to provide information about the level of pollutant contamination in rivers, lakes, and reservoirs. Therefore, most of the monitoring sites for the WQMN are located near large cities or on large rivers, where water pollution control is considered to be especially important. WQMN stations are frequently operated by the same personnel that operate the river discharge monitoring stations, but the locations of sites for water quality sampling are often different from those designated for river discharge monitoring. One river discharge monitoring station may operate several sites for water quality monitoring. For example, water quality sampling may be focused on locations upstream and downstream of potential contaminant sources. Currently sampling and analysis for the WQMN focuses on 35–40 physical and chemical parameters that are measured at least once during each of the main hydrological phases (winter low flow, spring flood, summer base flow, summer storm flow, etc.). Sampling is conducted more frequently on heavily contaminated water bodies. The WQMN water quality data are used mainly to define levels of contamination as they relate to official maximum allowable concentrations. Thus, the accuracy of analytical techniques and sampling procedures implemented by the WQMN is not always adequate for scientific studies.

The number of active WQMN stations in the Russian Arctic drainage by the beginning of 2011 was 755 and the number of water sampling sites was 947 according to the State Hydrochemical Institute (Nikanorov, 2012). However, in 2010 no samples were collected at 118 of those stations (~16%) because of a temporary closure. The number of WQMN samples analyzed in 2010 was 26 156, compared to 32 919 in 1991 and 24 537 in 1996 (Zhulidov et al., 2000). These data suggest that the current situation with the Russian WQMN is stabilized or even slightly improved compared to the 1990s.

Canada

At the federal level, Canadian water chemistry data are collected by Environment Canada, with data compilation organized by large-scale drainage basin. For north-draining systems, which account for ~75% of the watershed area in Canada, the large-scale basins include the Pacific, Arctic, and Hudson Bay drainages. The largest rivers within the Pacific, Arctic, and Hudson Bay drainages are the Yukon, Mackenzie, and Nelson Rivers, respectively. In many but not all cases, data are collected in collaboration with the Water Survey of Canada, which ensures that chemistry measurements can be paired with coincident discharge measurements. The length of record for water chemistry datasets collected in Canada's northern territories ranges from several years to several decades. Frequency of measurement also shows a relatively wide range, from once yearly for remote locations in the Canadian High Arctic, to more than 10 measurements per year. At present, Environment Canada actively collects water chemistry data at 42 sites throughout the Northwest Territories, Nunavut, and Yukon, as well as many additional sites within north-draining regions of the southern provinces, which include the majority of the Hudson Bay drainage. In addition, many historic federally collected water chemistry datasets are available from points no longer being monitored. Samples collected by Environment Canada are typically analyzed in centralized federal laboratory facilities. Metals, major ions, and nutrients are measured for most of the sampling points within the northern territories, and organic constituents are measured for a subset of stations.

Because water chemistry samples are taken throughout the Canadian provinces and territories, many sampling locations include sub-watershed sites within larger drainage basins. For example, Environment Canada actively collects water chemistry for many of the major Mackenzie River tributaries near their mouths, including the Liard River near its confluence with the Mackenzie main stem, the Peace and Athabasca Rivers above Lake Athabasca, the Great

Bear River at the outflow of Great Bear Lake, and the Peel River above its entry into the Mackenzie Delta. This sampling regime enables active chemistry datasets for tributary watersheds that range from largely permafrost-free (the Athabasca) to almost entirely underlain by continuous permafrost (the Peel), and which drain both the carbonate-rich and mixed sedimentary deposits of the western Mackenzie basin and the granitic shield of the eastern portion of the watershed.

In addition to the monitoring activities conducted by Environment Canada, other federal agencies (e.g., Aboriginal Affairs and Northern Development Canada in the northern territories) and provincial agencies collect water chemistry samples as required by their departmental mandates. These collection activities may provide additional chemistry records for locations that Environment Canada is not able to monitor for logistical or financial reasons.

USA (Alaska)

Water quality measurements in Alaska are conducted by the USGS and various other entities. However, measurements within the Yukon River drainage basin and watersheds north of the Yukon have been relatively scarce. The USGS is currently monitoring three fixed stations along the main stem of the Yukon River (Pilot Station, Stevens Village, and Eagle), as well as one station on each of the Yukon's major tributaries (the Porcupine River near Fort Yukon and the Tanana River at Nenana). Every year the fixed stations are sampled seven times (once under ice and six times in the open water period) for an extensive suite of water quality parameters, including concentrations of sediment, dissolved nutrients, organic matter, and major ions. The Porcupine River drainage comprises extensive wetland and peatland areas. In contrast, the Tanana River is dominated by meltwater from alpine glaciers and perennial ice and snowfields. Permafrost coverage is also greater in the Porcupine drainage as compared to the Tanana. In recent years, the USGS also conducted synoptic survey sampling throughout the Yukon River Basin, from headwater streams in Canada to Pilot Station, Alaska, near the mouth of the Yukon River on the Bering Sea. Only some (< 20%) of the synoptic survey sites have concurrent discharge and water quality data. However, the survey sampling results provide useful context for interpreting variations in water chemistry at the fixed sampling stations.

Water quality samples are also currently being taken by the Yukon River Inter-Tribal Watershed Council (www.yritwc.org) as part of an Indigenous Observation Network (ION). This network was developed in collaboration with the USGS to continue and expand upon the basin-wide water quality measurement efforts that were initiated during the synoptic surveys discussed above (the ION also includes permafrost monitoring sites). Water samples are collected by ION personnel and analyzed by the USGS. The network currently includes 39 fixed stations for water quality that range from headwater regions in Canada to the mouth of the Yukon River. This effort involves 23 indigenous governments and more than 100 local technicians.

PARTNERS and the Arctic Great Rivers Observatory

Parallel sampling programs on the six largest Arctic rivers, beginning as the Pan-Arctic River Transport of Nutrients, organic mattER, and suspended Sediments (PARTNERS) project in 2003 and continuing as the Arctic Great Rivers Observatory (Arctic-GRO) in 2008, were established with support from the U.S. National Science Foundation (NSF) to improve our understanding of biogeochemical fluxes from the pan-Arctic watershed to the Arctic Ocean (McClelland et al., 2008; www.arcticgreatrivers.org). PARTNERS was one of 18 projects funded in response to the NSF Arctic System Science "Arctic Freshwater Cycle: Land/Upper-Ocean Linkages" solicitation. This effort then continued as a component of the NSF Arctic Observing Network. The Arctic-GRO is currently funded through 2016. While primary funding for PARTNERS/Arctic-GRO has been provided by NSF, the work is highly collaborative. Scientists from the United States, Canada, and Russia have participated in both implementation and management of the observatory.

The PARTNERS effort was motivated by two key issues. First, it was recognized that previous efforts to characterize water chemistry and constituent fluxes from land to sea in the Arctic did not adequately capture seasonal dynamics. Second, it was recognized that historical and ongoing efforts to measure water chemistry in Arctic rivers were highly diverse with respect to the types of constituents being measured and the methods being used to measure them. PARTNERS addressed these issues by developing and implementing master protocols for sample collection and analysis, including season-specific sampling aimed at characterizing differences in chemistry during low flow in the winter, high flow in the spring, and intermediate flow in the summer. Continuation of this work through the Arctic-GRO was motivated by recognition that 1) river chemistry provides a critical link between land and ocean observing activities, and 2) the developing dataset would greatly facilitate identification and attribution of widespread change within the pan-Arctic watershed. Specific measurements include concentrations of organic matter, inorganic nutrients, major ions, and alkalinity; stable and radiogenic isotopes of organic matter ($\delta^{13}C$, $\Delta^{14}C$, and $\delta^{15}N$); and stable water isotopes ($\delta^{2}H$ and $\delta^{18}O$).

The PARTNERS/Arctic-GRO effort has captured wide seasonal and geographical variations in water chemistry that relate to watershed characteristics such as geology, vegetation, permafrost coverage, and active layer depth (Amon et al., 2012; Holmes et al., 2012; Tank et al., 2012a; Yi et al., 2012). These relationships provide a framework for tracking future changes in watershed characteristics through river water chemistry (McClelland et al., 2008). The PARTNERS/Arctic-GRO effort has also resulted in significant revision of river export estimates (Raymond et al., 2007; Cooper et al., 2008; Holmes et al., 2012; Tank et al., 2012c) that have supported exciting new insights about freshwater transport and biogeochemical cycling in the Arctic Ocean (Zimmerman et al., 2009; Manizza et al., 2009, 2011; Letscher et al., 2011; Tank et al., 2012b). As we look to the future, however, we must consider how to sustain water chemistry measurements at downstream sites on the major Arctic rivers over the long term. We must also consider how to expand spatial coverage of coordinated river network sampling so that we can take advantage of information generated at different scales (i.e., sub-watersheds of the major river basins) to improve data interpretation and predictive capabilities.

LINKING RIVER DISCHARGE AND WATER CHEMISTRY MEASUREMENTS

Measurements of river discharge and water chemistry must be linked as we work toward development of a long-term, internationally sustained Arctic observing network. Long-term monitoring of both water discharge and water chemistry in rivers is essential for identifying and understanding change in the Arctic. To date, however, these activities have not been tightly coupled within the context of an Arctic observing network. River discharge data generated by the various government agencies discussed above are used in combination with chemistry data to calculate fluxes of dissolved and particulate material, but the two types of data are not always collected at the same locations, and decisions about whether or not to continue monitoring river discharge and water chemistry are often made independently. As a consequence, in many instances it is not possible to take advantage of the synergistic information provided by parallel measurements of river discharge and water chemistry. River discharge data, acquired from the R-ArcticNET (www.R-ArcticNET.sr.unh.edu) and ArcticRIMS (Shiklomanov, 2012; Gordov et al., 2013; http://RIMS.unh.edu) data repositories at the University of New Hampshire, have (for the most part) been available from downstream hydrologic stations on the major Arctic rivers during the past decade, and these data have been essential to the success of the PARTNERS/Arctic-GRO effort. However, data continuity and access are far from assured. In fact, the R-ArcticNET and ArcticRIMS databases are not currently being supported, and acquiring discharge data (particularly from Russia) has become much more difficult as a consequence. Agreement among the United States, Canada, and Russia to maintain coupled river discharge and water quality monitoring efforts at downstream stations on the six largest Arctic rivers as a contribution to an international Arctic observing network is sorely needed. In addition, it would be beneficial for the agreement to include 1) a selection of stations representing major tributaries of the largest rivers and 2) a selection of stations from the Hudson Bay and Barents Sea regions. These additional stations would greatly enhance our ability to assess and understand changes occurring on a regional scale.

Although such an agreement among nations might initially seem difficult to reach, many of the pieces needed to support a coordinated international river observing effort are actually in place. The Arctic nations are already heavily invested in river discharge monitoring, and the sites selected for inclusion in the observatory agreement would undoubtedly be a subset of those that are currently active. Thus, the agreement would not amount to a major financial commitment at the outset but rather a commitment to making continued operation of select stations a top priority. If two major tributaries and a downstream station were included for each of the six largest river basins and approximately 10 sites (5 in Hudson Bay and 5 in the Barents Sea region) were selected from the existing discharge sites, the total number of sites would be ~28. This represents only a very small fraction of the hydrologic monitoring stations being operated within the pan-Arctic domain. The commitment would represent a nominal increase in the duties performed by personnel running the selected stations since they would add periodic water sampling to their routine where it is not already occurring. However, the most difficult aspect of the coordinated effort would be implementing consistent sample collection, preservation, and analysis procedures across international boundaries. A management board or some other entity would be needed to initiate standardized practices and maintain quality control on an ongoing basis. The management structure would also need to provide or oversee data dissemination. Focusing on a core set of parameters would be critical for keeping costs and complexity under control. Measurements of pH, alkalinity, optical properties (e.g., fluorescence and absorbance), concentrations of dissolved organic carbon and inorganic nutrients, and concentrations of the standard suite of major ions in water would be relatively easy to track and would provide valuable information about changing landscape processes and their potential downstream effects. Tracking the radiogenic carbon content of dissolved organic matter would also be very useful, although significantly more expensive. With rigorous lab inter-comparison procedures and shared analytical standards, chemical analyses could be performed at regional labs. Alternatively, specific analyses for all sites could be performed at designated facilities. Again, focusing on a limited number of sites (~28) would ensure that the total number of samples to be analyzed each year would not be overwhelming.

COMPLEMENTARY RESEARCH

While development of long-term datasets must be a primary goal of an international observing network, it is important to keep in mind that focused, short-term studies are very important for accurately interpreting the observatory data. With respect to rivers, we still have a tremendous amount to learn about how watershed characteristics and in-stream processes control water chemistry at scales ranging from headwater catchments to major river basins. We are only now beginning to understand how degradation and uptake processes at the soil-water interface and in headwater catchments modify the chemical signature of downstream constituents (e.g., Crawford et al., 2013; Mann et al., 2014). Our understanding of transport and processing of river-supplied constituents within the nearshore estuarine environment in the Arctic is also very limited, particularly with respect to seasonality. We have learned a great deal about seasonality in the Mackenzie delta and estuary (Macdonald, 2000; Carmack et al., 2004; Emmerton et al., 2008), but we are far from having a pan-Arctic understanding of relationships between seasonal river inputs and coastal ecosystem dynamics. We need studies focusing on watershed characteristics and in-stream processes at a wide range of scales to help us interpret temporal variability recorded at river observing stations, as well as studies focusing on estuarine processes, to understand what the impacts of variations in river inputs may be. We also need estuarine studies in order to take better advantage of river end-member information (e.g., river water tracers) in large-scale studies of Arctic Ocean dynamics.

SUMMARY OF RECOMMENDATIONS

The largest challenge to successful implementation of a cohesive system of Arctic observations is that such a system by nature will cross international boundaries. We recommend the following priorities for a successful, internationally based river observing system within the pan-Arctic watershed that is sustainable over the long-term.

- Establishment of an agreement between agencies in the United States, Canada, and Russia to maintain coupled river discharge and water quality monitoring efforts at 1) downstream stations on the six largest Arctic rivers, 2) stations on two major tributaries within each of the six largest river basins, and 3) stations at five strategic locations each within the Hudson Bay and Barents Sea drainage areas. This would be a total of 28 stations, all of which should be selected from existing water discharge gauge locations.
- Establishment of a river observing coordination board that includes partners from all Arctic countries. Members of this board should represent key governmental agencies that currently undertake sampling effort in the Arctic, the scientific community, and other stakeholders within the pan-Arctic drainage area. The board should be responsible for 1) defining the core set of parameters to be measured at each station, 2) initiating standardized protocols, 3) maintaining quality controls, and 4) facilitating data management and dissemination.
- High-priority measurements related to water chemistry include pH, alkalinity, optical properties (e.g., fluorescence and absorbance), concentrations of dissolved organic carbon and inorganic nutrients, and concentrations of the standard suite of major ions in water. Tracking the radiogenic carbon content of dissolved organic matter, although significantly more expensive, would also be very useful.
- Routine water quality analyses can be done at regional laboratories, but a system that enables inter-laboratory comparisons is needed to ensure that results are reliable and comparable among regions and with previously collected data.
- Specialized measurements such as radiogenic carbon content would best be done at centralized facilities.

Because this vision for long-term river observing in the Arctic largely relies on linkage of existing efforts, much of the required funding is already in place. Success would require a forward-looking commitment to continue monitoring of Arctic river discharge at key sites, and to add—where not already in place—the tracking of select biogeochemical parameters using methodologies that are comparable across international laboratories.

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