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Pan-Arctic river discharge: Prioritizing monitoring of future climate change hot spots

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Key Points:

- We project future Arctic river discharge and degree of agreement across climate models
- East-central Siberia, Alaska, and central Canada are hot spots for highest change
- We identify where present monitoring stations may suffice or need to be added

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2

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Pan-Arctic river discharge: Prioritizing monitoring of future climate change hot spots

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Abstract The Arctic freshwater cycle is changing rapidly, which will require adequate monitoring of river flows to detect, observe, and understand changes and provide adaptation information. There has, however, been little detail about where the greatest flow changes are projected, and where monitoring therefore may need to be strengthened. In this study, we used a set of recent climate model runs and an advanced macro-scale hydrological model to analyze how flows across the continental pan-Arctic are projected to change and where the climate models agree on significant changes. We also developed a method to identify where monitoring stations should be placed to observe these significant changes, and compared this set of suggested locations with the existing network of monitoring stations. Overall, our results reinforce earlier indications of large increases in flow over much of the Arctic, but we also identify some areas where projections agree on significant changes but disagree on the sign of change. For monitoring, central and eastern Siberia, Alaska, and central Canada are hot spots for the highest changes. To take advantage of existing networks, a number of stations across central Canada and western and central Siberia could form a prioritized set. Further development of model representation of high-latitude hydrology would improve confidence in the areas we identify here. Nevertheless, ongoing observation programs may consider these suggested locations in efforts to improve monitoring of the rapidly changing Arctic freshwater cycle.

1. Introduction

Arctic river flow, a key component in the Arctic and global climate systems [*Vörösmarty et al.*, 2001], is changing rapidly [*Rawlins et al.*, 2010], yet little is known about where monitoring of these flows should be strengthened to counteract reported declines in observational capacity.

Arctic rivers comprise some of the largest river systems on the Earth, and connect a vast and diverse region to the much smaller area of the receiving water body, the Arctic Ocean. Arctic rivers annually contribute about twice the amount of freshwater as net precipitation over the ocean [*Haine et al.*, 2015; *Carmack et al.*, 2016], and also act as conveyors of nutrients, carbon, and other elements from their diverse watersheds [*Bring et al.*, 2016], some of which extend as far south as the mid-latitudes. Thus, the rivers are integral to the freshwater circulation in the Arctic, a system that is changing rapidly with expected consequences also for global climate [*Prowse et al.*, 2015a, 2015b; *Newton et al.*, 2016].

The exact nature of long-term effects on the climate system from changing river flows and associated freshwater cycling in the Arctic is far from understood, but evidence suggests that these effects will be substantial [*Rawlins et al.*, 2010; *Hinzman et al.*, 2013; *Bintanja and Selten*, 2014; *Haine et al.*, 2015]. Notwithstanding unresolved couplings between components of the Arctic climate system [*Park et al.*, 2014, 2015; *Carmack et al.*, 2016; *Lique et al.*, 2016; *Vihma et al.*, 2016], changes to Arctic rivers will also strongly affect about 40 million people who reside in their combined drainage area [*Stephenson and Smith*, 2015; *Instanes et al.*, 2016]. River flow influences such diverse processes and systems as transportation routes, ecosystem functioning, permafrost degradation patterns, mining and fossil fuel extraction, and spatial planning. Therefore, there is a great need to understand how these river systems function and change.

Historically, observations indicate that flows have increased over much of the pan-Arctic [*Peterson et al.*, 2002, 2006; *McClelland et al.*, 2006; *Shiklomanov and Lammers*, 2009; *Dyurgerov et al.*, 2010; *Overeem and*

Syvitski, 2010; *Holmes et al*., 2013; *Bring and Destouni*, 2014]. Earlier reported flow decreases for North America [*Déry and Wood*, 2005; *Déry et al*., 2005] have reversed the trend in some cases and are now increasing instead [*Déry et al*., 2009; *Ge et al*., 2013]. For the combined set of basins draining to the Arctic Ocean, flows have increased to new levels of 4200 $\pm$ 420 km^3 during 2000–2010 from 3900 $\pm$ 390 km^3 during 1980–2000 [*Haine et al*., 2015].

Projections using global climate models (GCMs) indicate that flows will generally continue to increase over much of the pan-Arctic [*Milly et al*., 2005; *Nohara et al*., 2006; *Holland et al*., 2007; *Kattsov et al*., 2007; *Rawlins et al*., 2010]. Similarly, recent simulations with global hydrological models, with input from climate models, generally show increases on the order of 25%–50% over most of the pan-Arctic [*Arnell*, 2005; *Shiklomanov et al*., 2013; *van Vliet et al*., 2013; *Koirala et al*., 2014]. A synthesis of such earlier studies estimated overall increases of 10%–20% [*Walsh et al*., 2005]. Decreases are mostly concentrated to the southern interior of the pan-Arctic drainage basin [*van Vliet et al*., 2013; *Koirala et al*., 2014]. However, many of these projections provide only limited details, and the only study yet to use the latest generation of climate model data [*Koirala et al*., 2014] was global in extent, with no focus on the pan-Arctic.

While flows are changing rapidly in the Arctic, the capacity to observe changes has declined [*Lammers et al*., 2001; *Shiklomanov et al*., 2002, 2006; *Déry et al*., 2011; *Bring and Destouni*, 2013]. In response to this decline, a number of studies have pointed out potential pathways to improve monitoring [*Karlsson et al*., 2011; *Mlynowski et al*., 2011; *Azcárate et al*., 2013; *Bring and Destouni*, 2013; *McClelland et al*., 2015]. A detailed study of a number of major Canadian watersheds, based on information theory, provided specific recommendations on how to modify the network to make it more efficient [*Mishra and Coulibaly*, 2010]. Despite these useful suggestions, no study has so far provided any detailed recommendations on where to reinforce monitoring to observe the projected rapid changes across the pan-Arctic basin.

To understand changes, address them adequately, and plan for adaptation, there is a need for more detailed projections, better information on where projected flow changes are uncertain, and more knowledge about where monitoring stations could be added or reopened to strengthen networks and provide better information to researchers, environmental managers, and policymakers.

In this article, we aim to address the gaps outlined above by answering three questions: where is the greatest change in annual river discharge projected to occur? where should monitoring stations be located to observe that change? and how does that suggested configuration of station locations compare to the network of presently operational stations? We acknowledge that monitoring of the greatest discharge changes is only one of many possible information goals for monitoring networks, but nevertheless argue that this objective is particularly important under rapidly changing hydrological conditions. In addition to a general scientific interest, we hope that those in charge of monitoring river flow in the northern countries can use this information to help guide potential existing station reorganization, to identify additions to the existing network of stations, or identify high priority stations to maintain in the future.

2. Methods

In this section, we first describe how we estimated future changes in annual discharge, then how we used that information to identify a number of locations to monitor the change, and finally describe how we compared the suggested locations to the existing network.

2.1. Geographical Scope

From a hydrological perspective, a natural starting point for the study domain is the All Arctic Regions (AAR) domain outlined in *Shiklomanov et al*. [2000] and *Lammers et al*. [2001], which includes all land areas draining to the Arctic Ocean or its adjacent seas. However, for the scope of this analysis, we excluded the islands in the Arctic and Atlantic Oceans and restricted the area to the continental drainage (Figure 1). The motivation for this restriction was twofold: First, many Arctic islands are polar deserts and river flows there are generally very low. Changes to very low and intermittent flows are difficult to accurately evaluate, as even small changes in absolute terms can result in very large relative shifts. Second, most of the islands have extensive ice caps that dominate the landscape, and remaining ice-free areas are mostly composed of smaller watersheds, sometimes strongly influenced by glaciers. Although changes to those areas are

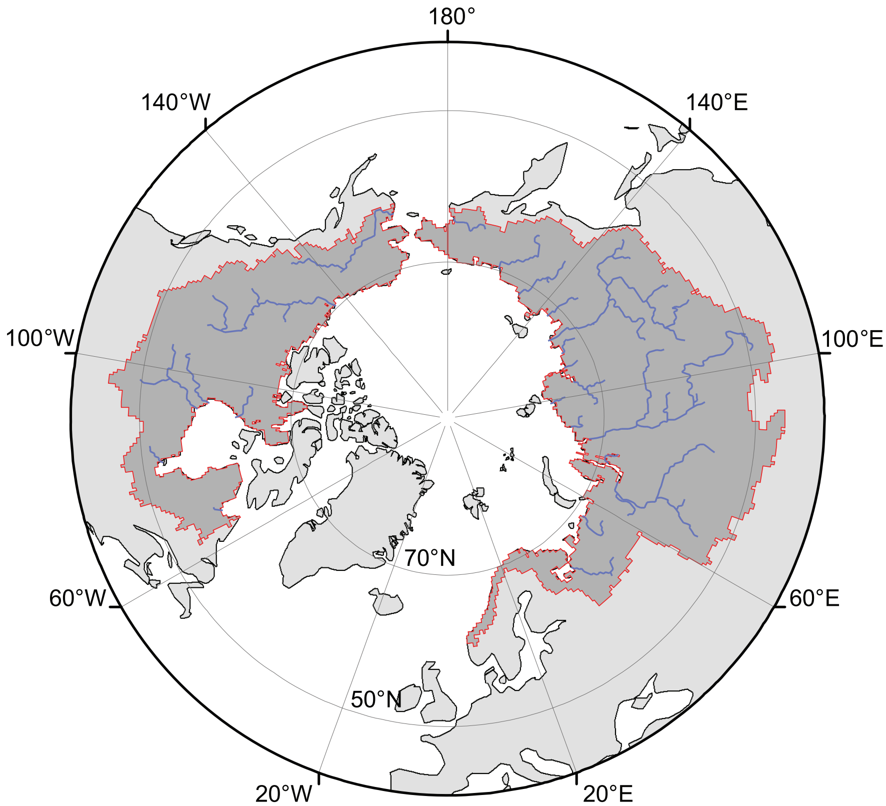

Figure 1. Map of the continental pan-Arctic drainage basin (shaded area) with major rivers indicated. Lambert azimuthal equal-area projection, approximate scale 1:90,000,000.

certainly of interest, we excluded them from the continental-scale analysis in this study due to their small size and special conditions.

2.2. River Discharge Projections

We estimated future changes to river discharge with the University of New Hampshire Water Balance/Transport Model (WBM), a process-based spatially distributed macro-scale hydrological model designed to investigate changes in the natural hydrological cycle and the major human influences over the Earth's land surface [see details in *Wisser et al*., 2010; *Grogan*, 2016]. The WBM is variable-resolution, grid-based, and simulates both vertical water exchanges with the atmosphere and lateral transport on a daily time step. Flow is routed downstream using the Muskingum–Cunge kinematic wave approximate solutions to the Saint-Venant partial differential equations for one-dimensional flow. We used a glacier submodule to provide more realistic output from permanent ice [*Huss and Hock*, 2015], irrigation of agricultural fields [*Wisser et al*., 2008; *Grogan et al*., 2015] to account for water loss from the rivers, important in the southern regions of the Ob' and Nelson basins, unsustainable groundwater mining in those irrigated regions [*Grogan et al*., 2015], dams, and reservoirs using the *Lehner et al*. [2011] database, and interbasin hydrological transfers (R. B. Lammers et al., in preparation, 2016). As earlier studies on historical changes have identified large impacts on the water cycle from human modifications, both globally [*Gordon et al*., 2005; *Vörösmarty et al*., 2010; *Jaramillo and Destouni*, 2015] and in the Arctic [*Yang et al*., 2004a, 2004b; *Stuefer et al*., 2011], considering these impacts in models is important to arrive at credible future projections [*Feddema et al*., 2005; *Bring et al*., 2015].

For a full description of the WBM, we refer to the studies above, where detailed accounts of the model structure, its various components, and all governing equations are available. In terms of validation, several earlier studies have evaluated the WBM in different settings with consistent results. For example, *Rawlins et al*. [2003] validated runoff simulations against observations for 650 gages in the pan-Arctic, and in *Fekete* *et al*. [2002], *Wisser et al*. [2010], and *Grogan* [2016], the WBM was validated on a global scale against runoff observations from the Global Runoff Data Centre. *Wisser et al*. [2010] found low overall bias in WBM model simulations. As shown in both *Wisser et al*. [2010] and *Grogan* [2016], the input climate dataset (mainly precipitation) contributes the most to uncertainty in model output, similar to results for other models of this kind [e.g., *Biemans et al*., 2009]. Although the choice of hydrological model is important [*Haddeland et al*., 2011; *Hagemann et al*., 2013], we expect that the reliability of our analysis will be principally limited by the input climate model data. Overall, we argue that the development and validation of the WBM over the last decade shows that it is appropriate for the application in this study.

For the simulation runs reported here, the model was forced with bias-corrected historical and projected climate from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble [*Taylor et al*., 2012] over a 30 arcminute × 30 arcminute gridded field. The CMIP5 multimodel ensemble consists of over 30 GCMs for which simulations of a number of scenarios have been carried out in a coordinated way.

We selected a sample of six GCMs (CCSM4, CESM1-CAM5, GFDL-CM3, GISS-E2-H, MIROC5, and MRI-CGCM3) that represented a large range of GCM responses to climate forcing, based on the model-estimated global mass loss of glaciers by 2100. This measure captures changes in several aspects of the climate system, including the key variables of temperature and precipitation. The historical time period from 1950 to 2005 and three future scenarios from 2006 to 2099 (termed RCP4.5, RCP6.0, and RCP8.5 and described in detail in *van Vuuren et al*. [2011]) were used as inputs to WBM to estimate river discharge across the entire continental pan-Arctic domain. We excluded the lowest-emission RCP2.6 scenario for two reasons: first, it assumes a peak in emissions before 2020 [*van Vuuren et al*., 2011], which is already an extremely unlikely development today, and second, adapting monitoring to climate change is more motivated by the larger impacts in the other, more plausible scenarios. We selected the periods 1961–1990 and 2061–2090 to represent the historical and future climatological periods, respectively. Although 2061–2090 may extend beyond the time horizon of current planning decisions on monitoring networks, a distant time period is a relevant benchmark for long-term changes and allows the signal of change to be distinguished from historical variability, which is generally larger for water cycle variables, such as precipitation and discharge, than temperature [*Hawkins and Sutton*, 2011].

2.3. Identification of Areas With Large Changes

There are many ways to classify model agreement, with some discussion in the literature as to which ones are appropriate [*Tebaldi et al*., 2011; *Collins et al*., 2013]. For the purpose of our analysis, we needed to identify areas where changes are expected to be large, as well as an indication of how certain the direction of change is.

We therefore used a method similar to the approach suggested by *Tebaldi et al*. [2011] to calculate model agreement. To identify the areas with large changes, we computed differences from the historical 30 years of annual mean discharge to the future 30 years of annual mean discharge, for each climate model and future scenario. For each cell, we then evaluated (1) whether at least half of the model–scenario combinations showed a significant change ($p < 0.05$) using a two-tailed t-test, and for the cells where this criterion was met, we also evaluated (2) whether at least 80% of the models with significant changes also showed a change of the same sign. The thresholds we used here are not fixed, but they were also used by *Tebaldi et al*. [2011], and we judged them to be appropriate for this study. Importantly, the values we evaluated for each cell always constituted an integrated response of a number of upstream cells in the river network, and thus represented changes over more than single cells.

Thus, cells where only criterion 1 was met corresponded to areas where a majority of models indicate substantial future change, but where the direction of change is uncertain. In contrast, cells where both criteria 1 and 2 were met are areas with significant changes and a more certain direction of change. Both these categories are of interest for monitoring, and we therefore considered them both as important areas of potentially high change. Depending on objectives, the emphasis may be placed on the first category, for improving understanding of uncertain changes in the water system and determining the eventual direction of change, or the second, when prioritizing monitoring efforts to places where a particular direction of change may be more likely, or both.

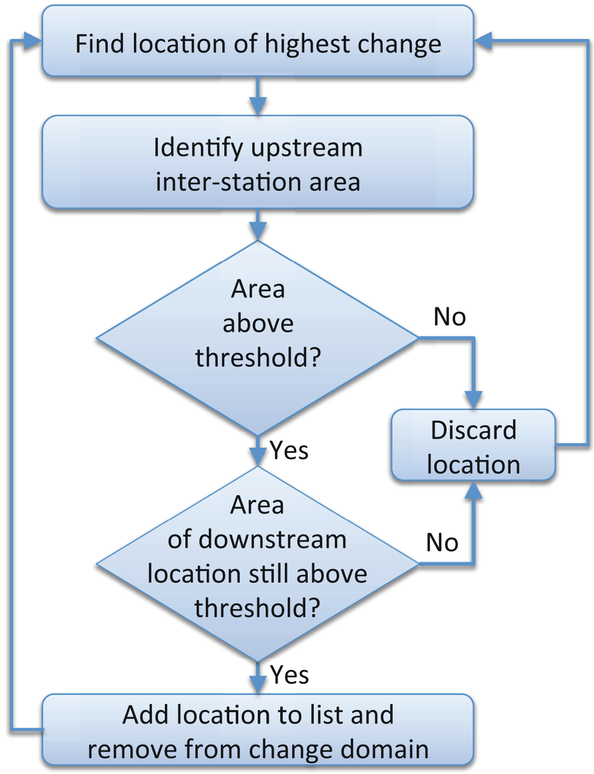

Figure 2. Illustration of the location selection algorithm.

In this study, we did not investigate the three climate scenarios separately, but instead pooled them into a larger set of model–scenario combinations. This approach was motivated for at least two reasons. First, we wanted to provide a basis for a long-term decision, but did not know which scenario will be closest to the eventual true pathway of the future climate system. With the exception of the very optimistic RCP2.6 scenario that we excluded (based on its emerging counter-factual properties), attributing likelihoods to the other scenarios is a very difficult task, and not only beyond the scope of this paper but possibly also beyond the capacity of hydrologic network managers. Therefore, we chose to base our analysis on the three scenarios combined, and identified changes that were consistent across them. This acknowledges the fact that the scenarios are only possible realizations of the future, with the true future unlikely to closely follow any particular one of them, and allows for a no-regret solution. Second, our sample of model runs became larger, which is relevant when considering that models may not provide identical outcomes from multiple runs, even for the same scenario, due to internal variability, changed initial conditions, and so on. Our combined set of 18 model–scenario combinations was therefore an attempt to broaden the sample and include as much information about plausible future pathways of the climate systems as possible.

2.4. Identification of Station Locations

We considered all 14,497 cells in the 30-arcminute × 30-arcminute grid that were within the continental pan-Arctic drainage system (Figure 1) as potential monitoring locations. Our objective was to identify and rank these locations with the highest change in river flow, while at the same time achieving a balanced set of hypothetical stations placed at these locations. We therefore devised an algorithm that considers both the magnitude of change at each monitoring location and the upstream basin area monitored by a potential station at the location.

Figure 2 shows an overview of the algorithm. In each step, the algorithm first selects the cell with the highest magnitude of change that has not been inspected previously. Second, the basin area upstream of the cell, up to any previously identified monitoring locations, is delineated. This area, termed the interstation area, must be above a threshold basin size for the cell to be considered as a potential monitoring location. For this continental-scale analysis, we used a lower limit of 25,000 km^2, which is on the same order of magnitude as earlier investigations of global and pan-Arctic hydrology and monitoring at half-degree resolution [*Vörösmarty et al.*, 2000; *Bring and Destouni*, 2009]. Similarly, the interstation area of any downstream monitoring location already identified, when considering the addition of the present cell to the set, is also inspected and must be over the area threshold. If both criteria are met, the cell is added to the set of potential monitoring locations. The procedure is repeated until all cells have been inspected.

2.5. Comparison With Existing Network

In a final step, we compared the set of optimal locations to the present network of stations. First, we gathered attribute information from all known river discharge monitoring stations from R-ArcticNet v.4.0 and other datasets developed at the University of New Hampshire [*Lammers et al*., 2001; *Shiklomanov et al*., 2002, 2007; *Shiklomanov and Lammers*, 2009, 2011, 2013], the Global Runoff Data Centre, and national agencies responsible for water data collection: U.S. Geological Survey, Environment and Climate Change Canada, Norwegian Water Resources and Energy Directorate, Finnish Environment Institute, and Russian RosHydromet. This included monitoring stations that are currently active and those that are no longer in operation. Although we were not able to obtain information on which stations that belonged to each of those categories, we show in Figure S1, Supporting Information the distribution of first and last data years for the stations. The station list was reduced in size by removing duplicate stations and by applying a spatial mask covering the continental pan-Arctic to eliminate those stations falling outside of the study domain. These stations were subsequently colocated to an updated version of the digital drainage network [*Vörösmarty et al*., 2000] by the aid of an automatic snapping algorithm. As we did not have complete information on which stations that were operational or not, nor cost estimates of the operation or establishment of stations, we chose to include all listed stations, not to exclude any potential existing monitoring sites. We acknowledge that this is a limitation as we cannot indicate which of the actually operational stations that are the most important to maintain, or which of the closed stations that should be considered for reestablishment, for example ones with high changes and previous long-term records. However, the information about the most important locations are still available in our results, and can therefore be used by the network managers together with any other criteria they may have in deciding which stations to prioritize.

For each cell in the set of potential locations, we first determined whether the cell contained an existing monitoring station. If so, that station (or set of stations) was inspected to determine whether the listed drainage area of the station matched the cell's upstream area, within a tolerance of 20%. If no stations with matching area were found, nearby cells in the drainage network, both upstream and downstream up to a 20% deviation in upstream drainage area, were inspected in a similar way. Thus, each cell in the set of potential locations fell into one of three categories: (1) an existing monitoring station was present in the cell, (2) an existing monitoring station was present in a nearby cell, or (3) there were no existing monitoring stations in the cell, nor in any nearby cells.

For cells in the latter category, we used the coordinates of the cell center to retrieve address information (name of nearest settlement or administrative area) from Google Maps (http://maps.google.com).

3. Results

Figure 3 shows the projected multimodel and multiscenario change in annual river discharge for 2061–2090, compared (in percentage terms) with the model-simulated historical values during 1961–1990. A salient distinction between areas with and without significant changes is evident.

Overall, areas with significant changes and agreement on the sign of change (stippled areas in Figure 3, almost exclusively agreement on increases) are strongly concentrated in Siberia, Alaska, and northern Canada and Quebec. Areas where projections indicate significant changes, but disagree on the sign of change (white areas in Figure 3), are concentrated in south-central Canada (Alberta, Manitoba, and Ontario) and the southern Ob' and Yenisey basins. Areas with nonsignificant changes (colored nonstippled areas in Figure 3) are predominant over much of central Canada, the central Ob' basin, and the European pan-Arctic west of the Ural Mountains. Similar to areas with significant changes, changes are biased toward increases, but for some regions in southern Canada and Western Russia, flows are projected to decrease.

For the countries in the pan-Arctic drainage, significant increases dominate in the U.S. and Russia, while nonsignificant changes are the most common in Canada. In Finland and Norway, areas with small changes (on average, increases only) dominate strongly, in contrast with Kazakhstan, and China, where significant increases are predominant. In Mongolia, smaller decreases are projected for a minor share of the country, while the remainder is almost equally split between significant and nonsignificant increases. It should be kept in mind, however, that Arctic drainage basins in the five latter countries are relatively small compared to the others, and results are based on a limited number of cells.

Based on these projections of change, Figure 4 shows the results of our analysis of potential monitoring station locations. Locations are ranked by the magnitude of change in each cell, and the colors therefore indicate a potential grouping of stations by priority, according to the size of the projected change in river flow.

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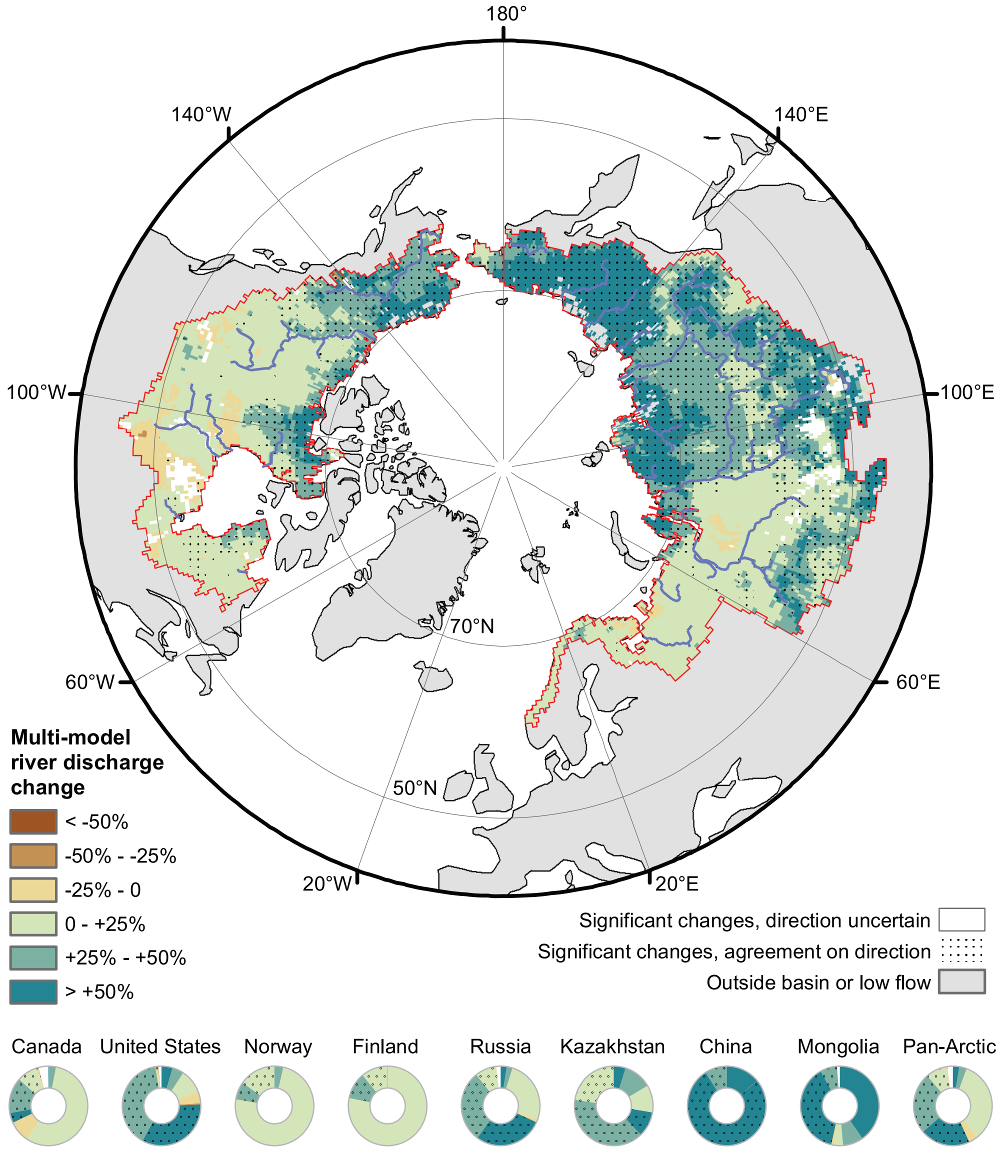

Figure 3. Changes to Arctic river flows. The map shows projected changes in average discharge across the pan-Arctic from 1961–1990 to 2061–2090, and the circle charts show the distribution of changes in each country and for the pan-Arctic as a whole. White areas, indicating agreement on significant changes but disagreement on sign, show where model agreement according to criterion 1 (at least half of the models indicate significant changes [$p < 0.05$] using a two-tailed t-test) is fulfilled. Stippled areas show where model agreement according to criterion 1 (as above) *and* criterion 2 (80% of the models that show significant change also agree on the sign of change) is fulfilled. Areas that are neither white nor stippled indicate changes with nonsignificant changes. Areas inside the red border on the map but shown in grey are masked due to low average flows (<1 m^3 s^{-1}).

Locations with the highest magnitude of change (red group, corresponding to the 1st quintile of locations) are concentrated in eastern (Yana, Indigirka, and Kolyma basins) and central Siberia (Yenisey basin). Locations in the lowest quintile of changes are also clustered (mainly in the Ob', Yenisey, and southern Lena basins), but to a lesser degree, and also have a more dispersed occurrence in a broad swath across the boreal forests of the southern Canadian pan-Arctic. Locations in the middle quintiles, although more interspersed across the entire basin than locations in the highest and lowest quintile, are generally more prevalent in central Canada, central Siberia and in Alaska.

The quintiles in Figure 4 show how the suggested locations rank by magnitude of change. However, the possibility to monitor a particular site with an already existing station (whether that station is presently operational or not) may also be an important consideration when deciding which locations to prioritize.

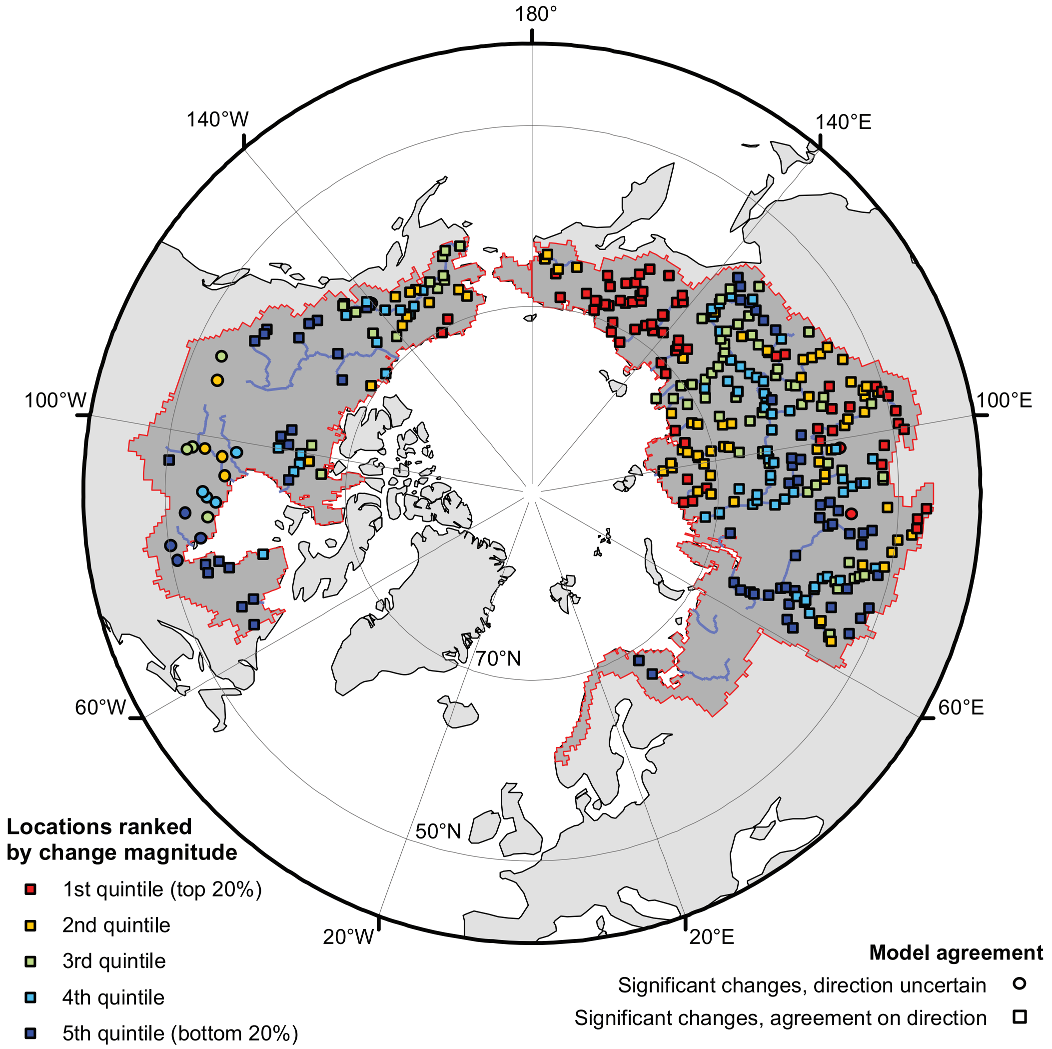

Figure 4. Potential locations of stations to monitor high change. The colors indicate the rank by magnitude of change. Circles are shown in locations where model agreement according to criterion 1 (at least half of the models indicate a significant change [$p < 0.05$] using a two-tailed *t*-test) is fulfilled (these locations fall in the white areas of Figure 3). Squares are shown in locations where model agreement according to criterion 1 (as above) *and* criterion 2 (80% of the models that show significant change also agree on the sign of change) are fulfilled (these locations fall in the stippled areas of Figure 3).

Figure 5 shows the same locations as in Figure 4, but with colors indicating whether a station exists there, or in a nearby cell along the river network. Overall, the high-change locations that overlap with the existing monitoring network (green and yellow locations in Figure 4) are about as many as the locations with no overlap (red locations). The cells without existing stations are distributed relatively even across the entire basin, but are somewhat less frequent in western Canada. The latter region instead constitutes a concentration of locations with existing (green) or nearby (yellow) stations, which are also otherwise interspersed relatively even across the pan-Arctic.

In Table 1, we show a breakdown of locations by quintiles (shown in Figure 4) and by their relationship to the existing network (shown in Figure 5). In total, the number of locations with existing stations at or nearby the location (177; sum of locations in last four columns) is similar to the number of locations where there are no stations nearby (178; sum of locations in first two columns). However, for the locations in the highest quintile, only half as many locations are with (23; sum of Quintile 1 over last four columns) as are without (47; sum of Quintile 1 over first two columns) stations.

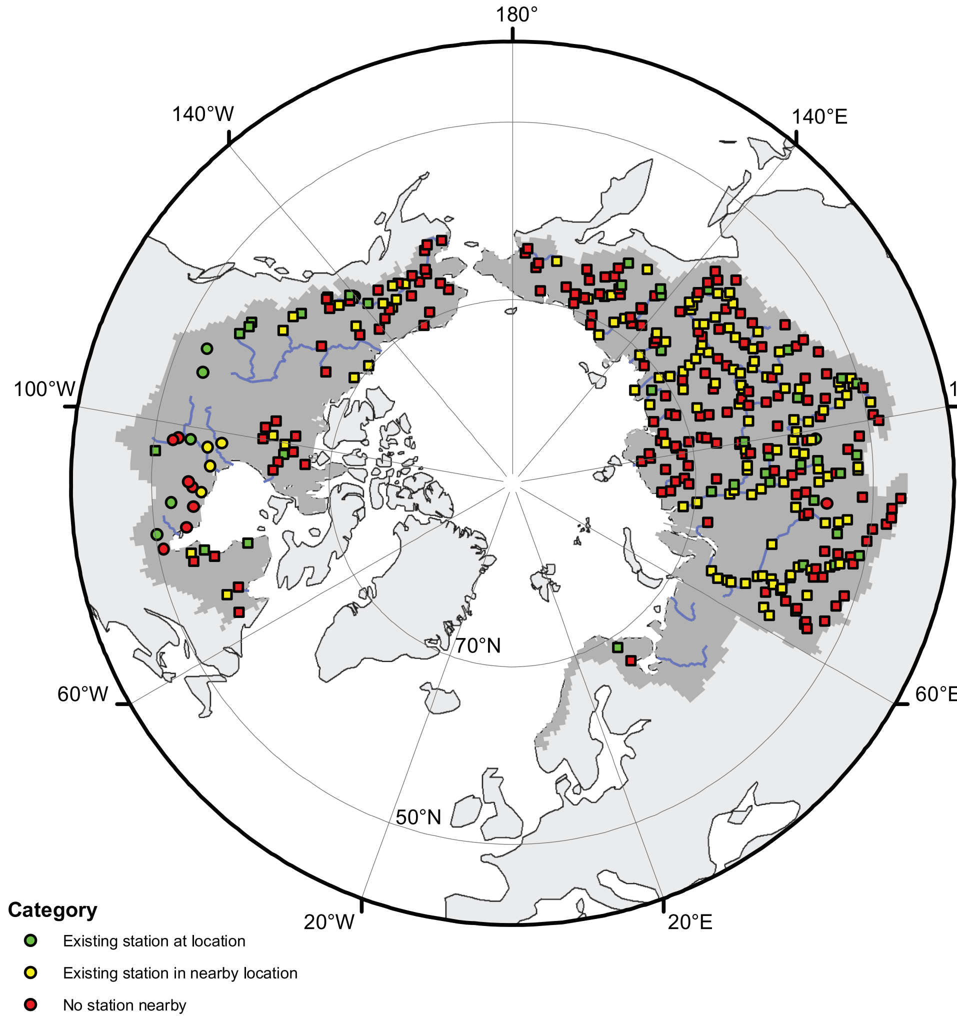

Figure 5. Comparison of high-change locations with existing stations. Monitoring locations from Figure 4 color-coded according to whether there is an existing station in the cell (green); in a nearby cell along the river network (yellow); or neither in the cell or in any nearby cells along the river network (red). As in Figure 4, circles are shown in locations where model agreement according to criterion 1 (at least half of the models indicate a significant change [$p < 0.05$] using a two-tailed *t*-test) is fulfilled (these locations fall in the white areas of Figure 3). Squares are shown in locations where model agreement according to criterion 1 (as above) and criterion 2 (80% of the models that show significant change also agree on the sign of change) are fulfilled (these locations fall in the stippled areas of Figure 3).

In Tables S1 and S2, we provide details of all locations, including coordinates, basin size, magnitude of projected change, and specifics of any existing monitoring stations at the location.

In Table 2, we present a subset of the information in Tables S1 and S2, and highlight the top locations, ranked by magnitude of change, for (a) locations with existing stations, (b) locations with stations nearby, and (c) locations without any stations nearby. Respectively, these lists indicate (a) a set of high-priority stations to maintain in the future, (b) a set of basins where monitoring exists but may need to be augmented, and (c) a set of basins where no stations exist and new stations are particularly motivated due to the agreement on expected change. As noted above, we do not distinguish between stations that are presently operational or not, as we have no information on operating costs or other network priorities that may be factors when deciding whether to continue, close, or reopen a particular station. For locations where models only agree on significant change but not on sign, all 19 locations are shown, while the 30 first locations are shown for areas where models agree on significant change of a particular sign.

Table 1. Classification of Potential Monitoring Locations.

	Number of Locations with					
	No Station Nearby		Station Nearby		Station at Location	
Agreement on Quintile	Magnitude	Magnitude and Sign	Magnitude	Magnitude and Sign	Magnitude	Magnitude and Sign
1	2	45	0	15	1	7
2	0	43	2	17	2	7
3	3	33	0	29	1	5
4	2	17	2	37	0	13
5	2	31	0	26	2	11
Total	9	169	4	124	6	43
	Without station: 178		With station: 177			

The table shows the number of locations that fall in each category, separated first by relation to existing network (whether there is no station at the location, a station in a nearby cell, or a station at the location) and second by the nature of model agreement (whether models agree on magnitude; i.e., a significant change but of uncertain direction, or agree on significant change as well as the sign of change).

4. Discussion

In this paper, we have evaluated changes to Arctic river discharge to the end of the present century, and found large areas with significant increases. For the pan-Arctic as a whole, we found larger areas where models agree on significant change than where they agree on little or no change. This is to be expected with a rapidly warming Arctic where changes over the next half century are likely to be substantial across most of the region, but we note here that this holds even when considering three RCP scenarios, including a moderate-emission mitigation pathway.

In an earlier study using a GCM-forced hydrological model, *van Vliet et al*. [2013] also found strong increases in mean annual flows across Alaska and central and eastern Siberia. In contrast, their results also indicated increases of similar magnitude, and model agreement, for much of central Canada, particularly in a relatively high-emission scenario [*van Vliet et al*., 2013]. Their study, however, only used three GCMs that were drawn from an earlier generation (CMIP3) than those in our study, and the emission scenarios did not include the larger range considered here.

Similarly, the results of *Koirala et al*. [2014] show almost total predominance of increases in average discharge across Arctic regions from 1971–2000 to 2071–2100, although their study was restricted to the most extreme high-emission scenario. They also present a measure of model agreement, defined somewhat differently from ours, that indicates moderate to strong agreement on increases in all of central and eastern Siberia, northern Quebec, and all of Alaska. For areas where we find significant changes of uncertain direction, their analysis generally indicates weak or no agreement.

In earlier studies that routed and mapped the projected runoff changes from climate models directly [*Milly et al*., 2005; *Nohara et al*., 2006], results are mostly in line with the general pattern we observe, with consistent increases across models over much of the pan-Arctic basin, and decreases for minor areas in interior North America. Although the geographical patterns of increases and decreases are similar, the runoff provided as a direct output of climate models is generally less reliable on drainage basin scales, at least in terms of model ability to reasonably close the water balance [*Bring et al*., 2015], and no effects of human modifications are included in such studies.

The differences between our results and those of the aforementioned are likely attributable partly to differences in climate model generation and selection, partly (but likely to a smaller degree) to differences in the hydrological model, and partly to differences in study design, such as choice of scenario and time period. Our study considers the largest range of potential emission scenarios and is the only study to combine the information from them.

Table 2. Details of Highest-Ranked Locations.

Criterion 1 Fulfilled: Model Agreement on Significant Change, Disagreement on Sign

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Station Listed Area (km^2)	Station Code	Station Name
Locations with existing stations—maintain monitoring									
4	2	53.75	−109.75	55,614	Nelson	19	57,153	05EF001	North Saskatchewan River near Deer Creek
5	2	54.25	−97.75	1,048,917	Nelson	17	—	05UB008	Nelson River (East Channel) below Sea River Falls
							—	05UB001	Nelson River at Norway House
9	3	53.25	−113.75	26,281	Nelson	15	28,096	05DF001	North Saskatchewan River at Edmonton
							28,000	05DF005	North Saskatchewan River at Edmonton Pumping Station
16	5	52.25	−86.75	26,708	Attawap.	12	24,200	04FB001	Attawapiskat River below Attawapiskat Lake
18	5	50.25	−81.75	26,414	Moose	9	23,400	04ME004	Abitibi River at Otter Rapids
Locations with stations nearby—potential need to reinforce monitoring									
6	2	56.25	−96.75	1,110,517	Nelson	16	1,090,000	05UF003	Split Lake at Split Lake
							—	05UF005	Butnau River Diversion near Gillam
							1,100,000	05UF002	Nelson River at Kettle Crossing
							1,100,000	05UF006	Nelson River at Kettle Generating Station
							1,100,000	05UF007	Nelson River at Long Spruce Generating Station
							1,050,000	05UE001	Nelson River above Shell Rapids
							1,050,000	05UE005	Nelson River at Kelsey Generating Station
							1,050,000	05UE003	Nelson River at Manitou Crossing
							1,050,000	05UE002	Nelson River at Mcmillan's Landing
							1,050,000	05UE004	Nelson River below Sipiwesk Lake
							1,050,000	05UD005	Sipiwesk Lake at Cross Portage
							1,040,000	05UD009	Cross Lake above Whitemud Falls
							1,040,000	05UD001	Cross Lake at Cross Lake

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Table 2. (continued).

Criterion 1 Fulfilled: Model Agreement on Significant Change, Disagreement on Sign

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Station Listed Area (km^2)	Station Code	Station Name
							1,040,000	05UD008	Cross Lake below Jenpeg
							1,040,000	05UD004	Nelson River above Bladder Rapids
							1,040,000	05UD002	Nelson River at Whitemud Falls
							—	05UB008	Nelson River (East Channel) below Sea River Falls
							—	05UB001	Nelson River at Norway House
7	2	56.75	−93.25	1,136,434	Nelson	16	1,090,000	05UF003	Split Lake at Split Lake
							—	05UF005	Butnau River Diversion near Gillam
							1,100,000	05UF002	Nelson River At Kettle Crossing
							1,100,000	05UF006	Nelson River at Kettle Generating Station
							1,100,000	05UF007	Nelson River at Long Spruce Generating Station
							1,050,000	05UE001	Nelson River above Shell Rapids
							1,050,000	05UE005	Nelson River at Kelsey Generating Station
							1,050,000	05UE003	Nelson River at Manitou Crossing
							1,050,000	05UE002	Nelson River at Mcmillan's Landing
							1,050,000	05UE004	Nelson River below Sipiwesk Lake
							1,050,000	05UD005	Sipiwesk Lake at Cross Portage
							1,040,000	05UD009	Cross Lake above Whitemud Falls
							1,040,000	05UD001	Cross Lake at Cross Lake
							1,040,000	05UD008	Cross Lake below Jenpeg
							1,040,000	05UD004	Nelson River above Bladder Rapids

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Table 2. (continued).

Criterion 1 Fulfilled: Model Agreement on Significant Change, Disagreement on Sign

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Station Listed Area (km^2)	Station Code	Station Name
							1,040,000	05UD002	Nelson River at Whitemud Falls
							—	05UB008	Nelson River (East Channel) below Sea River Falls
							—	05UB001	Nelson River at Norway House
12	4	57.75	−97.75	2,63,683	Churchill	14	2,89,000	06FD001	Churchill River above Red Head Rapids
							260,000	06EC006	Southern Indian Lake at Missi Falls
							271,000	06FB001	Churchill River below Fidler Lake
							261,000	06EC002	South Bay Diversion Channel at South Bay
							260,000	06EC003	Southern Indian Lake at South Bay
							260,000	06EC007	Southern Indian Lake near Opachuanau Lake
							260,000	06EC001	Southern Indian Lake near South Indian Lake
							230,000	06EA006	Churchill River above Granville Falls
							244,000	06 EB004	Churchill River above Leaf Rapids
							244,000	06 EB002	Granville Lake at Granville Lake
							212,000	06EA010	Churchill River above Maple Leaf Rapids
							222,000	06EA012	Pukatawagan Lake at Pukatawagan
14	4	55.75	−88.25	102,345	Severn	14	—	04CC002	Severn River below Sachigo River
							94,300	04CC001	Severn River at Limestone Rapids

Locations without stations—add new monitoring

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Nearest Settlement or Location Description
2	1	63.25	−139.75	49,386	Yukon	23	Yukon and White River Confluence
3	1	55.25	86.25	42,060	Ob’	22	Kemerovo, Kemerovo Oblast, Russia

Table 2. (continued).

Criterion 1 Fulfilled: Model Agreement on Significant Change, Disagreement on Sign

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Station Listed Area (km^2)	Station Code	Station Name
8	3	52.25	−97.25	491,125	Nelson	16	Berens River, MB, Canada		
10	3	52.75	−97.75	586,720	Nelson	15	Negginan, MB, Canada		
11	3	54.75	−85.75	56,767	Winisk	14	Peawanuck, ON, Canada		
13	4	54.75	−89.25	74,043	Severn	14	Severn River Near Outlet		
15	4	54.25	−90.25	46,496	Severn	13	Severn River Provincial Park, ON, Canada		
17	5	53.75	−82.25	25,634	Ekwan	12	Down river from Severn River Provincial Park, ON, Canada		
19	5	50.75	−79.25	26,148	Harric.	9	Asuwapamatikunan, QC, Canada		

Criteria 1 and 2 Fulfilled: Model Agreement on Significant Change and Sign

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Station Listed Area (km^2)	Station Code	Station Name
Locations with existing stations—maintain monitoring									
19	1	65.25	151.25	28,129	Kolyma	117	32,000	1578	Yasachnaya at Nelemnoye
25	1	51.75	94.75	56,215	Yenisei	105	58,600	9127	Malyi Yenisei at Kyzyl
28	1	63.25	142.75	26,940	Indigirka	101	24,500	3487	Indigirka at Oimyakon
29	1	50.25	106.25	284,994	Yenisei	97	282,000	7041	Selenga at Naushkiy
31	1	63.75	141.75	52,032	Indigirka	95	51,100	3488	Indigirka at Urtu
36	1	67.25	153.75	361,566	Kolyma	89	361,000	1801	Kolyma at Srednekolymsk
56	1	62.75	152.25	102,137	Kolyma	71	—	1012	Koluma at svkh.Iskra
68	2	51.75	107.75	37,850	Yenisei	67	34,700	7130	Uda at Ulan-Ude
72	2	68.25	131.75	31,029	Yana	64	29,700	3482	Butantai at Kustur
93	2	58.25	93.75	1,042,568	Yenisei	54	1,040,000	8091	Angara at Tatarka
Locations with stations nearby—potential need to reinforce monitoring									
5	1	49.25	102.75	95,748	Yenisei	152	92,300	7200	Mongoliya Selenga at Lake-Baikal
16	1	68.25	145.75	271,142	Indigirka	119	305,000	3871	Indigirka at Vorontsovo
17	1	69.25	147.75	301,491	Indigirka	118	322,000	3872	Indigirka at Chokurdakh
							305,000	3871	Indigirka at Vorontsovo

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Table 2. (continued).

Criteria 1 and 2 Fulfilled: Model Agreement on Significant Change and Sign

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Station Listed Area (km^2)	Station Code	Station Name
18	1	71.25	149.75	334,126	Indigirka	117	322,000	3872	Indigirka at Chokurdakh
							305,000	3871	Indigirka atat Vorontsovo
24	1	70.25	135.25	218,852	Yana	107	216,000	3860	Yana at Dzhangky
35	1	68.25	157.75	418,693	Kolyma	92	361,000	1801	Kolyma at Srednekolymsk
38	1	66.75	152.25	332,877	Kolyma	86	361,000	1801	Kolyma at Srednekolymsk
40	1	67.25	136.25	48,047	Yana	84	52,800	3443	Aducha at Ust'Charku
44	1	67.25	132.75	42,696	Yana	81	48,400	3416	Yana at Batagai
45	1	50.75	107.25	30,957	Yenisei	79	29,600	7099	Khilok at Maly Kunaley
							25,700	7098	Khilok at Maleta

Locations without stations—add new monitoring

Rank	Quintile	Latitude	Longitude	Upstream Area (km^2)	Basin	Discharge Change (%)	Nearest Settlement or Location Description
1	1	48.75	99.75	26,658	Yenisei	208	Orgil, Mongolia
2	1	46.75	87.75	34,007§	Ob'	200	Fuhai Xian, Aletai Diqu, Xinjiang Weiwuerzizhiqu, China
3	1	49.25	100.75	69,252	Yenisei	180	Tsengel, Mongolia
4	1	68.25	161.75	53,191	Kolyma	155	Anyuysk, Chukotka Autonomous Okrug, Russia
6	1	70.75	153.75	59,716	Alazeya	148	Alazeya Near Outlet
7	1	69.75	154.75	27,354	Alazeya	140	Alazeya Near Outlet
8	1	67.75	140.75	25,173	Indigirka	135	Selennyakh at Sourdakh
9	1	66.25	150.25	25,823	Kolyma	134	Usun-Kyuyol, Sakha Republic, Russia
10	1	66.25	143.75	28,202	Indigirka	134	Khonuu, Sakha Republic, Russia
11	1	68.75	171.75	26,170	Pegtymel	129	Rytkuchi, Chukotka Autonomous Okrug, Russia

For model agreement on significance of change (at least half of the models indicate a significant change [$p < 0.05$] using a two-tailed t-test) and on significance (as above) and sign of change (at least 80% of the models that show significant change also agree on the sign of change), respectively, and for locations with existing stations, with existing stations nearby, and without stations, the table shows the locations with the highest change. For model agreement on significant change (criterion 1), all 19 locations are shown. For model agreement on significance and sign of change (criteria 1 and 2), the 30 first locations are shown. Full details and list of all locations are available in Tables S1 and S2.

Overall, our results agree with the previous studies on a general picture of strongly increasing discharge for most of the pan-Arctic drainage basin. In addition to the earlier studies, however, our study, by utilizing the information on significant changes but disagreement on sign, reveals some areas where the direction of future discharge changes may be more uncertain, but potentially of large magnitude. This is an important addition that indicates regions of the pan-Arctic where particular scrutiny may be motivated when assessing future climate projections. We argue that these areas may also be of interest for developing and evaluating model representation of processes pertaining to cold region hydrology, but to determine this, a more in-depth and multimodel comparison would be required.

In identifying these locations, we considered all the major water diversions, dams, and irrigated areas of today, but these modifications are of course likely to change during the present century. In a future study, we hope also to construct plausible scenarios of anthropogenic modifications, and explore how these scenarios may in turn affect the choice of locations. Such a study could start from the shared socioeconomic pathways [*van Vuuren et al*., 2013] that complement the scenarios we here use for the physical climate change, but we would also need to make several further assumptions on demographics, economy, and politics to guide likely locations of new or modified dams, diversion schemes and irrigation. We expect that these potential future alterations to water flows would change the details of locations, but they would likely not overturn the overall pattern of hot spots for climate change effects on annual scales.

When we use the information on projected changes to identify locations of significant change, we identify two categories of locations: first, locations where there is agreement between models and scenarios that changes will be substantial, but where the direction of this change is uncertain, and second, locations where there is agreement on large changes in a particular direction (an increase, in most cases).

Naturally, there are many other ways that these specific locations could be identified, and our approach only considers the objective of finding places with large changes. Other objectives, as we will discuss later, require other approaches in identifying the station locations. Furthermore, we acknowledge that the confidence in the locations we do find is inherently limited by the reliability of the underlying discharge change projections, which are in turn dependent on the climate model projections. Nevertheless, these climate projections constitute the research community's best attempts to estimate the possible future changes to the climate system, and we therefore propose that our method to find potential monitoring locations (with results in Figures 4 and 5, and Tables S1 and S2) is useful for a river discharge monitoring network manager or end user of hydrological data who is interested in long-term monitoring of change. As an aid to prioritization, we also highlighted a subset of locations with the largest changes in Table 2.

In general terms, the concentration of locations with divergent changes in central Canada, in our view, points to this region as a potential hot spot for strengthening of monitoring with a view to improve understanding and development of the land surface hydrology in climate models (Figure 4). We identify another set of hot spots in eastern and south-central Siberia, where the changes (both with high and low agreement on the sign of change) rank in the highest quintile over the region (Figure 4).

From the set of highest-change locations in Table 2, it is clear that a set of top-ranked locations where there are existing stations and where models agree on significant changes of uncertain direction (criterion 1), is concentrated in the Nelson basin. Where the direction is more certain (criteria 1 and 2), locations are interspersed across several of the major basins in Eurasia. In particular, the Kolyma, Yenisey, Indigirka, and Yana basins dominate locations with existing monitoring, while the Ob', Alazeya and Pegtymel basins also appear among the top locations where monitoring should be added.

In addition to the average annual discharge we study here, there are many other aspects of the Arctic terrestrial hydrological system for which our understanding is limited, and for which both improved projections and monitoring is motivated. As shown in a number of other studies, such aspects include maximum and minimum flows [*Shiklomanov et al*., 2007; *Smith et al*., 2007; *St. Jacques and Sauchyn*, 2009; *Ehsanzadeh and Adamowski*, 2010; *Rennermalm et al*., 2010, 2012; *Karlsson et al*., 2012; *Walvoord et al*., 2012; *Karlsson*, 2014; *Yang et al*., 2014b], discharge variability [*Karlsson et al*., 2012, 2015; *Jaramillo and Destouni*, 2015], recession flows from daily discharge series [*Lyon et al*., 2009; *Lyon and Destouni*, 2010; *Brutsaert and Hiyama*, 2012], water chemistry [*Hasholt et al*., 2006; *Holmes et al*., 2011; *Tank et al*., 2012; *McClelland et al*., 2014, 2015], heat fluxes [*Yang et al*., 2014a; *King et al*., 2016], and water resources [*Alessa et al*., 2008; *Nilsson et al*., 2013;

Instanes et al., 2016]. There are many possible ways to design a monitoring network for even a single one of these objectives (see *Mishra and Coulibaly*, 2009, for a recent review of network design methods). Also, other factors than hydrological ones, such as accessibility and costs, typically play a role in the choice of locations. However, it is beyond the scope of this study to propose a method to reconcile such disparate concerns into a final selection of stations, as the recommendations are likely to vary with national policy priorities, budgetary constraints, and other local contexts across the pan-Arctic countries. In line with a recent analysis of Canadian network efficiency [*Mishra and Coulibaly*, 2010], we consider this problem as a fundamental matter of policy choices, and therefore think that it is best approached at the monitoring network agencies.

Overall, however, average discharge remains a fundamental integrator of catchment behavior and a useful variable as a first characterization of the interaction across components of the Arctic freshwater system, as recently explored in a synthesis of the Arctic freshwater system [*Prowse et al*., 2015b; *Bring et al*., 2016]. For larger basins and for regions with low density of gauges, remote sensing of discharge hold some promise to complement in situ observations [*Sheffield et al*., 2009; *Fichot et al*., 2013; *Famiglietti et al*., 2015]. As technology matures, becomes more accessible and more refined, such approaches may be an important complement to in situ observations, particularly in remote areas. Data from these platforms may also increasingly be integrated into hydrological models in the future [*Eicker et al*., 2014]. However, for medium-sized and small basins, and for many other aspects than discharge — such as water chemistry and daily forecasting — in situ observations will likely still be required for the foreseeable future, not to mention their important role for validation of satellite measurements. Naturally, we encourage further efforts to address the other components noted above, both in terms of how they are projected to change, and how their monitoring could be improved.

5. Conclusions

Our analysis reinforces confidence in the predominance of long-term increases over much of the Arctic by combining information from model runs of multiple scenarios. Overall, our results support conclusions from previous investigations, but here we also identify some areas where the direction of change is not consistent across models and scenarios. This noted divergence, however, contains information in itself that is of interest from a monitoring perspective, and we include it in this first assessment of specific geographic locations where Arctic hydrological monitoring can be improved.

For instance, we identify in Figure 3 areas where the model–scenario combinations indicate significant change but of uncertain direction. Although of limited extent, we argue that these areas are of interest for further investigation, both into the functioning of the hydrological system, but also regarding how hydrological process representation could possibly be improved in modeling. Similarly, the areas with agreement on both magnitude and sign of the change that we identify are important to consider in evaluating the monitoring priorities for areas that will potentially be subject to particularly large changes.

For a pan-Arctic strategy aiming at strengthening long-term monitoring efforts, the potential monitoring locations we identify in Figures 4 and 5, and Table 2 are useful starting points. Depending on the objective of the monitoring strategy and the availability of funding for new stations, the emphasis may be placed on either new stations at some of the highest-ranking locations (Figure 4), in areas of both diverging and consistent change, or on the locations where stations already exist, as identified in Figure 5 and listed in Table 2 and Tables S1 and S2. If cost is not a consideration, a pan-Arctic strategy coordinated across all countries to expand monitoring of the highest changes should focus on Alaska, eastern and central Siberia, and the southern margin of the pan-Arctic basin. In contrast, if a preferred strategy primarily needs to use existing stations, a cluster of current stations in southern and central Canada should be combined with a corresponding set of existing stations evenly interspersed over much of western and central Siberia. Other considerations than prioritizing the highest average change, as well as even more detailed scrutiny of model projections, may contribute to modifications of these suggested locations.

To improve our knowledge of future changes to Arctic river flows, a number of research and policy efforts are needed. Even if it is not certain that it would reduce variability in projections, incorporating more physical detail into models and refining their representation of processes relevant to high-latitude hydrology would increase our confidence in the results of new simulations. Some aspects that are likely to improve confidence in projections include a more complete consideration of the human modifications of river systems, and better representation of how river discharge will change under degrading permafrost conditions.

In terms of monitoring priorities, ongoing work to strengthen Arctic observing networks, such as Sustaining Arctic Observing Networks (SAON, see SAON Implementation Plan at http://www.arcticobserving.org/images/pdf/Board_meetings/1st_helsinki/11_SAON_Implementation_v1.0.pdf) and Arctic-HYCOS (see Arctic-HYCOS Project Implementation Plan at http://www.whycos.org/whycos/documents/Arctic-HYCOS-Project-Implementation-Plan-March2014%20Final.pdf), require continued support and remain important for prioritizing the research and practitioner use of hydrological information in the Arctic. Such processes may incorporate the information we present here in considering where to improve monitoring of river discharge in the Arctic.

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