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Hydro-climatic changes and their monitoring in the Arctic: Observation-model comparisons and prioritization options for monitoring development

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Abstract

The Arctic undergoes particularly large and rapid hydro-climatic changes, and information on hydrological responses to these changes is crucial to plan for societal adaptation. We investigate hydro-climatic change severity and monitoring in 14 major hydrological basins across the pan-Arctic, in view of different possible strategies for their monitoring prioritization. Results show that the current distribution of monitoring density in these basins is more relevant for so far observed precipitation changes than for observed temperature changes, or for projected future temperature and precipitation changes. Furthermore, present and projected future hot-spots of greatest hydro-climatic change differ spatially, so that major spatial shifts must occur in the future among the different Arctic basins in order for observations and climate model projections to converge with regard to hydro-climatic change severity. Also temporally, observation-model convergence requires that important change direction shifts occur in major Arctic basins, which have currently decreasing precipitation while model projections imply future increasing precipitation within them. Different prioritization options for rational development of hydro-climatic monitoring can be argued for based on the present results. The divergent prioritization options imply a need for an explicit strategy for achieving certain information goals, which must be selected from a larger set of different possible goals based on societal importance.

1. Introduction

The effects of global change on society and the Earth system will to a large degree appear through changes to the water cycle, such as altered precipitation, evapotranspiration and runoff patterns, and drought and flood pressures (Askew, 1987; McCabe et al., 2004; Pall et al., 2008; Bengtsson, 2010; Destouni et al., 2012; Jarsjö et al., 2012). In the rapidly changing Arctic region, climate change brings large hydrological changes (Vörösmarty et al., 2001), as well as hydrologically mediated ecological regime shifts (Karlsson et al., 2011). The Arctic is also particularly vulnerable to changes related to water due to extensive reliance on hydro-climatically dependent infrastructure such as ice roads and construction on permafrost (Nelson et al., 2002; Stephenson et al., 2011). Furthermore, evidence indicates that the rate of climate change so far is particularly high in the Arctic, with warming rates twice the global average (ACIA, 2005; Christensen et al., 2007). At the same time, projections based on different scenarios presented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) indicate a very wide range of future states of the Arctic region, with modeled increases in regional average temperature ranging from about 2 °C to over 10 °C by the end of this century (Christensen et al., 2007, their figure 11.18).

The imminent but uncertain climate change, its strong feedback to and coupling with the water system, and the strong dependence in the Arctic on the physical state of water implies that relevant monitoring of the water cycle in the Arctic will be critical to successful adaptation in the region. However, several recent studies have highlighted the declining number of hydrological monitoring stations (Lammers et al., 2001; Shiklomanov et al., 2002; Arctic-HYDRA consortium, 2010), and also identified critical spatial gaps with regard to monitoring of changes in water chemistry (Bring and Destouni, 2009) and ecosystems (Karlsson et al., 2011). Bring and Destouni (2011) showed in particular that the decline in hydrological stations has been greatest in areas where future climate change is expected to be greatest.

The reduction in monitoring networks implies that prediction and understanding of the water system is hindered. For instance, Spence et al. (2007) showed that the closure of 12 out of 34 discharge monitoring stations in the Mackenzie basin lead to 16% larger extrapolation errors in forecasting streamflow. Notwithstanding reductions, the station density in many parts of the PADB, for example Northern Canada, is below World Meteorological Organization (WMO) recommendations (Mishra and Coulibaly, 2009).

Some international efforts, such as the Sustaining Arctic Observing Networks (SAON) process, aim to generally strengthen monitoring in the Arctic. Nevertheless, the question of how to develop the monitoring of discharge and water chemistry in the face of its severe limitations and the uncertain future climate development in the Arctic has so far received little attention, despite its importance for deciding on where to spend limited monitoring and adaptation funds. Monitoring systems should be designed and extended with both today's and tomorrows expected environmental conditions in mind, and observation system design must explicitly take the non-stationarity of hydrological variables into account (Milly et al., 2008). The degree to which changes can be reliably predicted and the spatiotemporal distribution of the most severe changes are therefore essential in deciding monitoring priorities, as is the fundamental question of which rationale that should guide the distribution of monitoring effort. These questions all fall within the grand challenge of developing, enhancing and integrating observation systems to manage global and regional environmental change, a task identified to be of highest priority for Earth system science (Reid et al., 2010).

In this study, we investigate the relevance of hydrological monitoring, and the prioritization basis for it, in the region draining to the Arctic Ocean (AO), specifically with regard to climate change. Over a time horizon to the mid-2050s, we identify two extreme ends of future projected climate change for the 14 largest Arctic basins (Figure 1), and investigate how the hitherto observed climate change agree with the patterns of projected climate change for these two scenario ends. Furthermore, we analyze the present distribution of the discharge monitoring effort across the Arctic basins and investigate how it relates and may need to be adapted to the currently observed or the projected future severity of climate change. Finally, we also study how the current monitoring of discharges into the AO relates to the relative contribution of different river basins to the total discharge into AO from the whole pan-Arctic drainage basin. A general aim is to investigate if and how different hydro-climatic change perspectives can form a consistent relevance and prioritization basis for formulation of a robust hydrological monitoring strategy to capture and follow up the most severe hydro-climatic changes in the Arctic.

2. Material and methods

Based on the R-ArcticNET 4.0 database of Arctic hydrological monitoring stations (http://www.r-arcticnet.sr.unh.edu; Lammers et al., 2001), we identified 14 independent major Arctic drainage basins with an area of at least 2×10^5 km^2 (Figure 1); an area sufficiently large to include a reasonable number of grid points for the General Circulation Models (GCMs) included in IPCC Fourth Assessment Report (AR4). For these basins, the most downstream monitoring station in the R-ArcticNET database was used to identify the upstream watershed. The stations were co-referenced to a digitized representation of the physical stream network (STN-30p v6.01; Vörösmarty et al., 2000), and the contributing upstream area for each station was identified using the Watershed algorithm in the ESRI ArcGIS software.

In order to include as wide a spectrum of future climate change as possible over the next half-century, we inspected the IPCC AR4 report to identify which scenarios are the furthest apart with regard to surface temperature and precipitation. Of the scenarios simulated by GCMs for AR4, scenarios A2 and B1 present the largest spread between them (Solomon et al., 2007, their figure TS.27). From the IPCC data distribution centre (http://www.ipcc-data.org), we therefore downloaded GCM projections of temperature and precipitation anomalies for these scenarios for the period 2040-2069. We then proceeded to calculate average changes in these parameters for the combined 14 basins and all GCMs with data for the relevant scenarios in AR4 (Table 1). From this analysis, we selected the five warmest (wettest) models in the warmer (wetter) scenario A2, and the five coldest (driest) models from the cooler (drier) scenario B1 (Table 1). These models were then included in a final calculation of climate change projections for each of the 14 basins, for a hot (wet) A2 and a cold (dry) B1 scenario.

GCM projections of future climate change provide information on the possible direction of changes, but to form a more complete picture, the agreement of GCM results with observations of climate change so far is also important. As observations in the Arctic are associated with challenges, particularly for precipitation, we combined two observational datasets to achieve a more robust estimate of recent climate changes: the Climate Research Unit (CRU) and the Willmott and Matsuura (WM) gridded monthly time series at 0.5° × 0.5° global resolution. These two data sources have been specifically identified as representing a best available understanding of global precipitation patterns (Fekete et al., 2004). We downloaded the updated and most recent versions of CRU (TS 3.10/3.10.01; Harris et al., in review; available at http://www.cru.uea.ac.uk/cru/data/hrg) and WM (Gridded Monthly Time Series V3.01; Willmott and Matsuura, 1995; available at http://climate.geog.udel.edu/~climate) data and then proceeded to calculate area-weighted averages of temperature and precipitation changes for all basins between the most common climate reference period of 1961-1990 and the most recent period 1991-2009 for which the datasets overlap. Although inherent limitations of sampling, bias in measurements, and particular local complicating factors, such as gauge undercatch of snow, imply that the observation datasets do not strictly reflect true environmental conditions, we believe that they still represent a reasonable best estimate of the distribution of climate conditions across the basins. Since the Arctic is relatively sparsely monitored, particularly in the northern end of basins, representativity of observational data is a potential problem. However, for both gridded hi-res datasets we use, several procedures have already been taken to minimize the impact of this problem, and the datasets are also specifically aimed at applications such as the one in this paper (priority is given to conserving realistic large-scale spatial averages and patterns, rather than maintaining strict time-series consistency for individual cells). Since our scale of investigation is at least 2×10^5 km^2 in spatial terms and at least 19 years in temporal terms, even a sparse network is probably sufficient to formulate a regional average for such extensive areas. Furthermore, we are here not specifically investigating any sub-basin processes or properties, nor the spatial distribution of hydrological parameters. Therefore, we expect that the long-term monitoring values can be considered relatively reliable over the large scales used in our study.

In analyzing the data, we first investigated and compared absolute projected and observed changes across the 14 basins. To test whether the distribution of climate change severity across the basins is in agreement between observations and GCM results, we ranked all basins by their increase of temperature or precipitation for each case (warm/wet A2, cool/dry B1, and observations), and calculated Spearman's rank correlation between observations and GCM results of expected future changes across the different basins. Since the temporal extent differs between observations and GCM results (observed changes cover a time span of 25 years, while GCM results cover 75 years, extending from recent to projected future changes), and since the two future scenarios are here explicitly selected to represent extremes of potential change, we neither assume nor expect any linear translation or simple continuation of recently observed changes into the future with respect to the actual magnitude of change. However, for monitoring prioritization purposes, we do need to investigate how the present distribution pattern of relative severity (rather than actual magnitude) of climatic changes across different Arctic river basins relates to GCM scenario results for expected future changes. Rank correlation between the data-based and the GCM-based ranking of climate change severity in the different basins is then an appropriate measure for such investigation. Spearman's rank correlation method (discussed in Spearman,1904) has also been applied previously in other climate-related research, e.g., Thuiller et al. (2005) for species loss in Europe, Westerling et al. (2006) for wildfires in the western U.S., and Both et al. (2006) for bird-migration patterns. Our sample is complete (the entire population of the 14 basins) and we therefore define the rank correlation as

$$\rho = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$$

where X and Y are basin ranks.

To assess the basis for rationality in the distribution of hydrological monitoring stations for the 14 basins, we investigated how this monitoring station distribution compares with the distribution of observed climate changes, and the distribution of climate changes based on GCM results. For each basin, we investigated the R-ArcticNET database and summarized the number of discharge monitoring stations per 10^5 km^2 that provided data for that basin for the years 1995-1999. Although additional stations may be accessible through direct contact with national hydrological agencies or through other channels, we choose here to use the R-

ArcticNET dataset to represent current accessible monitoring status as it is publicly published, widely recognized, and openly available. The R-ArcticNET database is also representative as it is a commonly used data source for pan-Arctic hydrological analysis, and the most accessible data source for any user without resources to obtain data from national hydrological agencies. The SAON process may eventually contribute to extended multilateral collaboration and data sharing agreements in the Arctic, but presently there is no pan-Arctic hydrological database that is more extensive (Bring and Destouni, 2009).

The reasons for not studying a more recent period than 1995-1999 are twofold: major efforts in making data accessible during the early 2000s left many stations with published data series ending in 1999, and choosing too recent a period risks missing stations for reasons of data distribution delay or non-disclosure policies rather than an actual change in station operation status (Bring and Destouni, 2009). As we neither expect nor presume any causal relationship between network density and climate changes, we used also here rank correlation as a quantitative measure of how network density relates to (observed and modeled, recent and projected future) climate changes.

Because station density can only have positive values, while temperature and precipitation change can have both positive and negative values, we rank here the basins by absolute magnitude of temperature and precipitation change. For temperature, for which only positive changes are both projected and observed, the ranking by absolute change magnitude gives the same ranking order as that done by increase (positive change) magnitude for investigating the agreement between observations and GCM results. For precipitation, however, for which only positive changes (increases) are projected, but both positive (increases) and negative (decreases) changes are observed, the ranking by absolute change magnitude gives a different order than that by increase. The absolute magnitude ranking is the relevant one for comparison with the station density ranking because we want to investigate if there is higher station density in basins with higher (observed or modeled) climate changes, regardless of whether they are positive or negative.

As a final step in the analysis, we also weighted the climate changes by the area of each drainage basin. This weighting procedure measures the intensity of the different basin changes from the perspective of their common discharge recipient, the AO; the larger the area changes appear in, the greater their influence on the total freshwater discharge into the AO and also on the related (through the multi-basin annual water balance, as total precipitation minus total discharge) large-scale water flux by evapotranspiration back into the atmospheric climate and circulation system. In order to compare the relative magnitude of changes across observations and GCM scenario results, absolute values of change were normalized in the following way: for both observations and the two future scenarios, separately, the changes across all basins were adjusted to give an average change of 1.0 across the 14 basins.

3. Results

Figure 2 show the observations of recent changes from the 1961-1990 to the 1991-2009 period, compared with the projected changes in temperature and precipitation for the warm (wet) A2 and cool (dry) B1 scenarios from the 1961-1990 to the 2040-2069 period across the 14 Arctic basins. The projected average temperature rise is for all basins systematically greater in the warm A2 than in the cool B1 scenario, and is in both scenarios greater than seen in observations so far, as expected for continued further climate change from present until 2040-2069. With regard to change severity, there is notable differences in temperature change between the basins that are expected to experience the greatest warming and the ones where warming is expected to be less severe, particularly for the warm A2 scenario – a projected increase of just above 3 °C for the Yukon contrasts with a projected warming of almost 5 °C for the Khatanga and Pechora basins.

For precipitation changes the picture is more complex. As for temperature, precipitation change is of course systematically greater in the wet A2 than in the dry B1 scenario, but the spatial distribution pattern of observed changes so far differs more from that of the GCM scenario results for precipitation than for temperature. That is, the spatial distribution pattern of observed recent changes does not only differ in magnitudes, but also in directions for some basins (Yukon, Mackenzie, Kolyma, Indigirka) from the spatial distribution patterns of future changes implied by the GCM scenario results. Furthermore, for both the precipitation and the temperature changes, also the actual basins projected by the GCM results to experience the greatest/smallest changes in the future differ from those that have so far been observed to experience the greatest/smallest changes according to available data.

Table 2 shows basin ranks for observations and projections of both temperature and precipitation changes. Table 3 further shows the Spearman rank correlation coefficient (ρ) between the change severity ranking based on so far observed changes and that based on GCM-projected changes. The rank correlation for temperature is then very close to zero for both GCM scenarios, while that for precipitation is slightly stronger, but negative, between observations and the two different GCM scenarios. The strongest negative correlation is that between the observed precipitation changes so far and the GCM projections for future changes in the wet A2 scenario; this negative correlation implies a tendency for basins that rank high in change severity based on observed precipitation changes to rank low in change severity based on GCM projections of future changes, and vice versa. In general, however, most correlation values are small, meaning that, for these comparisons, no monotonic (linear or non-linear) relationship can be claimed between the relative severity of observed climate changes so far and that of GCM-projected future changes.

Figure 3 shows the recent density distribution of hydrological monitoring stations against both the so far observed and the GCM-projected future climate changes across the 14 Arctic basins. Table 4 further shows basin ranks by network density and by absolute magnitude of observed climate changes, and Table 5 shows the resulting Spearman rank correlation coefficient (ρ) between basin network density and observed and GCM-projected climate change severity. The patterns that can be visually inferred from Figure 3 are also confirmed by the rank correlations in Table 5.

For temperature, the station density decreases with increasing temperature change (negative correlations in Table 5), for both the so far observed changes (Figure 3a) and the GCM-projected future changes (Figures 3b-c), although the correlation for the cool B1 scenario is small. For precipitation, a slightly divergent pattern is found between observed and GCM-projected changes (Figures 3d-f and Table 5). Of the four basins with observed changes (Figure 3d) closest to zero (Churchill, Indigirka, Kolyma, Khatanga), three basins (Khatanga, Indigirka, Kolyma) are also among the four basins with lowest network density. The spread in station density increases with increasing magnitude of change in observed precipitation, and of the six basins with highest precipitation changes observed so far (Pechora, Yukon, Lena, Nelson, Mackenzie, Severnaya Dvina), four basins (Yukon, Nelson, Mackenzie, Severnaya Dvina) are also among the six basins with the highest monitoring density. The positive correlation between observed precipitation changes and monitoring density (Table 5) may be viewed as a relatively rational (intentional or non-intentional) prioritization of hydrological monitoring, focusing slightly more on basins with relatively large recent changes. This possible rationality is then in contrast to the results for GCM-projected future changes (Figures 3e-f), for which station density declines considerably with increasing expected change (Table 5).

Figure 4 shows the area-weighted and normalized values for temperature (a) and precipitation (b) changes. Due to the large influence of a few large basins, the changes in these basins outweigh the change contributions from smaller basins to the area-weighted Pan-Arctic change patterns. For temperature, the pattern of area-weighted changes does not differ much between observations so far and future GCM scenario results. For precipitation, however, the change directions differ between observations so far and GCM projections of future changes for some large and thereby important basins, in particular Mackenzie and Yukon.

4. Discussion

Formulating a robust strategy for hydrological monitoring based on the most severe (greatest magnitude of) climate changes requires that future projection scenarios agree reasonably well with each other, and with actually observed changes across different geographic locations. This is not the case in the Arctic for available observations so far. Both the magnitudes and the geographic patterns of change severity differ there greatly between the observations so far and the GCM scenario projections for forthcoming changes of both temperature and precipitation, even though the geographic severity patterns (but not actual magnitudes) of greatest/smallest expected future changes agree well between the extreme future A2 and B2 scenarios of GCM projections. For precipitation, projections and observations differ also in terms of change direction; the GCM projections for both scenarios show only increased precipitation for all basins, while observations so far show decreasing precipitation in some basins, in particular Yukon and Mackenzie, which are through their large sizes also important for total discharges to the AO.

As noted previously, observational uncertainties are particularly large for precipitation data, which may explain part of the differences between observations and GCMs, apart from the separation in time. The most important error in precipitation observations is the systematic underestimation of winter precipitation, due to gauge undercatch of snow. In this study, however, we investigate precipitation change (in contrast to absolute values of precipitation), which implies that any systematic bias to measurements also has to change during the compared periods for this error to have an influence on our results. Such changes to the systematic undercatch error could potentially arise from increase in winter precipitation, which has been reported for Russia (Bulygina et al., 2009; Rawlins et al., 2009) but with contrasting evidence for North America (Callaghan et al., 2011). Although this effect may contribute to lowering our estimates of precipitation changes, the majority of precipitation in the studied basins falls in snow-free months, which limits the effect on annual scales.

Apart from observation uncertainty, inadequacies in GCM simulations of the high-latitude hydrologic cycle also limit their reliability, and potentially also the agreement between GCMs and observations on basin-wise climate change severity studied here. For example, Kattsov et al. (2007) reported overestimation of precipitation over major Arctic watersheds, partly due to biases in atmospheric circulation and sea ice patterns.

Further climate changes are of course expected for all basins, for instance with continued temperature increases from the so far observed, relatively small ones. However, the present results show that several spatial changes, as well as temporal trend shifts must then occur, sooner or later in the future, in order for forthcoming observations to start agreeing with GCM projections with regard to precipitation change directions and spatial patterns of change severity across the different Arctic basins. More specifically, spatial changes must occur that shift the locations of basins with the greatest changes, and directional trend shifts must occur in several basins to turn observed declines in precipitation so far, in some cases large, into the general GCM-projected future precipitation increases. Until such spatial changes and temporal trend shifts are seen, or the lack of them is sufficiently explained, a possible rational monitoring strategy may then involve strengthened monitoring of basins where the largest such temporal directional shifts and spatial changes must occur for hydro-climatic observations and GCM results to converge. This is an alternative strategy to one based just on expected change severity (which is not robust across the Arctic according to present results and above discussion); this alternative strategy should yield improved understanding of the Arctic hydro-climatic system regardless of whether observation and GCM result convergence will actually occur in the end or not.

The actual present distribution of monitoring station density could further also be thought of as representing a third option for rational prioritization of hydrological monitoring with regard to precipitation. The rationality basis for this option would then be that the most monitored basins should be the ones where the greatest changes have been observed so far. The fact of this being the actual situation for precipitation today is most likely due to chance, but different considerations may rationally motivate such an observation-based monitoring strategy. For instance, it is rational to prioritize monitoring in basins with clear ongoing precipitation increase/decline trends where flooding/water shortages are pressing regional concerns, even if the longer-term regional changes in climate are projected to be different from the recent ones.

Finally, a fourth potential option for monitoring prioritization could be to focus on basins with the greatest expected or observed total impact on the greater AO and atmospheric climate-circulation systems. This would imply that the largest basins should be the most important ones to monitor.

Further studies, investigating in more detail optimal placements of monitoring stations under conditions of climate change and limited resources, and with specific given information goals, could benefit from incorporating the theory of random fields and their optimal sampling, as described in, e.g., Rodríguez-Iturbe and Mejía (1974) and Manfreda and Rodríguez-Iturbe (2006). Using this approach, one can model a property of interest, e.g., precipitation, as a random process in two dimensions, and then estimate the number of stations and their optimal locations for a robust regional assessment of the value of the random field. However, for discharge and water chemistry assessments, placement of stations is restricted to the watercourse. Several associated methods that also incorporate this condition are extensively reviewed in Mishra and Coulibaly (2009), who also note the importance of further research on monitoring network design under non-stationary climate conditions.

5. Conclusions

Water monitoring systems have to cover a range of information goals of relevance to society and to the scientific understanding of Earth System changes. In this study, we show that establishing regional priorities for hydrological monitoring systems with regard to the specific issue of climate changes in the Arctic currently cannot be achieved based solely on a reconciliation of observations and projections. There are several different ways to claim rationality in hydrological monitoring priorities, and no way is by definition superior to another. When taking different data and system/change perspectives as starting points, different conclusions about what constitutes rational priorities arise. Our analysis presents a set of methodological tools and considerations that can be used to formulate such prioritizations, not only in the Arctic but also in other parts of the world.

Establishing the relative experienced and expected future severity of climate changes across a region, by ranking hydrological drainage basins, facilitates quantitative assessment of which hydrological basins in the region that are most important for impact adaptation, and how strong the agreement is between observations and future projections of change severity in those particular basins. This general framework can be applied on various scales, with the drainage basin perspective ensuring relevance and consistent spatial boundaries for the assessments of climate changes as for the physical flow and transport of water that these changes affect.

In the end, the basis for rational monitoring prioritization must also include an explicit strategy to achieve certain information goals that are selected from a larger set of different possible goals based on societal importance; longer-term scientific needs and interests should then also be accounted for in that importance assessment.

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Author contributions

A.B. has been mainly responsible for the initial idea, methods, analysis and writing the paper. G.D. has made significant contributions to the interpretation and formulation of the paper.

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Figure legends

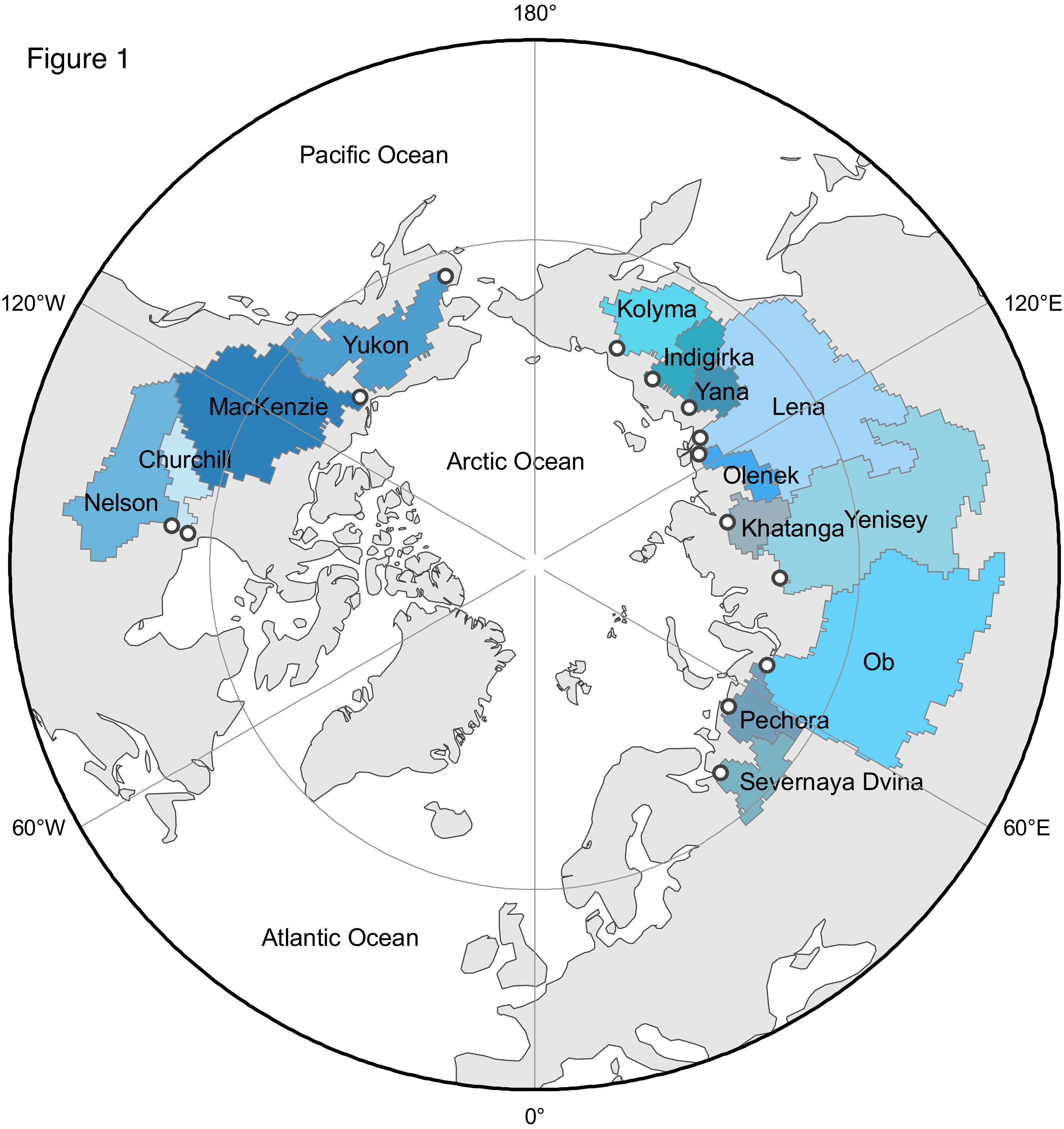
Figure 1. Map of the investigated 14 major Arctic basins.

Figure 2. Absolute basin changes. Changes to temperature (left) and precipitation (right) from 1961-1990 to 1991-2009 for observations and to 2040-2069 for GCM-projections across the 14 major Arctic basins. Error bars indicate one standard deviation of different GCM results from the model ensemble mean for the each basin.

Figure 3. Climate change vs. monitoring network density. Density of hydrological monitoring station networks in relation to observed (top row) and GCM-projected (middle and bottom rows) changes in temperature (a-c) and precipitation (d-f) for the 14 major Arctic basins.

Figure 4. Area-weighted and normalized basin changes. Changes to temperature (left) and precipitation (right) from 1961-1990 to 1991-2009 for observations and to 2040-2069 for GCM-projections for the 14 major Arctic basins. By normalization, the average change is equal to 1 across all basins, separately calculated across each of the sets of observed changes and GCM-projection results of changes.

Figure 1



180°
Pacific Ocean
120°W
120°E
Kolyma
Indigirka
Yana
Lena
Yukon
MacKenzie
Churchill
Nelson
Arctic Ocean
Olenek
Khatanga
Yenisey
Ob
Pechora
Severnaya Dvina
60°W
60°E
Atlantic Ocean
0°

Figure 2

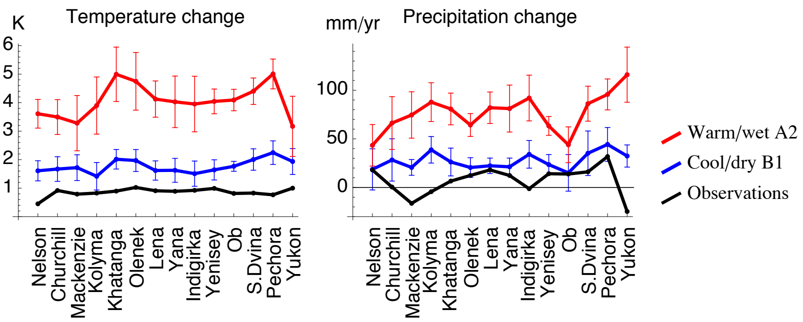

K
Temperature change
6
5
4
3
2
1
Nelson
Churchill
Mackenzie
Kolyma
Khatanga
Olenek
Lena
Yana
Indigirka
Yenisey
Ob
S.Dvina
Pechora
Yukon
mm/yr
Precipitation change
100
50
0
Nelson
Churchill
Mackenzie
Kolyma
Khatanga
Olenek
Lena
Yana
Indigirka
Yenisey
Ob
S.Dvina
Pechora
Yukon
Warm/wet A2
Cool/dry B1
Observations

Figure 3

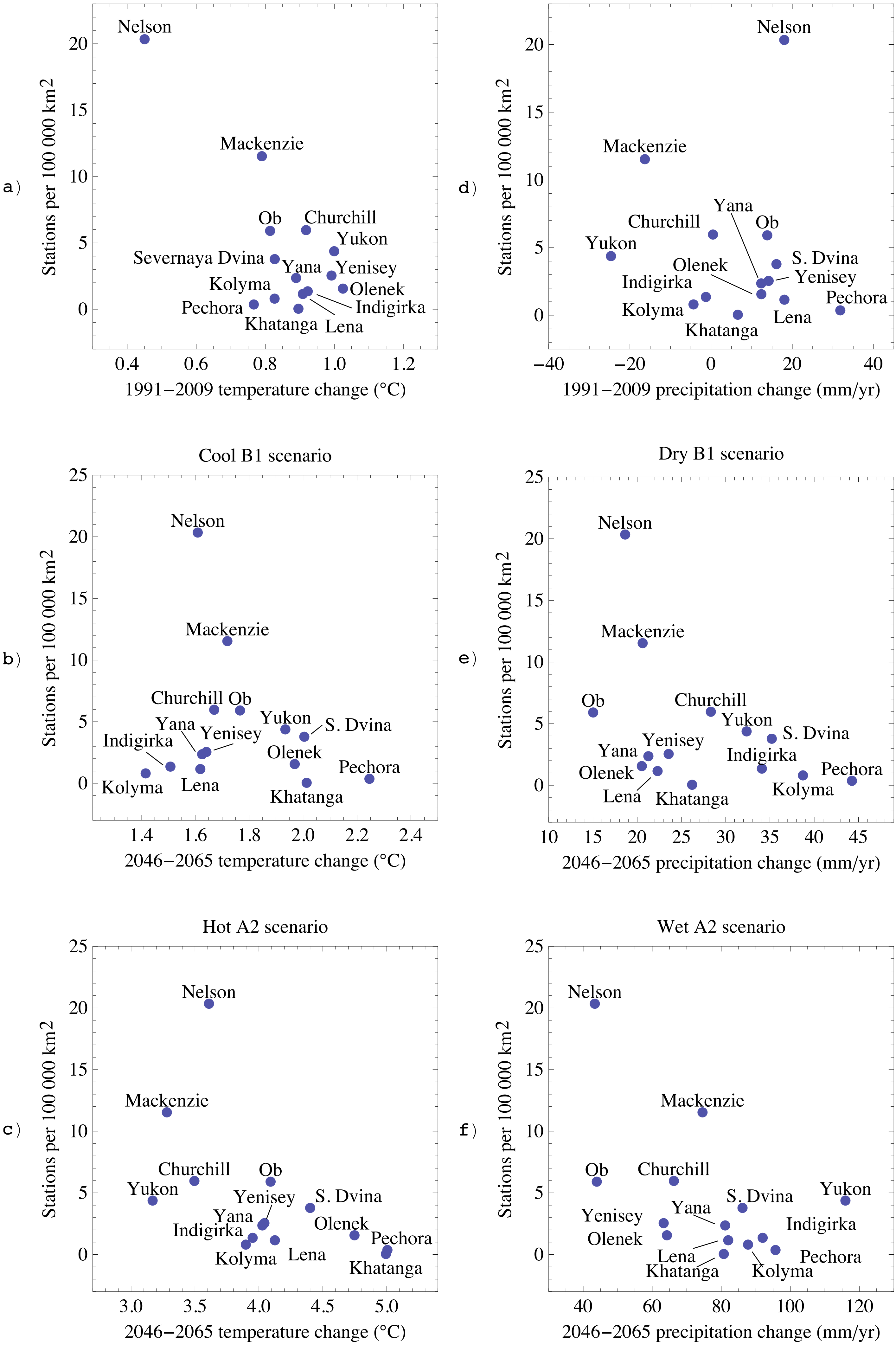
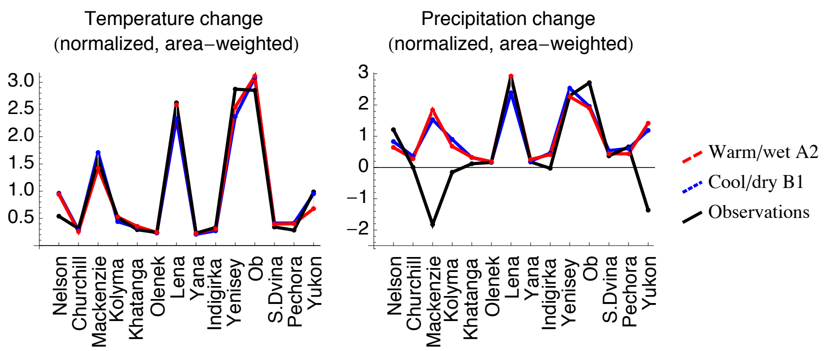

a)
Observations
Stations per 100 000 km2
1991−2009 temperature change (°C)
Nelson
Mackenzie
Ob
Churchill
Yukon
Severnaya Dvina
Yana
Yenisey
Kolyma
Olenek
Pechora
Indigirka
Khatanga
Lena
d)
Observations
Stations per 100 000 km2
1991−2009 precipitation change (mm/yr)
Nelson
Mackenzie
Yana
Churchill
Ob
Yukon
S. Dvina
Olenek
Yenisey
Indigirka
Pechora
Kolyma
Lena
Khatanga
b)
Cool B1 scenario
Stations per 100 000 km2
2046−2065 temperature change (°C)
Nelson
Mackenzie
Churchill
Ob
Yukon
Yana
S. Dvina
Yenisey
Indigirka
Olenek
Pechora
Kolyma
Lena
Khatanga
e)
Dry B1 scenario
Stations per 100 000 km2
2046−2065 precipitation change (mm/yr)
Nelson
Mackenzie
Ob
Churchill
Yukon
S. Dvina
Yenisey
Yana
Indigirka
Olenek
Pechora
Kolyma
Lena
Khatanga
c)
Hot A2 scenario
Stations per 100 000 km2
2046−2065 temperature change (°C)
Nelson
Mackenzie
Churchill
Ob
Yukon
Yenisey
S. Dvina
Yana
Olenek
Indigirka
Pechora
Kolyma
Lena
Khatanga
f)
Wet A2 scenario
Stations per 100 000 km2
2046−2065 precipitation change (mm/yr)
Nelson
Mackenzie
Ob
Churchill
S. Dvina
Yukon
Yenisey
Yana
Indigirka
Olenek
Lena
Pechora
Khatanga
Kolyma

Figure 4



Temperature change
(normalized, area−weighted)
3.0
2.5
2.0
1.5
1.0
0.5
Nelson
Churchill
Mackenzie
Kolyma
Khatanga
Olenek
Lena
Yana
Indigirka
Yenisey
Ob
S.Dvina
Pechora
Yukon
Precipitation change
(normalized, area−weighted)
3
2
1
0
−1
−2
Nelson
Churchill
Mackenzie
Kolyma
Khatanga
Olenek
Lena
Yana
Indigirka
Yenisey
Ob
S.Dvina
Pechora
Yukon
Warm/wet A2
Cool/dry B1
Observations

Table 1. GCMs included in the analysis. A dash indicates that model data was not available for that scenario.

	Temperature scenario		Precipitation scenario	
Model	Cool	Hot	Dry	Wet
BCM2	X		X	-
CGHR		-		-
CNCM3			-	
CSMK3	X		X	
ECHOG	-	X	-	X
FGOALS		-		-
GFCM20				
GFCM21				
GIAOM	X	-		-
GIER	X		X	
HADCM3				X
HADGEM	-	X	-	X
INCM3				X
IPCM4		X	X	
MIHR		-		-
MIMR		X		
MPEH5				
MRCGCM	X		X	
NCCCSM		X		X
NCPCM	-		-	

Table 2. Basin ranks for observed and GCM-projected changes to temperature and precipitation.

Basin	Basin rank by temperature increase[#]			Basin rank by precipitation increase[*]		
	Current observed 1991-2009	Projected future 2040-2069		Current observed 1991-2009	Projected future 2040-2069	
		Cool	Hot		Dry	Wet
Nelson	14	12	11	3	13	14
Churchill	5	8	12	10	6	10
Mackenzie	12	7	13	13	11	9
Kolyma	10	14	10	12	2	4
Khatanga	7	2	2	9	7	8
Olenek	1	4	3	7	12	11
Lena	6	11	5	2	9	6
Yana	8	10	8	8	10	7
Indigirka	4	13	9	11	4	3
Yenisey	3	9	7	5	8	12
Ob	11	6	6	6	14	13
S. Dvina	9	3	4	4	3	5
Pechora	13	1	1	1	1	2
Yukon	2	5	14	14	5	1

[#] For temperature, only positive changes (increases) are both observed and projected, so the ranking order is unambiguous and the same as that by absolute change magnitude in Table 4.
[*] For precipitation, only positive changes (increases) are projected, but both positive (increases) and negative (decreases) changes are observed. In this table, rank 1 is given for the greatest positive change (precipitation increase) and rank 14 to the greatest negative change (precipitation decrease), so that the ranking order reflects the inconsistency between a projected precipitation increase and an observed precipitation decrease. This ranking order differs from that by absolute precipitation change in Table 4.

Table 3. Spearman's correlation of GCM-projected climate change ranking with observed climate change ranking (Table 1).

Scenario	ρ
Temperature	
Cool B1	0.01
Hot A2	-0.03
Precipitation	
Dry B1	-0.10
Wet A2	-0.23

Table 4. Basin ranks by network density and by absolute magnitude of observed changes to temperature and precipitation.

Basin	Basin rank by network density	Basin rank by absolute temperature change#	Basin rank by absolute precipitation change*
		Current observed 1991-2009	Current observed 1991-2009
Nelson	1	14	4
Churchill	3	5	14
Mackenzie	2	12	5
Kolyma	11	10	12
Khatanga	14	7	11
Olenek	9	1	9
Lena	10	6	3
Yana	8	8	10
Indigirka	13	4	13
Yenisey	7	3	7
Ob	4	11	8
S. Dvina	6	9	6
Pechora	12	13	1
Yukon	5	2	2

For temperature, with only positive changes (increases) observed (and projected), this ranking order is the same as that by increase in Table 2.

* For precipitation, with both positive (increases) and negative (decreases) changes observed (even though only positive changes (increases) are projected), this ranking order differs from that by increase in Table 2. Rank 1 is here given for the greatest change and rank 14 to the smallest change, whether the change is positive or negative, so that the ranking correlation with the station density ranking reflects if the latter is higher in basins with higher climate changes, regardless if they are positive or negative.

Table 5. Spearman's correlation of GCM-projected (Table 2) and observed (Table 4) climate change ranking, and ranking of monitoring density during 1995-1999 (Table 4).

	ρ
Temperature	
Observations	-0.23
Cool B1	-0.08
Hot A2	-0.57
Precipitation	
Observations	0.22
Dry B1	-0.48
Wet A2	-0.49