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REPORT

Relevance of Hydro-Climatic Change Projection and Monitoring for Assessment of Water Cycle Changes in the Arctic

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Abstract Rapid changes to the Arctic hydrological cycle challenge both our process understanding and our ability to find appropriate adaptation strategies. We have investigated the relevance and accuracy development of climate change projections for assessment of water cycle changes in major Arctic drainage basins. Results show relatively good agreement of climate model projections with observed temperature changes, but high model inaccuracy relative to available observation data for precipitation changes. Direct observations further show systematically larger (smaller) runoff than precipitation increases (decreases). This result is partly attributable to uncertainties and systematic bias in precipitation observations, but still indicates that some of the observed increase in Arctic river runoff is due to water storage changes, for example melting permafrost and/or groundwater storage changes, within the drainage basins. Such causes of runoff change affect sea level, in addition to ocean salinity, and inland water resources, ecosystems, and infrastructure. Process-based hydrological modeling and observations, which can resolve changes in evapotranspiration, and groundwater and permafrost storage at and below river basin scales, are needed in order to accurately interpret and translate climate-driven precipitation changes to changes in freshwater cycling and runoff. In contrast to this need, our results show that the density of Arctic runoff monitoring has become increasingly biased and less relevant by decreasing most and being lowest in river basins with the largest expected climatic changes.

Keywords Hydrology · Climate change · General circulation models · Monitoring · Pan-Arctic drainage basin · Runoff

INTRODUCTION

During recent decades, temperatures in the Arctic have increased at more than twice the rate in the rest of the world, with greater than global average changes also expected during the present century (ACIA 2005). Many of the environmental changes that have been observed, and also are expected in the future, manifest themselves through changes in the hydrological cycle (Vörösmarty et al. 2001; White et al. 2007; Dyurgerov et al. 2010). Changing dynamics of the water cycle may have large impacts on infrastructure (Lawrence and Slater 2005), transportation, natural resource exploration (Lange 2008), and other economic activities in the region.

The hydrological drainage basin is a relevant scale for both understanding these changes and planning for adaptation to them. Since the topographically given water divide that defines such a basin constitutes a physical boundary for surface water flow, the basin constitutes a geographical unit for which water budgets can be reasonably well closed. This is a clear advantage in estimating water fluxes. For instance evapotranspiration, which is an essential link between land and atmospheric hydro-climatic conditions, is hard to measure over large areas and difficult to model without the bounds provided by the water budget closure over a hydrological drainage basin (Shibuo et al. 2007; Jarsjö et al. 2008). Therefore, investigating climate and water parameter dynamics on the basin scale may facilitate better understanding of complex water processes than climate model grids, which are commonly unrelated to hydrological basins.

Furthermore, the hydrological basin is of increasing significance in water resource management (Pahl-Wostl 2007) because it is a naturally and firmly bounded geographic unit rather than an arbitrary administrative division. In the European Union, for instance, the Water Framework Directive (2000/60/EC; http://ec.europa.eu/environment/water/water-framework/index_en.html) requires basin-scale management of all the member states waters (surface, ground, coastal, and transitional waters) for national as well as international basins. Also in other parts of the world, a general tendency to move away from issue-specific management of local problems toward integrated water resource management with the physical water catchment as base unit is evident since the 1970s (Heathcote 1998). Therefore, it is also of critical importance to investigate climate and water parameter dynamics on basin scales an information basis for water management and climate adaptation strategies.

Previous studies has investigated the performance of Global Circulation Models (GCM) with regard to Arctic temperatures (Chapman and Walsh 2007) and with regard to freshwater fluxes in four large Arctic river basins (Kattsov et al. 2007; Finnis et al. 2009a, b). These studies assessed model performance for 14 models of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). In this study, we investigate how the ability of climate change projections to assess and inform adaptation planning about forthcoming water cycle changes has evolved between the two successive generations of climate modeling, from the IPCC Third Assessment Report (TAR) and the AR4, for the pan-Arctic drainage basin and its major river basins. We compare observed changes to precipitation and temperature with corresponding climate change projections on the pan-Arctic drainage scale, and investigate also the actual runoff response to already observed precipitation changes on the scales of the different river basins. Furthermore, we investigate the prevalence and development of hydrological monitoring in relation to the information required to accurately relate climate change projections to associated basin-scale water cycle changes in the Arctic river basins.

METHOD

We have here defined major Arctic basins as independent watersheds of more than 200,000 km^2 in size, an area large enough to include a sufficient number of grid points for all GCMs in the basins. Using station metadata from the R-ArcticNET v4.0 database (http://www.r-arcticnet.sr.unh.edu/v4.0), we identified 14 separate drainage basins for which the most downstream hydrological monitoring station covered an area of at least 200,000 km^2 (Fig. 1). These stations were then co-referenced to a simulated flow direction drainage network at 30’ resolution (STN-30p; Vörösmarty et al. 2000). Drainage basins were delineated from the monitoring stations by the Watershed algorithm in ArcGIS.

From the IPCC Data Distribution Centre (http://www.ipcc-data.org), we downloaded grid-based model simulations of temperature and precipitation, in the form of text (TAR) and NetCDF (AR4) files for the 6 TAR and the 14 AR4 models with monthly means, for the periods 1961–1990, 2010–2039, 2040–2069, and 2070–2099. For the future time periods, the SRES scenario A2 was used. The monthly mean grids were then combined to annual values. Using the Climate Data Analysis Tools software package (CDAT; http://www2-pcmdi.llnl.gov/cdat), area-weighted mean values for each basin and time period were calculated for all TAR and AR4 models.

We also assessed and compared observations of temperature and precipitation in the river basins during the recent period of 1991–2002 and the climate reference period of 1961–1990. Gridded temperature and precipitation data from the CRU TS 2.1 dataset (Mitchell and Jones 2005) were averaged over these time periods and area-weighted mean values for each basin were calculated. To present a picture for the whole pan-Arctic drainage basin, a combined basin area-weighted average of both simulated and observed values in all 14 basins was calculated.

To determine patterns in runoff changes compared to precipitation changes in the different river basins, the annual runoff of each basin was calculated as an average value for the two periods studied. Monthly discharge data were gathered from the Water Survey of Canada (HYDAT, http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=main_e.cfm) for the three Canadian rivers included, from the Arctic Rapid Integrated Monitoring System (ArcticR-IMS, http://rims.unh.edu) for nine of the ten Russian rivers included and for one US river, and from the Regional, Hydrometeorological Data Network for the Pan-Arctic Region (R-ArcticNET; http://www.r-arcticnet.sr.unh.edu) (Lammers et al. 2001) for one Russian river. The monthly data were then combined to calculate annual runoff. This analysis excluded the Khatanga basin, for which no runoff data were accessible after 1990. For all basins, only years with complete runoff data for all months of the year were included. We have not corrected for the influence of dams in our analysis, as their effect on annual discharge trends over longer time periods has been shown to be relatively insignificant (McClelland et al. 2006; Adam et al. 2007; Shiklomanov and Lammers 2009).

In a recent study, Bring and Destouni (2009) assessed the present runoff monitoring status in the pan-Arctic drainage basin, showing it to be quite limited. To also determine whether and how the distribution of runoff monitoring stations across the pan-Arctic drainage basin has changed in relation to observed and projected climate changes, we analyzed here the development of the monitoring network

Fig. 1 Map of the pan-Arctic region with the 14 major basins included in this study indicated. Runoff observation stations are indicated with circles

density, expressed as number of stations per 100,000 km^2, in the studied river basins. The peak monitoring density was then found to be in the period 1982–1986. We therefore compared the monitoring density for temperature and precipitation in this period with that in the more recent period of 1995–1999 and with the AR4 model-projected changes for the period 2010–2039 in the different river basins. Since there is always a lag in data entry, the period 1995–1999 was chosen to represent present conditions, as choosing a too recent period would confound the analysis with missing stations for reasons of reporting delays rather than observation inactivity.

RESULTS

Figure 2 shows CRU observations (averages for the periods 1961–1990 and 1991–2002) and GCM simulations (summary means for 1961–1990, 2010–2039, 2040–2069, and 2070–2099) of (a) temperature and (b) precipitation for the 14 basins studied within the pan-Arctic drainage basin. The points represent area-weighted averages over all 14 basins, and for GCM simulations also the average result of the included GCMs. Error bars correspond to one standard deviation for the inter-model variation around the model average.

Between the TAR and the AR4, the change projections for both future temperature and future precipitation have shifted to smaller projected changes. For temperature, the trend in observed data during the late twentieth and early twenty-first century is compatible with both the TAR and the AR4 projections for 2010–2039. However, the large precipitation increases projected by both the TAR and the AR4 GCMs are so far not evident in the trends of available observation data for the pan-Arctic drainage basin. Moreover, in contrast with temperature, the precipitation projections deviate markedly in absolute value from the available observation data. Except for the TAR temperature projections, the inter-model spreading among the TAR and AR4 models increases for more distant future periods among both the TAR and the AR4 models (Fig. 2c, d). However, the AR4 model ensemble represents a precision improvement, and for precipitation also an accuracy improvement over the TAR ensemble.

Figure 3 shows observed changes between 1961–1990 and 1991–2002 for average annual precipitation and runoff for each of 13 major pan-Arctic basins (the Khatanga basin, which was included in Fig. 2, is here missing due to lack of accessible runoff data after 1990). The inclined solid line indicates the 1:1 line of perfect correlation between precipitation and runoff changes, which would only prevail if both evapotranspiration and water storage in the drainage basins remained constant under the climate and other changes in the region. Indeed, most runoff versus precipitation changes in the 13 major Arctic basins do not fall on this line, but exhibit instead widely varying runoff responses to precipitation changes. The majority of basins lie above the 1:1 line, indicating that the runoff has

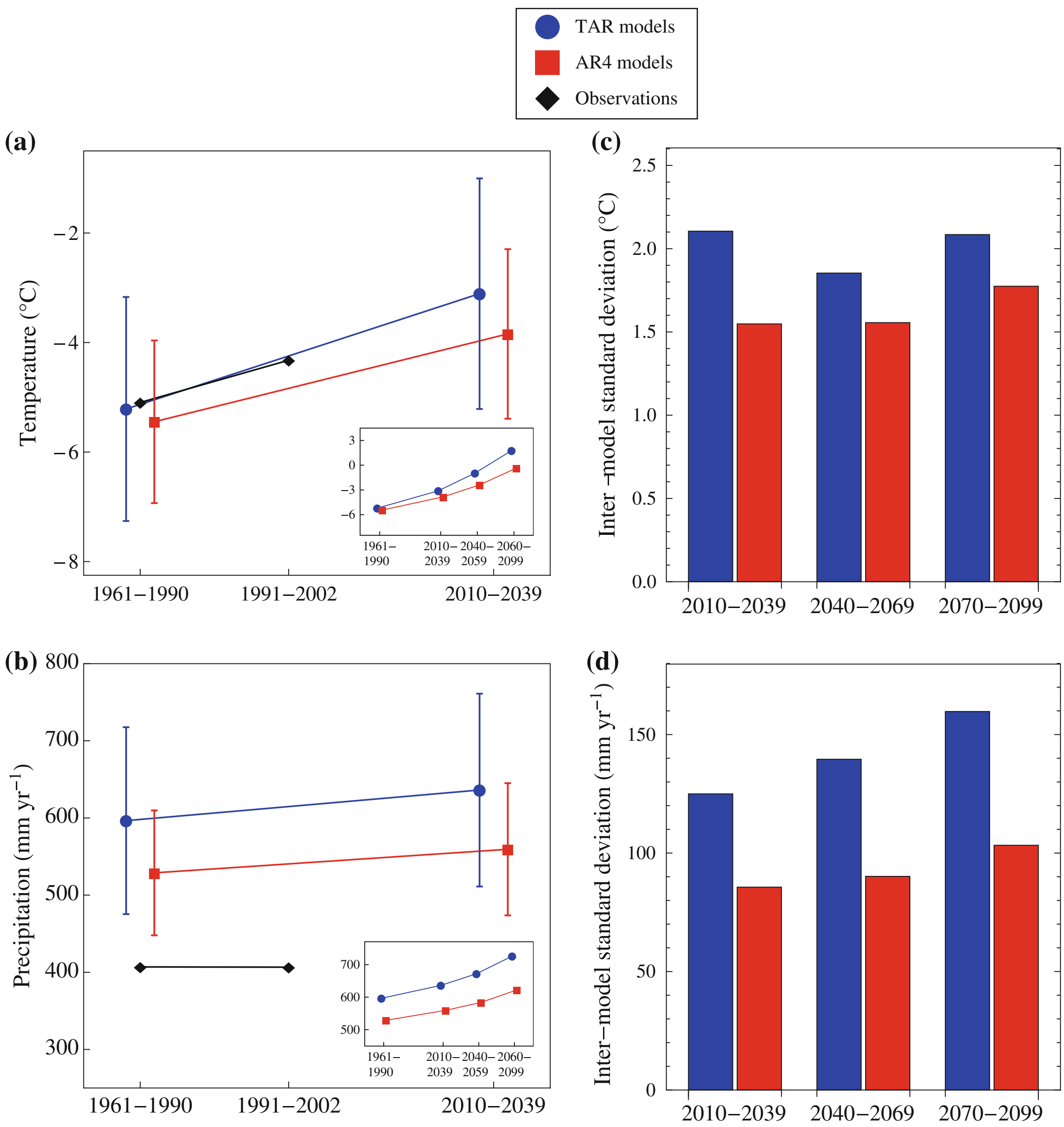

Fig. 2 Observation data (*black*), and GCM results from TAR (*blue*) and AR4 (*red*) ensembles for average annual temperature and precipitation in terms of their area-weighted mean values for the 14 Arctic drainage basins included in this study (Fig. 1). Observation means, and GCM ensemble means with error bars of 1 standard deviation indicating the inter-model variation are shown in main **a** for temperature and **b** for precipitation, for the time periods 1961–1990 (models, observations), 1991–2002 (observations only) and 2010–2039 (models only). The small insets in **a** for temperature and **b** for precipitation show the continued development of the GCM ensemble means for 2040–2069 and 2070–2099, with the inter-model standard deviations for these periods shown in the bar charts **c** for average annual temperature and **d** for average annual precipitation

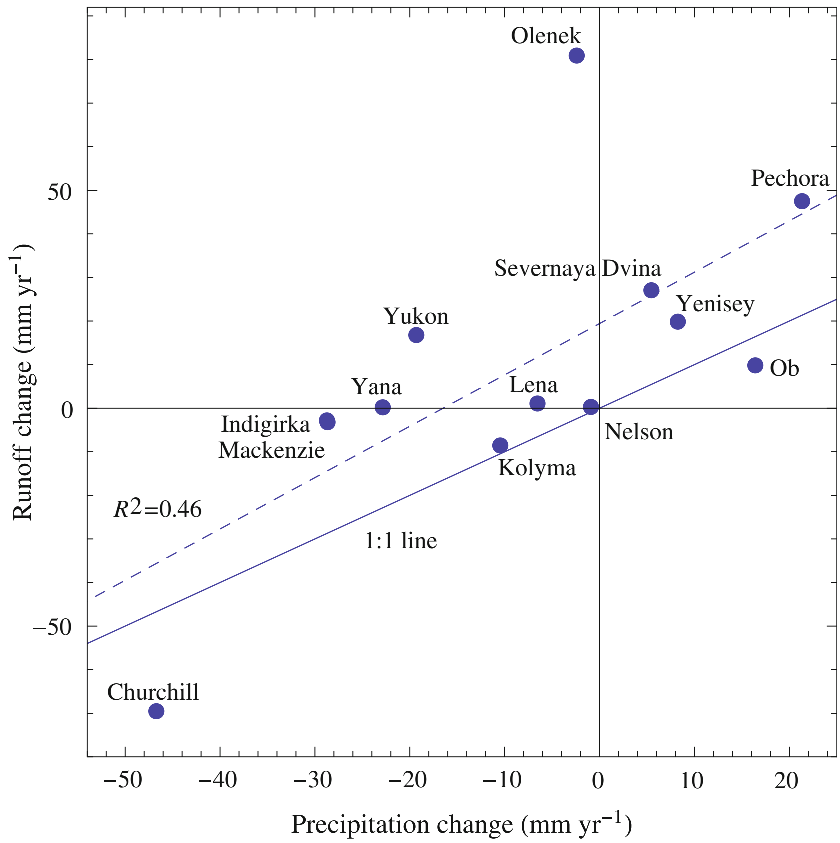

Fig. 3 Changes from 1961–1990 to 1991–2002 in observed annual average precipitation and corresponding runoff for 13 major Arctic basins (Fig. 1). The solid line indicates a 1:1 change in precipitation and runoff. The *dashed line* is a linear best-fit regression of actual changes in all basins except the Churchill watershed, which is affected by major artificial water diversion

increased more (or decreased less) than the precipitation. For some basins, the runoff changes seem extreme: in the Olenek basin, the runoff has increased by more than 80 mm year^{-1} while precipitation has decreased slightly during the same period. Only two basins fall below the 1:1 line, thus exhibiting less increase (or greater decrease) in runoff that the total precipitation change, and only two basins fall on the 1:1 line.

Our analysis of runoff monitoring networks for all the 14 basins (Fig. 4) shows that, contrary to what would be needed for relevant runoff monitoring to capture the most important climate change effects, the change in station density since the period of peak monitoring density (1982–1986) has shifted the network observation weight toward basins with the lowest, rather than with the highest expected future changes in temperature and precipitation. Also the relative decline in station density, expressed as the share of stations remaining relative to the peak monitoring density, has been particularly large in basins with the largest expected future changes in temperature and precipitation.

DISCUSSION

Although significant improvements have been made to climate models between the TAR and AR4, significant errors and inter-model scatter are still evident for simulations of parameters in the Arctic region (Kattsov et al. 2007). Nevertheless, the AR4 model ensemble converges more closely on the model ensemble mean than the TAR modeling. The AR4 models have also revised the aggregate projections for the major basins in the pan-Arctic drainage basin, pointing overall to somewhat lower increases in temperature and precipitation than previously anticipated for the early twenty-first century, and to a considerably lower increase by the end of the century. In an analysis of modeled precipitation for the twentieth century control runs, Kattsov et al. (2007) found a similar change toward lower precipitation values for the AR4 ensemble. This is most likely due to changes in the model representation of precipitation (Kattsov et al. 2007), but effects of outlier models may also have influenced TAR results more strongly than the AR4 average results, which are based on more models.

The fact that the climate models converge better on the mean, however, is not a sufficient indicator of good model performance if the mean itself is inaccurate. The improved AR4 precipitation projections still fall short of a good agreement with available CRU observation data on the pan-Arctic scale.

Part of this discrepancy is likely due to uncertainties and biases in the observation data. Estimations of spatially averaged precipitation suffer from biases both in the actual

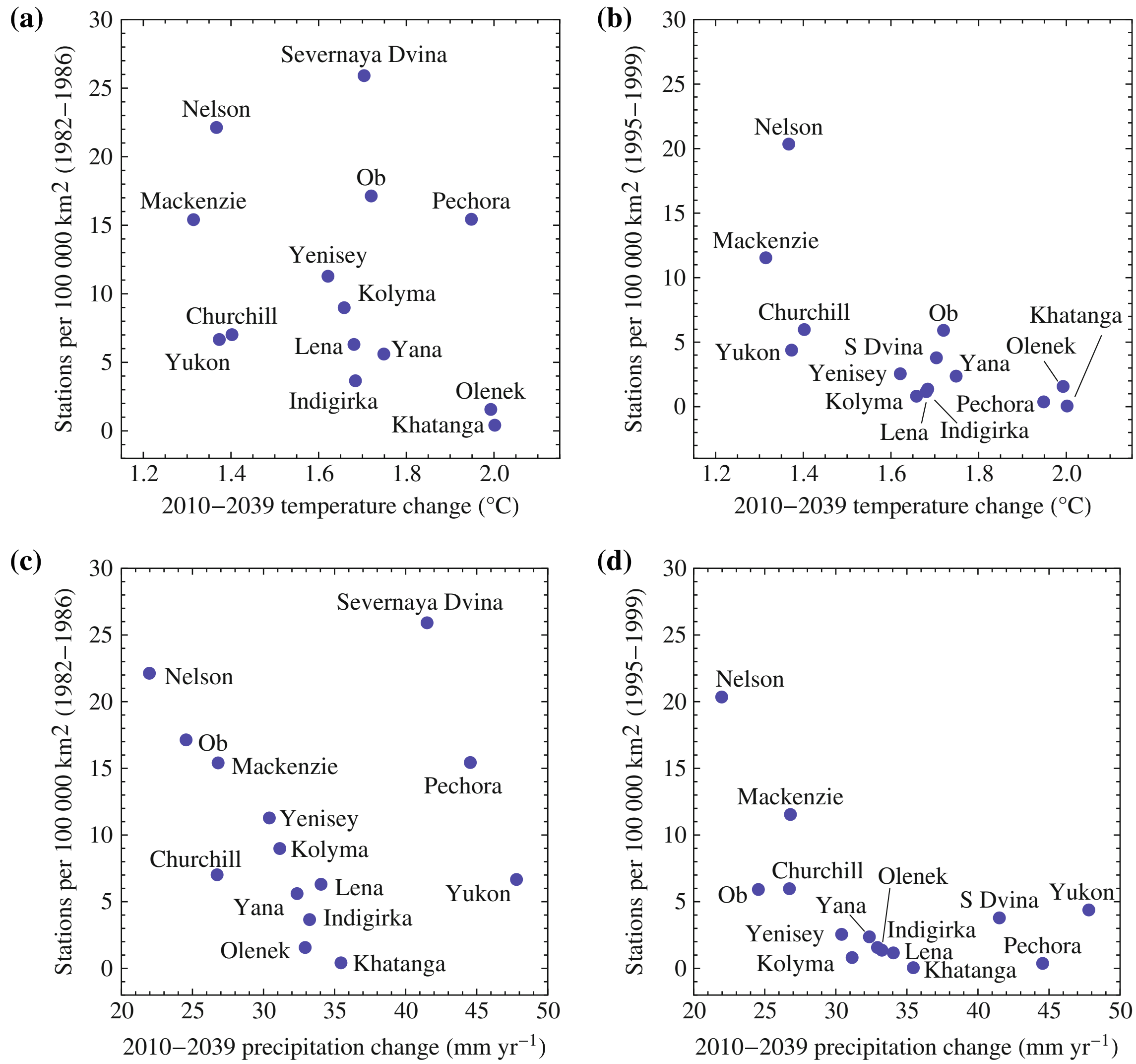

Fig. 4 Monitoring network density in 14 major Arctic basins (Fig. 1) during 1982–1986 (*left column panels*) and 1995–1999 (*right column panels*), in relation to AR4 GCM-projected changes from 1961–1990 to 2010–2039 in average annual temperature (*top row panels*) and precipitation (*bottom row panels*)

measurements and in the interpolations that usually are necessary in data-sparse regions such as the Arctic.

The most important systematic bias in Arctic precipitation measurements is a wind-induced undercatch of snow (Adam and Lettenmaier 2003; Rawlins et al. 2009a). Correcting for this bias requires extensive data on wind speed, gauge type, and height of recording instruments. Several attempts at bias correction for various time periods and regions have recently been performed (e.g., Yang and Ohata 2001; Adam and Lettenmaier 2003; Yang et al. 2005), and these studies have generally indicated an underestimation of annual precipitation of about 10–25% over most of the pan-Arctic drainage, with higher values occurring in drainage basin parts that extend far north.

The drainage basins included in our study mostly exclude the parts along the Arctic coast with the most severe underestimations of precipitation (Yang et al. 2005). In general, the relative bias of precipitation underestimation increases northward together with increasing proportion of solid precipitation during the year. At the same time, absolute annual precipitation and basin area decrease northward, which tends to reduce the absolute underestimation for larger Arctic basins on annual and longer timescales. Nevertheless, gauge undercatch and other biases in precipitation measurements likely explain part of the difference between models and observations seen in Fig. 2b.

Interpolation between measurement points introduces additional problems with precipitation value estimates far away from these points. In the Arctic, estimated precipitation mostly represents interpolated values between actual measurement points, which can have significant impact on analyses of precipitation at single points or over small areas. Averaging over larger regions and time periods, however, reduces the effect of this problem (Serreze et al. 2003).

Our analysis of recent observed changes in precipitation and runoff (Fig. 3) further indicates that, even if precipitation changes could be predicted with great accuracy, estimating the runoff responses to those changes is difficult without finer resolved hydrological change modeling of relevant processes at the relevant basin scales.

A general picture of increasing runoff trends in the pan-Arctic drainage basin has been established in recent years (Peterson et al. 2002, 2006; Dyurgerov and Carter 2004; McClelland et al. 2006; Shiklomanov and Lammers 2009). Dyurgerov et al. (2010) have further reported that river runoff to the Arctic Ocean has increased independently of, but with similar magnitude as the increase in freshwater input from glacier melting. This points to the importance of establishing the source of the growing river component in the Arctic Ocean freshwater budget. Increasing precipitation has been suggested as the main driver of increasing river runoff (Dyurgerov and Carter 2004; McClelland et al. 2004). However, contradictory trends in discharge and precipitation have also been reported (Berezovskaya et al. 2004; Milliman et al. 2008). For some of the basins in our study, gauge undercatch in combination with recently reported increases in snowfall over Siberia (Bulygina et al. 2009, Rawlins et al. 2009b) can to some degree explain the greater increases in observed runoff than in observed precipitation.

Local anthropogenic water-use changes, for instance the construction and use of dams, may also influence the runoff and complicate the assessment of precipitation–runoff relations (Shibuo et al. 2007; Adam et al. 2007; Rawlins et al. 2009b; Shiklomanov and Lammers 2009), although the effect of dams on annual discharge in the Arctic is generally small over longer time periods (McClelland et al. 2006). In the Churchill basin, however, large-scale diversions of water out of the basin have strongly influenced the river flow (Déry et al. 2005), yielding a considerably greater decrease in runoff than in precipitation over the studied period.

Decreased evapotranspiration, due to earlier snowmelt and associated runoff, and/or due to changes in water storage within the drainage basins have also been proposed as potential sources of excess water (Milliman et al. 2008). Serreze et al. (2002) however found only low correlation between P-E and runoff across the pan-Arctic drainage basin, except for the Lena basin. Several studies have discussed a possible contribution of melting permafrost to increased runoff (Serreze et al. 2002; Adam and Lettenmaier 2008; Lyon and Destouni 2009; Dyurgerov et al. 2010), but at least for the Eurasian Arctic, the total volumes of melting permafrost that are needed to explain the long-term runoff increases seem unrealistic (McClelland et al. 2004). Most likely, a combination of several factors has generated the observed runoff changes, and that combination may vary from basin to basin (Adam and Lettenmaier 2008).

A multi-model approach, linking climate model results to hydrological modeling that can resolve evapotranspiration and other runoff-affecting processes, such as groundwater and permafrost storage changes, at and below the relevant drainage basin scales would enable better understanding and model projections of hydrological change.

To resolve main cause-and-effect relations and uncertainties, and to calibrate and validate both hydrological and global climate modeling, at least some time series of relevant hydrological observations under changing conditions are required, for instance for assessing possible permafrost thawing effects on runoff (Lyon et al. 2009; Lyon and Destouni 2009). In contrast to this requirement, our analysis of changes in the monitoring network density shows that the relative decline of network density after the peak period 1982–1986 has been greatest in the basins where the expected future changes in both temperature and precipitation are the greatest. Also, the absolute network density is lowest in the basins with the greatest expected changes. Much of the decline is due to overall cost cutting efforts, and in Russia, also the fall of the former Soviet Union, with less priority given after that to government presence in remote locations (Lammers et al. 2001). However, our analysis cannot distinguish between stations where observations have really stopped and stations with continued observation data that are no longer openly accessible.

CONCLUSIONS

We analyzed and compared recently observed changes and future projections of temperature and precipitation change for 14 major basins in the pan-Arctic drainage basin. The combined average results show a considerable temperature increase during the recent period of 1991–2002, compared with 1961–1990. In contrast, the combined estimate for all basins shows only a small precipitation change, while runoff has changed more considerably and mostly increased from the 1961–1990 to the 1991–2002 period.

A main difference between the TAR and the AR4 model ensemble is that the AR4 projections are more convergent on the model ensemble mean for both temperature and precipitation changes. That is, the GCM projections have become more precise. However, while the temperature projections for the early twenty-first century are in line with the observed changes, the precipitation projections are neither capturing the trend nor aligned with the absolute observation values. Part of the difference between models and observations is likely attributable to imperfect precipitation estimates, resulting both from measurement bias and uncertainties introduced by spatial interpolation. Nonetheless, the inaccuracy makes the small precision improvement, evident in the smaller inter-model spread in the AR4, relatively less important for improving water cycle change assessments and adaptation planning.

There is further low correlation between the observed basin-scale precipitation changes and runoff changes. Most basins exhibit excess runoff relative to the observed precipitation changes, with in some cases extreme discrepancies. Snowfall observation bias, which implies that increases in snowfall are not fully accounted for in precipitation measurements, may explain the apparent excess water for some basins (Bulygina et al. 2009; Rawlins et al. 2009b). Reduced evaporation due to earlier snowmelt and earlier associated runoff (Milliman et al. 2008) is another possible contributing factor. However, the temperature increase found consistently in both direct measurements and GCM projections indicates also a trend component of increasing evapotranspiration and associated decreasing runoff, which should to some degree counteract the effects of unobserved snowfall increase and evaporation reduction due to earlier snowmelt. Other uncertainties that complicate the resolution of the precipitation–discharge change relation include effects of water storage changes (Rawlins et al. 2009b). The present results are not conclusive, but indicate that some of the observed river runoff increase is due to other factors than just increasing effective precipitation (precipitation minus evapotranspiration), such as for example melting of permafrost, groundwater storage changes and/or groundwater mining changes within the drainage basins. Such causes of runoff change affect also sea level, in addition to ocean salinity, and inland water resources, ecosystems and infrastructure. The large span of runoff responses to precipitation changes indicates that process-based hydrological modeling is needed in addition to climate modeling in order to accurately interpret and translate projected temperature and precipitation changes into corresponding runoff changes.

For accurate modeling and relevant future projections of water cycle changes under changing climatic conditions, also observational data are needed for at least some hydrological time series that are long enough to capture the changing conditions. In contrast to this need, we found here that the supply of such time series is declining and mostly so in basins where the greatest temperature, and in particular, precipitation changes, are expected. Analogous biases in hydrological monitoring have also been reported for other parts of the world, in studies showing gaps prevailing most in the hotspots of greatest population and other water pollution pressures (Hannerz and Destouni 2006; Destouni et al. 2008). Such results converge with the present in indicating an increasing need to identify and prioritize relevant hydrological monitoring for observing climate and environmental change in the Arctic and worldwide.

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REFERENCES

ACIA. 2005. *Impacts of a warming Arctic: Arctic Climate Impact Assessment*. Cambridge, UK: Cambridge University Press.

Adam, J.C., I. Haddeland, F. Su, and D.P. Lettenmaier. 2007. Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei and Ob' rivers. *Journal of Geophysical Research* 112: D24114.

Adam, J.C., and D.P. Lettenmaier. 2003. Adjustment of global gridded precipitation for systematic bias. *Journal of Geophysical Research* 108: 1–14.

Adam, J.C., and D.P. Lettenmaier. 2008. Application of new precipitation and reconstructed streamflow products to streamflow trend attribution in northern Eurasia. *Journal of Climate* 21(8): 1807–1828.

Berezovskaya, S., D. Yang, and D.L. Kane. 2004. Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds. *Geophysical Research Letters* 31: L21502.

Bring, A., and G. Destouni. 2009. Hydrological and hydrochemical observation status in the pan-Arctic drainage basin. *Polar Research* 28: 327–338.

Bulygina, O.N., V.N. Razuvaev, and N.N. Korshunova. 2009. Changes in snow cover over Northern Eurasia in the last few decades. *Environmental Research Letters* 4: 045026.

Chapman, W.L., and J.E. Walsh. 2007. Simulations of Arctic temperature and pressure by global coupled models. *Journal of Climate* 20: 609–632.

Déry, S.J., M. Stieglitz, E.C. McKenna, and E.F. Wood. 2005. Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964–2000. *Journal of Climate* 18: 2540–2557.

Destouni, G., F. Hannerz, C. Prieto, J. Jarsjö, and Y. Shibuo. 2008. Small unmonitored near-coastal catchment areas yielding large mass loading to the sea. *Global Biogeochemical Cycles* 22: GB4003.

Dyurgerov, M., A. Bring, and G. Destouni. 2010. Integrated assessment of changes in freshwater inflow to the Arctic Ocean. *Journal of Geophysical Research* 115: D12116.

Dyurgerov, M.B., and C.L. Carter. 2004. Observational evidence of increases in freshwater inflow to the Arctic Ocean. *Arctic, Antarctic, and Alpine Research* 36: 117–122.

Finnis, J., J.J. Cassano, M. Holland, M.C. Serreze, and P. Uotila. 2009a. Synoptically forced hydroclimatology of major Arctic watersheds in general circulation models; Part 1: The Mackenzie River Basin. *International Journal of Climatology* 29: 1226–1243.

Finnis, J., J.J. Cassano, M. Holland, M.C. Serreze, and P. Uotila. 2009b. Synoptically forced hydroclimatology of major Arctic watersheds in general circulation models, part 2: Eurasian watersheds. *International Journal of Climatology* 29: 1244–1261.

Hannerz, F., and G. Destouni. 2006. Spatial characterization of the Baltic Sea drainage basin and its unmonitored catchments. *Ambio* 35: 214–219.

Heathcote, I.W. 1998. *Integrated watershed management: Principles and practice*. New York: Wiley.

Jarsjö, J., Y. Shibuo, and G. Destouni. 2008. Spatial distribution of unmonitored inland water discharges to the sea. *Journal of Hydrology* 348: 59–72.

Kattsov, V.M., J.E. Walsh, W.L. Chapman, V.A. Govorkova, T.V. Pavlova, and X. Zhang. 2007. Simulation and projection of Arctic freshwater budget components by the IPCC AR4 global climate models. *Journal of Hydrometeorolgy* 8: 571–589.

Lammers, R.B., A.I. Shiklomanov, C.J. Vörösmarty, B.M. Fekete, and B.J. Peterson. 2001. Assessment of contemporary Arctic river runoff based on observational discharge records. *Journal of Geophysical Research* 106: 3321–3334.

Lange, M. 2008. Assessing climate change impacts in the European north. *Climatic Change* 87: 7–34.

Lawrence, D.M., and A.G. Slater. 2005. A projection of severe near-surface permafrost degradation during the 21st century. *Geophysical Research Letters* 32: L24401.

Lyon, S., and G. Destouni. 2009. Changes in catchment-scale recession flow properties in response to permafrost thawing in the Yukon River Basin. *International Journal of Climatology*. doi:10.1002/joc.1993.

Lyon, S.W., G. Destouni, R. Giesler, C. Humborg, M. Mörth, J. Seibert, J. Karlsson, and P.A. Troch. 2009. Estimation of permafrost thawing rates in a sub-arctic catchment using recession flow analysis. *Hydrology and Earth System Sciences* 13: 595–604.

McClelland, J.W., S. Déry, B.J. Peterson, R.M. Holmes, and E.F. Wood. 2006. A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century. *Geophysical Research Letters* 33: L06715.

McClelland, J.W., R.M. Holmes, B.J. Peterson, and M. Stieglitz. 2004. Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. *Journal of Geophysical Research* 109: D18102.

Milliman, J., K. Farnsworth, P. Jones, K. Xu, and L. Smith. 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global Planetary Change* 62: 187–194.

Mitchell, T.D., and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25: 693–712.

Pahl-Wostl, C. 2007. Transitions towards adaptive management of water facing climate and global change. *Water Resources Management* 21: 49–62.

Peterson, B.J., R.M. Holmes, J.W. McClelland, C.J. Vörösmarty, R.B. Lammers, A.I. Shiklomanov, I.A. Shiklomanov, and S. Rahmstorf. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298: 2171–2173.

Peterson, B.J., J.W. McClelland, R. Curry, R.M. Holmes, J.E. Walsh, and K. Aagaard. 2006. Trajectory shifts in the Arctic and Subarctic freshwater cycle. *Science* 313: 1061–1066.

Rawlins, M.A., M.C. Serreze, R. Schroeder, Z. Xiangdong, and K.C. McDonald. 2009a. Diagnosis of the record discharge of Arctic-draining Eurasian rivers in 2007. *Environmental Research Letters* 4: 045011.

Rawlins, M.A., H. Ye, D. Yang, A. Shiklomanov, and K.C. McDonald. 2009b. Divergence in seasonal hydrology across northern Eurasia: Emerging trends and water cycle linkages. *Journal of Geophysical Research* 114: D18119.

Serreze, M.C., M.P. Clark, and D.H. Bromwich. 2003. Monitoring precipitation over the Arctic terrestrial drainage system: Data requirements, shortcomings, and applications of atmospheric reanalysis. *Journal of Hydrometeorology* 4: 387–407.

Serreze, M.C., M.P. Clark, A.J. Etringer, T. Zhang, D.H. Bromwich, and R. Lammers. 2002. the large-scale hydro-climatology of the terrestrial Arctic drainage system. *Journal of Geophysical Research* 107: 8160.

Shibuo, Y., J. Jarsjö, and G. Destouni. 2007. Hydrological responses to climate change and irrigation in the Aral Sea drainage basin. *Geophysical Research Letters* 34: L21406.

Shiklomanov, A.I., and R.B. Lammers. 2009. Record Russian river discharge in 2007 and the limits of analysis. *Environmental Research Letters* 4: 045015.

Vörösmarty, C.J., B.M. Fekete, M. Meybeck, and R.B. Lammers. 2000. Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles* 14: 599–622.

Vörösmarty, C.J., L.D. Hinzman, B.J. Peterson, D.H. Bromwich, L.C. Hamilton, J. Morison, V.E. Romanovsky, M. Sturm, et al. 2001. *The hydrologic cycle and its role in Arctic and global environmental change: A rationale and strategy for synthesis study*. Fairbanks, AK: Arctic Research Consortium of the U.S.

White, D., L. Hinzman, L. Alessa, J. Cassano, M. Chambers, K. Falkner, J. Francis, W.J. Gutowski, et al. 2007. The arctic freshwater system: Changes and impacts. *Journal of Geophysical Research* 112: G04S54.

Yang, D., D. Kane, Z. Zhang, D. Legates, and B. Goodison. 2005. Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions. *Geophysical Research Letters* 32: L19501.

Yang, D., and T. Ohata. 2001. A bias-corrected Siberian regional precipitation climatology. *Journal of Hydrometeorology* 2: 122–139.

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