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Arctic river discharge trends since 7 ka BP

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ABSTRACT

The Arctic hydrological cycle throughout the Holocene is analyzed based on the results of transient simulations with the coupled atmosphere-ocean circulation model ECHO-G. The results suggest a ~2% increase of mid-Holocene to preindustrial Arctic river discharges for the Eurasian continent. However, rivers of the North America Arctic realm show a moderate runoff decline of approximately 4 to 5% for the same period. The total river discharge into the Arctic Ocean has remained at an approximately constant preindustrial level since the mid-Holocene. The positive discharge trend within Eurasia is caused by a more rapid decrease in local net evaporation compared to a smaller decline in advected moisture and hence precipitation. This effect is neither recognized within the North American Arctic domain nor in the far eastern part of the Eurasian Arctic realm. A detailed comparison of these model findings with a variety of proxy studies is conducted. The collected proxy records show trends of continental surface temperatures and precipitation rates that are consistent with the simulations. A continuation of the transient Holocene runs for the 19th and 20th century with increased greenhouse gasses indicates an increase of the total river influx into the Arctic Ocean of up to 7.6%. The Eurasian river discharges increase by 7.5%, the North American discharges by up to 8.4%. The most rapid increases have been detected since the beginning of the 20th century. These results are corroborated by the observed rising of Arctic river discharges during the last century which is attributed to anthropogenic warming. The acceleration of the Arctic hydrological cycle in the 20th century is without precedence in the Holocene.

1. Introduction

High northern latitudes are known to play a prominent role in global climate changes. Minor variations of the overall climate system are presumed to cause accelerated nonlinear responses within the Arctic and Antarctic subsystems (Screen and Simmonds, 2010). In particular, atmospheric moisture transport from lower latitudes to the Arctic realm is predicted to increase substantially due to global warming (e.g., Trenberth, 1999; New et al., 2001; Huntington, 2006; Jansen et al., 2007).

The Arctic Ocean contains only 1% of the global volume of sea water while receiving 11% of the world's annual river discharge (Shiklomanov et al., 2000). River discharges, as primary source in the Arctic freshwater budget (~3300 km^3/a; Aagaard and Carmack, 1989; Bowling et al., 2000; Carmack, 2000; Prange and Gerdes, 2006) are crucial for the Arctic Ocean stratification (Steele and Boyd, 1998) and hence drive the distribution of Arctic sea-ice (Dean et al., 1994; Steele and Boyd, 1998). Moreover, Arctic river discharges affect the Arctic circulation pattern (Prange and Lohmann, 2003) and the North Atlantic thermohaline circulation (Ottera and Drange, 2004; Tarasov and Peltier, 2005; McClelland et al., 2006; Rennermalm et al., 2006).

Even though the hydrological cycle of the Arctic is accelerating, river discharges do not show uniform trends. Recent papers (Lammers et al., 2001; Peterson et al., 2002; Wu, 2005; White et al., 2007; Milliman et al., 2008; Shiklomanov and Lammers, 2009) indicate a significant upward trend of Eurasian Arctic river discharges in the course of the twentieth century while river runoff in the domain of the North American watershed exhibits heterogeneous changes. Déry and Wood (2005) and Shiklomanov and Shiklomanov (2003) detected a descending trend in the Hudson Bay domain. The other parts of the North American Arctic domain display a positive trend of river runoff that is even larger than the trend throughout Eurasia (Shiklomanov and Shiklomanov, 2003). Whether these changes in Arctic river discharges can be seen in the context of anthropogenic global warming or as a combination of natural long-term fluctuations of climate elements (Shiklomanov et al., 2000) is arguable. As river gauging stations span only the short-range time interval since the latter half of the 19th century (Arctic Runoff Data Base, R-ArcticNet [v3.0], 2004), they are unqualified to respond to the persisting issue. Time series derived from satellite and reanalysis datasets are even shorter. By contrast, proxy and model studies encompassing the

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paleo-evolution of Arctic river discharges provide the possibility to interpret these recent discharge trends from a long-term perspective. As transient model simulations of the Holocene became available (Lorenz and Lohmann, 2004; Renssen et al., 2006), a more detailed analysis of Arctic river discharges can be conducted.

An in-depth examination of two transient ensemble simulations with the global climate model ECHO-G is presented in this study. The discharge trends for the major Arctic Eurasian (Kolyma, Lena, Ob, Yenisei, Pechora and Severnaya Dvina) and Arctic North American (Mackenzie) watersheds as well as for the pan-Arctic catchment area are analyzed. Opposing discharge trends across the Eurasian and North American Arctic watersheds have been detected. Two major mechanisms govern the modeled Arctic discharge trends. Firstly, a local terrestrial evaporation effect, which is directly correlated to the continental temperature pattern. Decreasing temperatures across the river catchment areas correlate with decreasing local evaporation. Secondly, a remote effect, which transports moisture from the oceanic source regions (NE-Atlantic and NE-Pacific) to the river catchment areas. This process is governed by the oceanic sea surface temperatures (SST's) and the wind pattern.

Our study demonstrates the consistency of a concurrent reduction in precipitation with an increase in river discharges. The effect occurred throughout the Eurasian Arctic during the Holocene.

2. Data and methods

Model simulations have been conducted by Lorenz and Lohmann (2004) with the coupled atmosphere-ocean general circulation model ECHO-G (Legutke and Voss, 1999), which was primarily designed for the use of long-term climate simulations. The horizontal resolution of the atmospheric Gaussian grid is ~$3.75° \times 3.75°$. Continental river discharges are computed by a river transport scheme designed by Sausen et al. (1994). The amount of precipitation (P) and snow melt water which may leave each grid point is dependent on the structure of the catchment area (Dümenil and Todini, 1992). The calculated amount of river water for each grid box follows the downward gradients, reaches the coast lines and is finally passed on to the ocean model. As water reservoirs like permafrost and lakes are not included in the river scheme, mean discharge amounts arise exclusively from the difference between P and evaporation (E) on long time scales.

Computation of the orbital parameters has been performed following Berger (1978). Other forcings like solar variations due to varying sunspot activities or volcanic eruptions are not included. Model runs have been accelerated by the factor 10. The applied acceleration technique (Lorenz and Lohmann, 2004) has been used for the time period covering the mid-Holocene (7 ka BP) to the preindustrial (1800 CE[1]). For the industrial period (last 200 years), no acceleration of the orbital forcing has been performed to catch a closer look at the anthropogenic effect on climate parameters. Detailed information about the acceleration method and the greenhouse gas configurations of the analyzed model runs are described in Lorenz and Lohmann (2004).

A set of two model runs has been conducted for the simulation of mid-Holocene to preindustrial (7 ka BP until 1800 CE) climate conditions. Subsequently, the two Holocene model simulations have been restarted at 1800 CE. The amount of anthropogenic greenhouse gas concentrations has been gradually increased by time following Etheridge et al. (1996), Flückiger et al. (1999), Indermühle (1999), Monnin et al. (2001), and Sowers (2003): 280 to 370 ppm CO_2, 650 to 1715 ppb CH_4, and 270 to 315 ppb N_2O. The most relevant CFC's (chlorofluorocarbons) have been considered. As for the preindustrial model simulations, volcanic eruptions and aerosol effects are not embodied as forcing parameter in the model experiments. For the following analysis, the average of the two runs has been taken.

3. Results

The largest Arctic rivers, referring to the discharge volume into the Arctic Ocean, have been taken into account within this study (see Fig. 1). The Eurasian Arctic part is represented by the rivers Severnaya Dvina, Pechora, Ob, Yenisei, Lena and Kolyma. The North American part in this study is characterized by the Mackenzie River.

Model experiments reveal heterogeneous discharge trends for the preindustrial period (Figs. 2, 3). The generally positive trends among Eurasian riverine systems (Fig. 3a–d) are contrasted by negative trends in East Eurasia and North America (Fig. 3e, f). This regional inhomogeneity in discharge trends turns into a homogenous phase since the beginning of the Industrial Age around 200 years ago. Both the North American and the Eurasian Arctic catchment areas show a steep industrial increase in terrestrial freshwater releases to the Arctic Ocean of up to 8.4 and 7.5% (Fig. 2b, c).

3.1. Mid-Holocene to preindustrial discharge evolution throughout the Eurasian Arctic catchment area

Preindustrial discharge trends throughout the Eurasian Arctic domain increased significantly by $2.14 \pm 0.56\%$ (Fig. 2a). A detailed focus on the major Arctic river systems unravels i) a West Eurasian region encompassing the discharge systems Severnaya Dvina and Pechora situated west of the Ural Mountains with slightly positive significant trends (Fig. 3a, b), ii) a central-Eurasian zone, covering the West Siberian plains, the Central and South Siberian Plateau as well as the central-Sakha lowlands represented by the major Arctic rivers Ob, Yenisei and Lena with a moderate positive discharge trend (Fig. 3c, d), and iii) the East Eurasian part east of the Verkhoyansk Range passed through by the Kolyma river system, for instance, with a strong negative trend (Fig. 3e).

Fig. 4 shows the P minus E (P–E) trends and their seasonal variations. In winter, December–January–February (DJF), and spring, March–April–May (MAM, Fig. 4a, b), the West and central-Eurasian P–E trends reveal a slight decrease, which is superimposed by a strong increase during boreal summer, June–July–August (JJA). In consideration of all seasons, JJA (Fig. 4c) emerges as the one of capital importance, dominating the annual mean P–E trend. Within the East Eurasian domain, autumn, September–October–November (SON), is of equal sign compared to JJA. These findings are consistent with the analyzed JJA discharge trend (Fig. 2c), amounting to more than 65% of the total annual discharge of all Arctic rivers.

Fig. 5 displays annual mean P–E, surface air temperature, precipitation and evaporation trends during the last 7 ka BP. Total annual P–E trends throughout Eurasia show a positive trend over the Western and central-Eurasian domains (Fig. 5a), whereas that evolution is reversed within the East Siberian domain.

P over Eurasia and North America is largely controlled by subtropical and temperate (roughly 20–60°N) ocean surface and near surface air temperatures and the prevailing wind systems between the source and convergence regions of atmospheric moisture (e.g. Trenberth, 1998; Trenberth and Guillemot, 1998; Trenberth, 1999). Surface temperatures over the northeast Atlantic sector show a decreasing trend signal (Fig. 5b). As a consequence of partly reduced temperatures and the change in wind systems (Lohmann et al., 2005), less water evaporates over the eastern North Atlantic, which is then transported to northern Eurasia, such that summer (not shown) and annual mean P (Fig. 5c) over Eurasia experience a decreasing trend. From that, one would hypothesize a decline of Eurasian riverine discharge trends.

This applies for the Kolyma river drainage domain (Fig. 3e), however, it fails for the West and central-Siberian catchment areas. The largest Siberian rivers (Ob, Yenisei and Lena) delineate significant positive

[1] Common Era: numbering notation that is identical to the Christian calendar “Anno Domini”, however CE is most commonly used in non-Christian cultures and academics (Irvin and Sunquist, 2001).

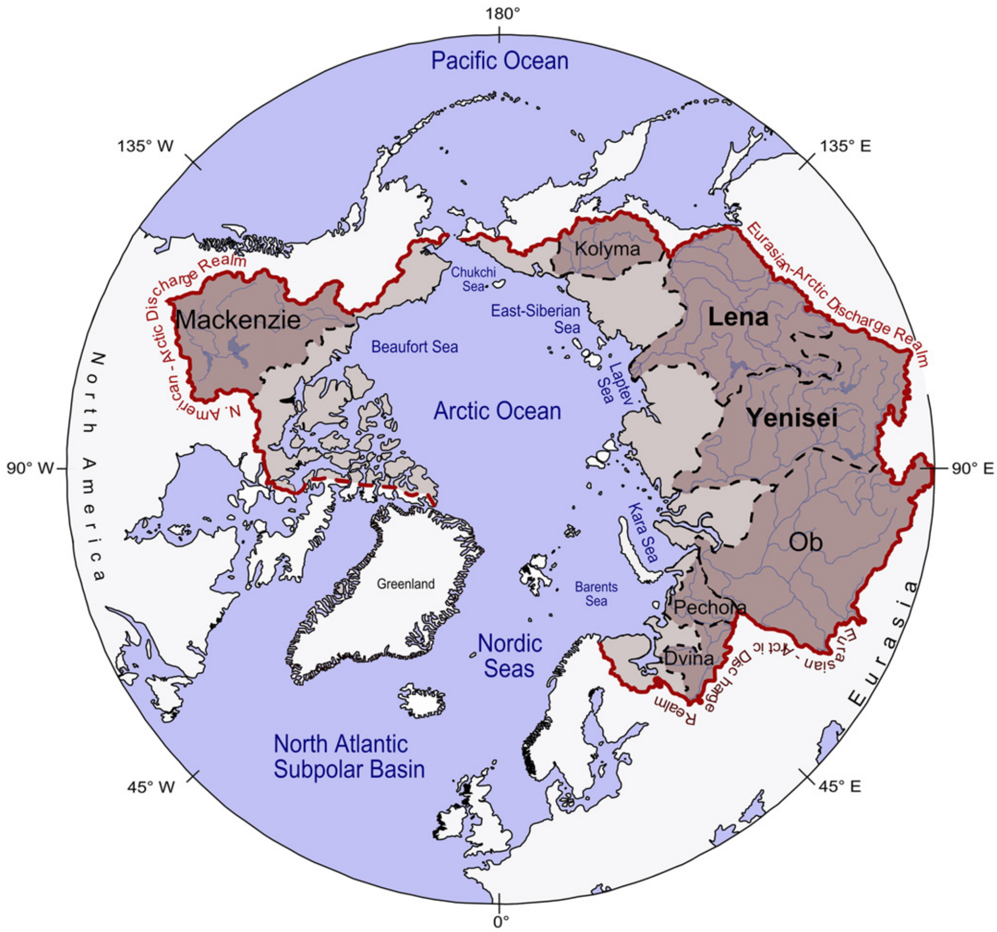

Fig. 1. Terrestrial Arctic drainage system (light and dark shaded areas), delineating the pan Arctic catchment area. It is subdivided into the Eurasian Arctic and the North American Arctic discharge realm. Drainage areas of the major Arctic river systems Mackenzie, Kolyma, Lena, Ob, Yenisei, Pechora and Severnaya Dvina are dark shaded, whereas smaller rivers are combined within the light gray shaded zone.

discharge trends (Fig. 3c, d); Severnaya Dvina and Pechora show slightly increasing trends (Fig. 3a, b). An explanation for these positive trends is given by the terrestrial Eurasian E processes, which are primarily a function of local land surface temperatures, wind speed, the magnitude of available surface water and the saturation vapor pressure near the ground surface (Penman, 1948; Monteith, 1965). Preindustrial terrestrial JJA temperatures over Eurasia experience a negative trend of up to 0.2 K/ka, causing negative E trends. Temperatures, P and E tend to decrease over northern Eurasia throughout the mid-Holocene to the preindustrial period. However, P trends are exceeded by local E trends, resulting in positive discharge trends. Corroborating these results, mean sea level pressure trends (boreal summer) over Eurasia show high pressure anomalies (Fig. 6a). The Holocene intensification of continental derived high pressure cells is closely related to an amplified sinking of air masses and consequently to a reduction in cloud formations lowering precipitation. The effect is most pronounced during boreal summer, whereas changes during winter remain insignificant (central and eastern Siberia) or capture a subsidiary order (western Eurasia; Fig. 6b).

Kolyma is significantly influenced by the Pacific Ocean and shows strongly negative P and minor negative E trends (Fig. 5c, d), resulting in a negative P–E balance (Fig. 5a). Hence, less moisture from the North Pacific reaches the Kolyma domain (Fig. 6).

In synopsis, an ascent of ~2% in total Eurasian river discharge is observed for preindustrial conditions (Fig. 2b). The negative trend in the East Eurasian catchment area is subordinated compared to the high discharges of the central-Siberian rivers Ob, Yenisei and Lena.

3.2. Mid-Holocene to preindustrial discharge evolution throughout the North American Arctic realm

The North American Arctic discharge evolution, represented by the largest North American river system, the Mackenzie, is characterized by a descending Holocene discharge trend of $-4.3 \pm 0.8\%$ (Fig. 3f). River discharges into the Hudson Bay are not taken into account as they do not represent freshwater flowing into the Arctic Ocean.

P over Alaska and northern Canada is influenced by Northeast-Pacific surface and near surface air temperatures and the prevailing wind systems over these areas. The Northeast-Pacific surface air temperatures tend to descend during all four seasons. However, taking the total area into consideration, negative Northeast-Pacific temperature trends are most distinctive during JJA and SON. The reduced Northeast-Pacific temperatures (Fig. 5b) are associated with reduced E (Fig. 5d). The loss in evaporated oceanic water results in a negative trend of annual atmospheric moisture transported into the Mackenzie drainage domain. Alike for the Eurasian domain, sea level pressure tends to increase during boreal summer, causing a reduction in continental P (Fig. 6a). The effect is reversed during winter (Fig. 6b), however only of subsidiary order in terms of the annual precipitation budget for the Mackenzie domain.

In contrast to the mid-Holocene to pre-industrial discharge mechanism, recognized for the West and central-Siberian Arctic rivers, the more rapid descent in P compared to E (Fig. 5a) has governed the decline of the Mackenzie river discharge since the mid-Holocene (Fig. 3f).

Summarizing the preindustrial discharges for the Arctic domain, provides a positive discharge trend throughout West and central-

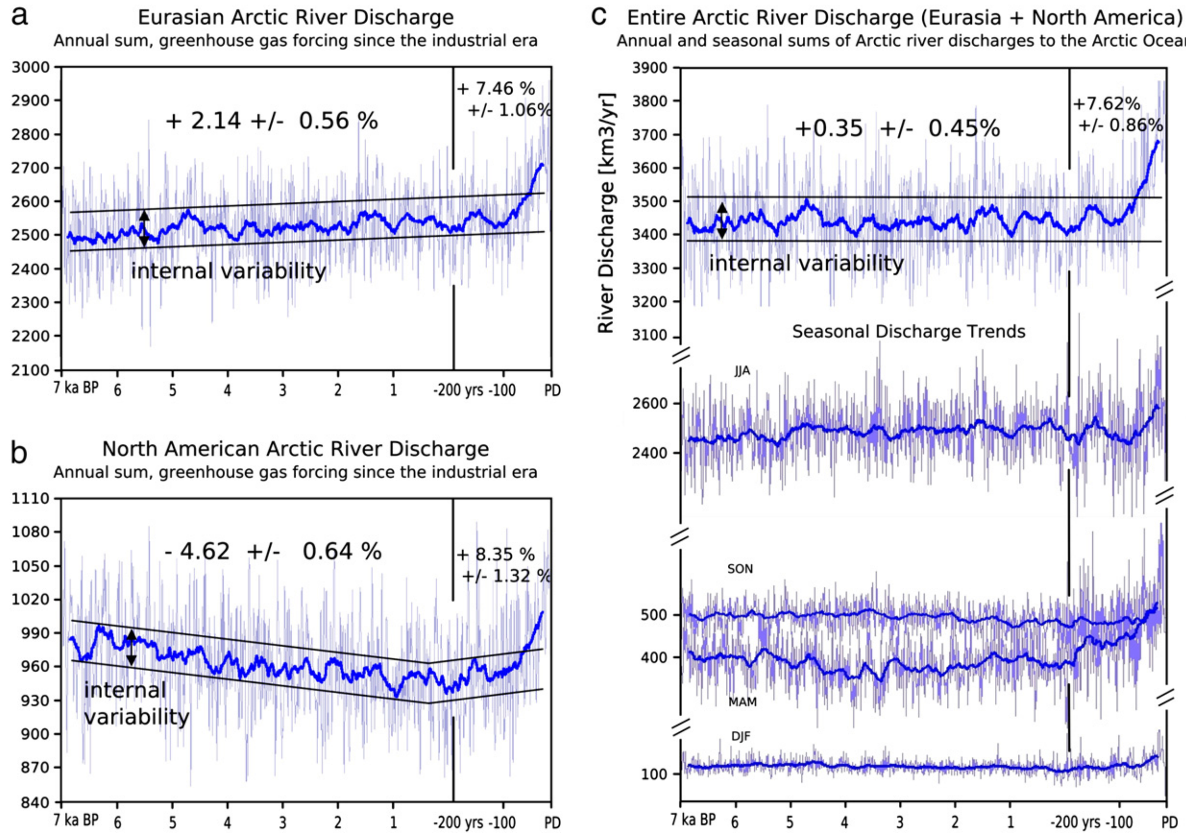

Fig. 2. Annual and seasonal ensemble means of Arctic river discharges [km^3/a] as derived by the ECHO-G model simulations. The time period covers the mid-Holocene (MH) to present day (2000 CE) period. Discharges have been divided into two distinctive phases: MH to Preindustrial (PI) as well as PI to present-day (PD) discharge trends. Trends have been calculated by linear regression. The significance level has been set to $\alpha = 0.05$. The dark blue curves are low-pass filtered discharges with a moving average of 30 time steps representing 300 years due to 10× accelerated simulations. (a) Integrated Eurasian-Arctic river discharge and (b) North American Arctic discharge as annual sums and (c) pan-Arctic river discharge as annual and seasonal sums. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Siberia which is counteracted by negative discharge trends within the North American and East Siberian regions. Considering both effects, the integrated discharge of the Arctic catchment area (Fig. 2c) remains at an approximately constant level of ~3450 km^3/a.

3.3. Preindustrial to present-day discharge evolution

Under industrial conditions with consistently increasing atmospheric greenhouse gas concentrations Arctic river discharges show a tremendous increase of $+7.62 \pm 0.86\%$. These results are reflected both in the Eurasian Arctic and North American Arctic domain. All Eurasian Arctic river systems describe abrupt and steep ascents ranging from 5.2 (Fig. 3c) to 17.4% (Fig. 3e). A view on all Eurasian Arctic discharges results in a positive trend of approximately 7.5%. Discharges tend to increase more steeply throughout the eastern parts of Eurasia, e.g. across the Lena and Kolyma river watersheds (Fig. 3d, e) while increases become smaller within the central- and western Eurasian Arctic catchment areas, represented by Severnaya Dvina, Pechora, Ob, and Yenisei (Fig. 3a–c).

These findings are consistent with industrial P–E alterations throughout Eurasia (Fig. 7). A seasonal analysis of P–E leads to a complex set of seasonal P–E patterns on a regional scale (Fig. 7a–d). For the Eurasian domain, most of the P over E surplus is generated during DJF and SON (Fig. 7a, d), whereas no significant large-scale alterations can be traced for JJA (Fig. 7c). P–E surpluses tend to smoothen during MAM, with an already reversed trend over central Eurasia.

Fig. 8a shows the total annual mean values of P–E, delineating sustainable positive trends across the mid- and high-northern Eurasian latitudes. Terrestrial temperatures over Eurasia increase strongest during DJF with more than 1.5 K/100 a across the catchment areas of Severnaya Dvina, Ob and Yenisei, other Asian areas reveal a rise between 0.5 and 1.5 K/100 a. On an annual mean basis, the surface air temperatures across Eurasia show the highest positive trends across the western and central Eurasian catchment areas of up to 1.5 K/100 a (Fig. 8b).

The predominance of P over E across Eurasia (Fig. 8c,d) arises from an area-wide change in subtropical and temperate North Atlantic temperatures (Fig. 8b) and wind patterns over the industrial era, which is unprecedented regarding the last 7 ka. This warming of North Atlantic temperatures in combination with stronger westerlies causes higher E over the ocean. The additional atmospheric moisture is then transported by the prevailing wind systems over the Eurasian continent, where it falls as P and generates higher discharge amounts.

Discharges throughout the North American Arctic domain delineate a steep industrial ascent of approximately 8.4% (Fig. 2b). The relative discharges in North America increase more rapidly than those in Eurasia. However, absolute values show higher discharge rates throughout Eurasia. The mechanisms of the North American and Eurasian Arctic river discharge-rises are basically identical.

All Holocene as well as industrial discharge trends and their influence on the Eurasian Arctic and North American Arctic discharges have been summarized in Fig. 9. For the Eurasian Arctic domain, the P–E balance continuously increases toward the industrial age. The mechanism is illustrated in terms of diverging P and E trends (Fig. 9a). Across the North American Arctic domain, this mechanism is reversed, leading to converging P and E trends during the Holocene (Fig. 9b). This diverging P–E balance across the Eurasian Arctic results in a positive discharge trend (Fig. 9a), whereas the reversed effect

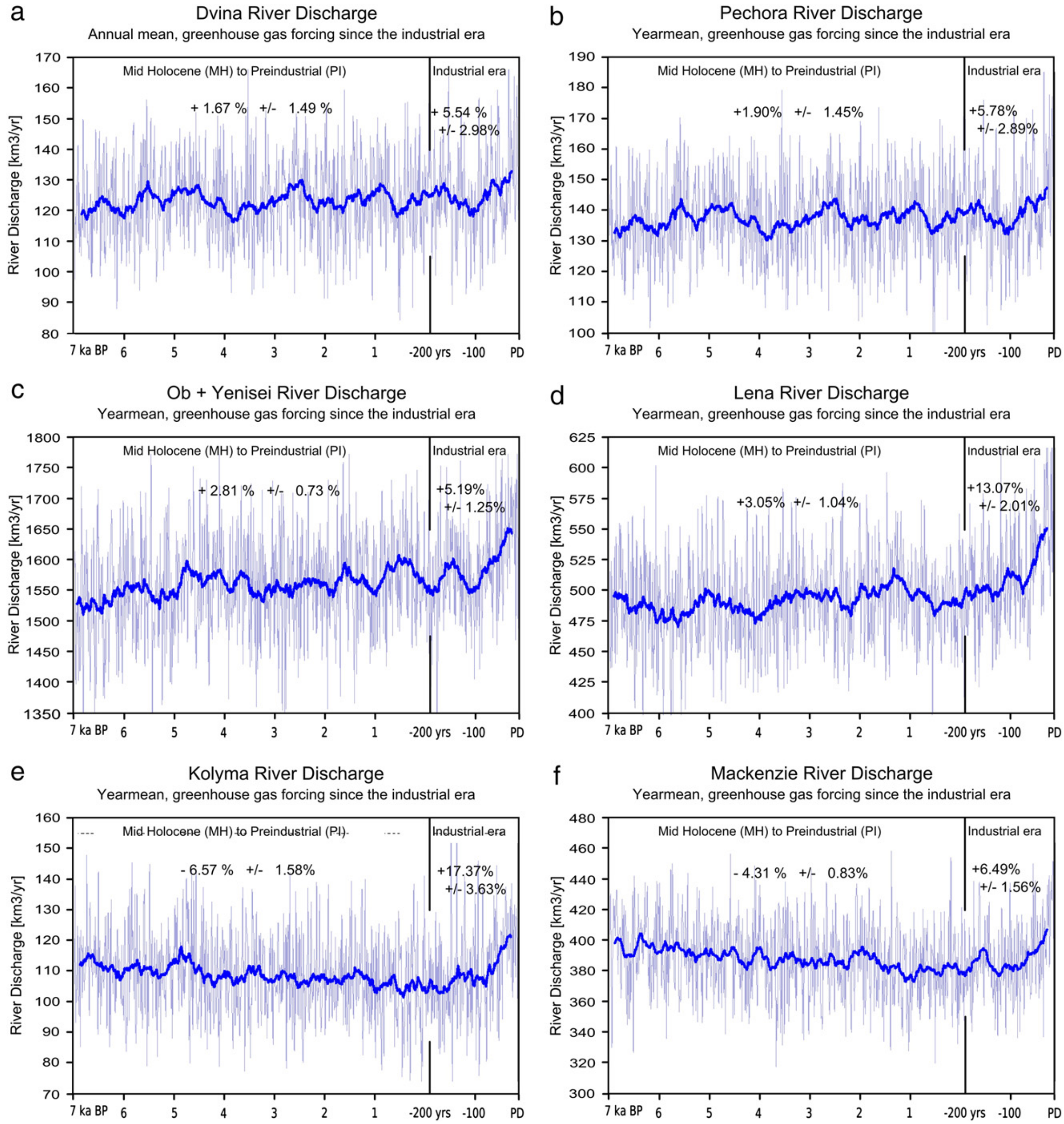

Fig. 3. ECHO-G model results showing annual ensemble means of Arctic river discharges from the mid-Holocene (MH) to the year 2000 (PD). Further information is given in the caption of Fig. 2. (a) Severnaya Dvina River, (b) Pechora River, (c) Ob + Yenisei Rivers, (d) Lena River, (e) Kolyma River, and (f) Mackenzie River.

across the North American Arctic territory gives rise to a negative evolution (Fig. 9b). Since the industrial era, trends evolve homogeneously, yielding diverging P–E balances and increasing Arctic river discharges (Fig. 9a, b).

4. Discussion

4.1. Mid-Holocene to preindustrial discharge history of Arctic rivers

Our model findings provide quantitative results for Holocene Arctic river discharges. The ECHO-G model simulations reproduce increasing Holocene discharges for the Eurasian Arctic domain, which have been unexpected, and decreasing North American Arctic discharges that are in general agreement to quantitative P reproductions of Renssen et al. (2004). In what follows, the ECHO-G results are compared to other model simulations and proxy reconstructions.

An ensemble mean of PMIP2 model simulations (mid-Holocene minus preindustrial) has been investigated by Braconnot et al. (2007). The study reproduced decreasing temperature anomalies over the Eurasian and North American Arctic domains that are consistent with our ECHO-G model findings. The model study by Renssen et al. (2004) with an Earth System Model of Intermediate Complexity showed a decreasing Arctic precipitation trend (JJA) during the Holocene. This decrease in precipitation also supports our hypothesis. Monserud et al. (1998) applied a bioclimatic vegetation model in order to reconstruct mid-Holocene climate conditions. Their investigations indicate mid-Holocene JJA temperatures that tend to be increased relative to present-day conditions. P across the Lena and Kolyma river catchment area depicts an almost

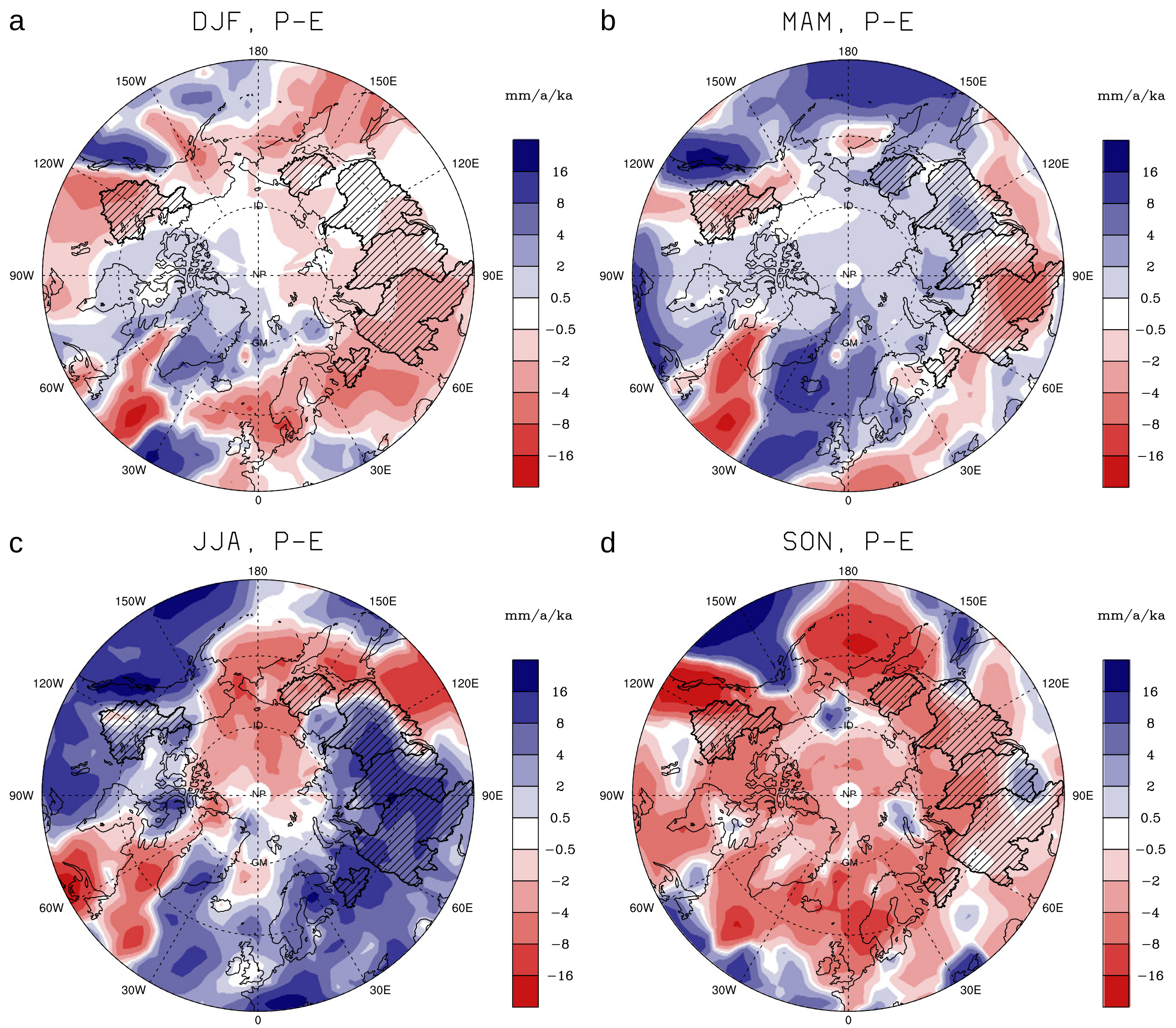

Fig. 4. ECHO-G results displaying mid-Holocene to preindustrial (7 ka BP to 1800 CE) precipitation minus evaporation trends [mm/a/ka] for the (a–d) four seasons. The significance level for the Mann–Kendall test has been set to $\alpha = 0.05$. Domains shaped as white areas are masked out as they do not show significant trends. River catchment areas, except for the Pechora domain, are sketched in as striped patches.

area-wide mid-Holocene surplus of approximately +200 mm/year. The temperature and precipitation signals from the bioclimatic vegetation model are consistent with our findings. Also, reconstructed NE-Atlantic SST trends (Holocene) by Kim et al. (2004) match the ECHO-G results.

Lake level stands across Arctic Eurasia and North America have been reconstructed by e.g. Webb et al. (1993), Tarasov et al. (1994), Cheddadi et al. (1996), Harrison et al. (1996), Yu and Harrison (1996), Grunert et al. (2000), Andreev et al. (2002), and An et al. (2008). The hydrological trend signals of the lake level studies are highly variable on a regional scale. Moreover, there is a lack of homogeneously distributed data points within the Eurasian and North American Arctic catchment areas. As the ECHO-G model simulations are not capable of reproducing local patterns of the Arctic hydrological cycle, a model-data comparison is hampered.

Over Eurasia, our model results reproduce colder and "wetter" conditions from the mid-Holocene to the preindustrial, with a surplus in runoff based on a higher reduction of E compared to P. Regarding the decrease of Holocene precipitation trends across Eurasia, our model studies coincide with proxy studies from e.g. Granina et al. (2003). They reconstructed a descending P trend since the onset of the Atlantic period (7.5–5 ka BP; affecting the Yenisei and Ob catchment areas). For Central Yakutia, Andreev et al. (2002) used palynological records that implied decreasing annual temperatures by around 1.5 K during the Holocene. The East Siberian lowlands have been examined by pollen records of the Yana River (Andreev et al., 2001). Between 6 and 4.5 ka BP annual mean temperatures were partly more than 2 K above present-day conditions. Moreover, annual P has been approximated to be 75 mm higher compared to modern conditions. Compared to the paleoclimate curves from Kazach'e (Andreev et al., 2001), annual mean temperatures and P within the surroundings of the record sites tend to decrease from 6 ka until 480 ± 150 a BP. Andreev and Klimanov (2000) used fossil pollen spectra to reconstruct paleo-temperatures and P rate for Arctic Russia, including areas of the Ob, Yenisei, Lena and Yana River watersheds. The interpreted temperature trends evolved in accordance with P, where P showed a mid-Holocene maximum at around 6 to 4.5 ka BP with P approximately 100 mm higher than present. Both, terrestrial Holocene temperature and precipitation trends of the proxy studies discussed for the East Siberian domain are consistent with our model results.

Temperature reconstructions across the Mackenzie catchment area have been carried out by Kaufman (2004). His results support our ECHO-G model findings of decreasing terrestrial temperature patterns

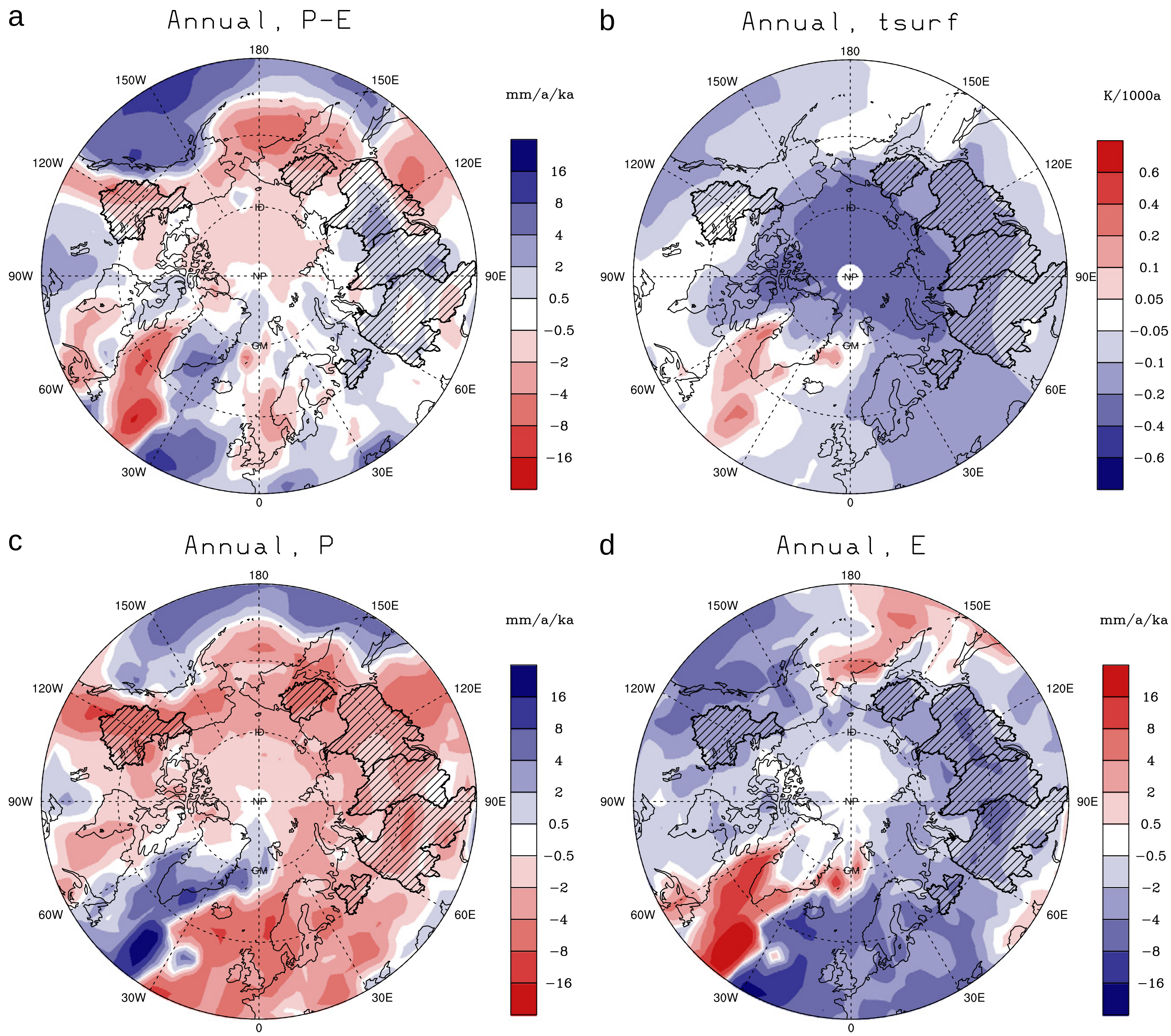

Fig. 5. ECHO-G model results showing the annual mean mid-Holocene to preindustrial (7 ka BP to 1800 CE) precipitation minus evaporation trend [mm/a/ka] (a), surface air temperature trend [K/ka] (b), precipitation trend [mm/a/ka] (c), and evaporation trend [mm/a/ka] (d). Trends are treated as described in Fig. 4. Domains shaped as white areas are masked out as they do not show significant trends. River catchment areas, except for the Pechora domain, are sketched in as striped patches.

during the Holocene. Humidity conditions throughout the Mackenzie basin have been investigated by lake level status changes (e.g., MacDonald, 1987 and studies therein). After the mid-Holocene period (after 7 ka BP), proxy reconstructions suggest increasingly humid conditions. This humidity evolution opposes our results. In terms of the NE-Pacific ocean SST's, the study by Kim et al. (2004) confirms the decreasing ECHO-G trends.

Long-term water storage components of the terrestrial Arctic catchment areas are not included in our analyzed ECHO-G simulations. However, they might affect Arctic discharge changes on millennial time scales. The classical water balance equation for terrestrial river discharges is composed of runoff = precipitation − evaporation + storage changes. The major components of long-term storage changes of the terrestrial hydrological cycle are permafrost volume changes, ground water table fluctuations (correlated to lake levels changes) and glacier mass balance variations. After Velichko et al. (1995), the permafrost layers over northern and eastern Siberia thawed during the Holocene. This effect would enhance our hypothesized increase in Siberian river discharges during the Holocene. However, there are no quantitative estimations of permafrost volume changes for the Holocene, which makes the valuation of this effect incalculable. Comparable to permafrost, there are no studies concerning changes of the Eurasian Arctic land glacier budget for the Holocene. The effect on river discharges is therefore not calculable.

4.2. Preindustrial to present-day discharge history of Arctic rivers

Arctic river-monitoring in terms of, e.g., gauging stations, remote sensing technologies or P and E measuring devices as well as the establishment of Hydrographic Data Networks like, e.g., the R-ArcticNET or data centers like the Global Runoff Data Center (GRDC) in Koblenz, Germany, has enabled a more accurate analysis of changes in river discharges and related parameters since the beginning of the twentieth century.

Evaluating discharges of the major Eurasian rivers, Peterson et al. (2002, 2006) found an increase in annual runoff by approximately 7% (~128 km^3/64 a) in the time range from 1936 to 1999. These findings are qualitatively consistent with discharge measurements analyzed by McClelland et al. (2006) for the years 1964 to 2000. Discharge calculations for the six largest Eurasian rivers, responsible for 87% of the total Eurasian Arctic river discharge, resulted in a cumulated increase of 198 km^3/37 a (11.3%) by the end of the regarded time period. Hydrometeorological investigations by Berezovskaya et al. (2005) suggest

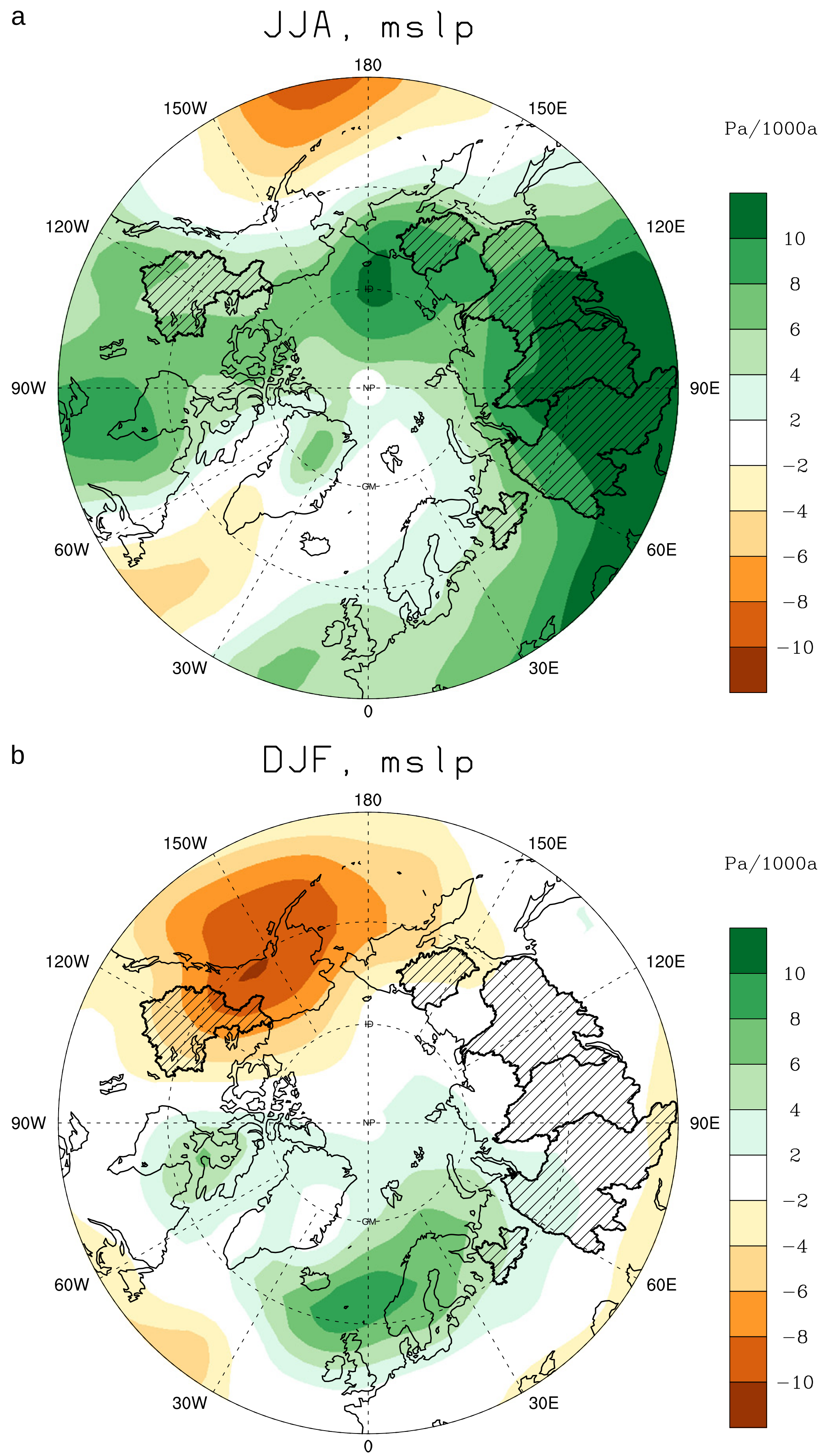

Fig. 6. Simulated ECHO-G trends of mean sea level pressure are depicted for the (a) boreal summer and (b) winter season. Units are Pa/1000a. Domains shaped as white areas are masked out as they do not show significant trends. River catchment areas, except for the Pechora domain, are sketched in as striped patches.

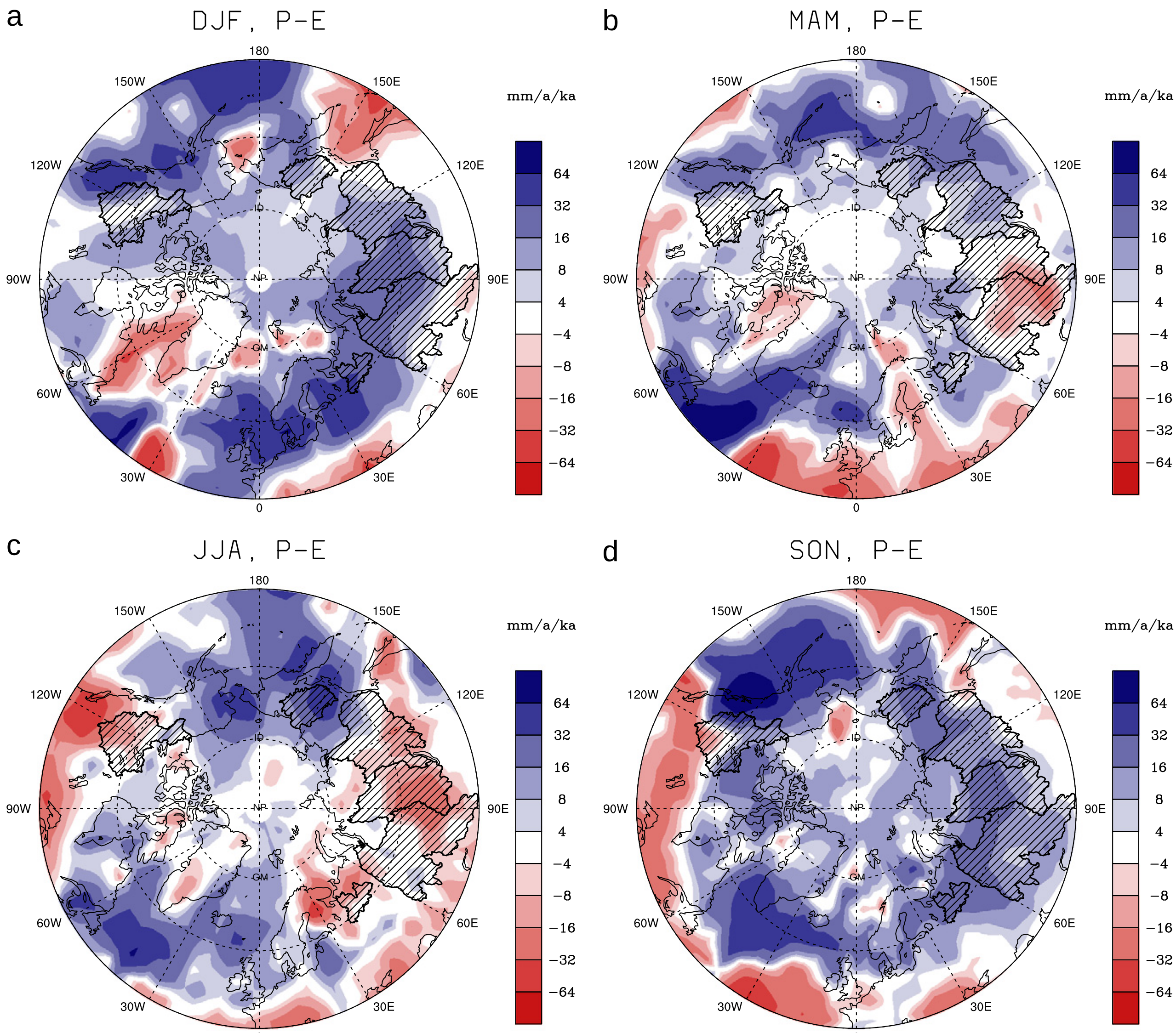

Fig. 7. ECHO-G model results showing industrial (1800 to 2000 years CE) precipitation minus evaporation trends [mm/a/100 a] for the seasonal means (a–d). Trends are treated as described in Fig. 4. Domains shaped as white areas are masked out as they do not show significant trends. River catchment areas, except for the Pechora domain, are sketched in as striped patches.

an increase in Lena river runoff of around 10% from 1936 to 2001 that is consistent with the results by Peterson et al. (2002, 2006). Annual discharge of the major Siberian rivers (Yenisei, Lena, Indigirka, Kolyma, Anabar and Ob) has increased markedly from the 1940s to recent times (Savelieva and Semiletov, 2001; Peterson et al., 2002; Yang et al., 2002; Shiklomanov and Lammers, 2009). These findings are consistent with increases in total annual land precipitation across the Eurasian Arctic catchment area (Wang and Cho, 1997), positive temperature trends across the oceanic source regions of moisture (Jones et al., 2011), as well as increasing surface land temperatures (Jones and Moberg, 2003). And they are in good accordance to our model results.

For the North American Arctic domain, freshwater discharges to the Arctic Ocean have been analyzed by e.g. Déry and Wood (2005), Déry et al. (2009), Shiklomanov (2010), and Shiklomanov and Shiklomanov (2003). Déry and Wood (2005) investigated Canadian gauging stations derived from the Water Survey of Canada's Hydrometric Database (HYDAT) (Water Survey of Canada, 2004, http://www.wsc.ec.gc.ca/). They calculated a 2% increase of total annual discharge between 1964 and 2003 CE for the North American Arctic domain. An update of these hydrological datasets revealed a steep discharge increase of 15.5% between 1989 and 2007 CE (Déry et al., 2009). Large-scale teleconnection patterns such as the Arctic Oscillation (AO), the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) or the Pacific North American pattern (PNA) are suggested to primarily influence these freshwater changes (Peterson et al., 2002; Déry and Wood, 2005; Overland and Wang, 2005).

Shiklomanov and Shiklomanov (2003) analyzed river monitoring datasets distributed across the North American Arctic domain (including Hudson Bay) and statistically extrapolated the datasets back to 1921. The results depict a positive trend of 7.8% toward increasing discharges between 1921 and 1999 CE. As a direct cause of this positive discharge trend, atmospheric temperature changes of +0.5 °C in the high Arctic over the last 100 years, have been constituted. Expanding this dataset until 2008, Shiklomanov (2010) suggested a positive discharge trend of approximately 5% (0.8 km^3/a) in the time period from 1970 to 2008. These results by Déry and Wood (2005), Déry et al. (2009), Shiklomanov (2010), and Shiklomanov and Shiklomanov (2003) are consistent with our model findings.

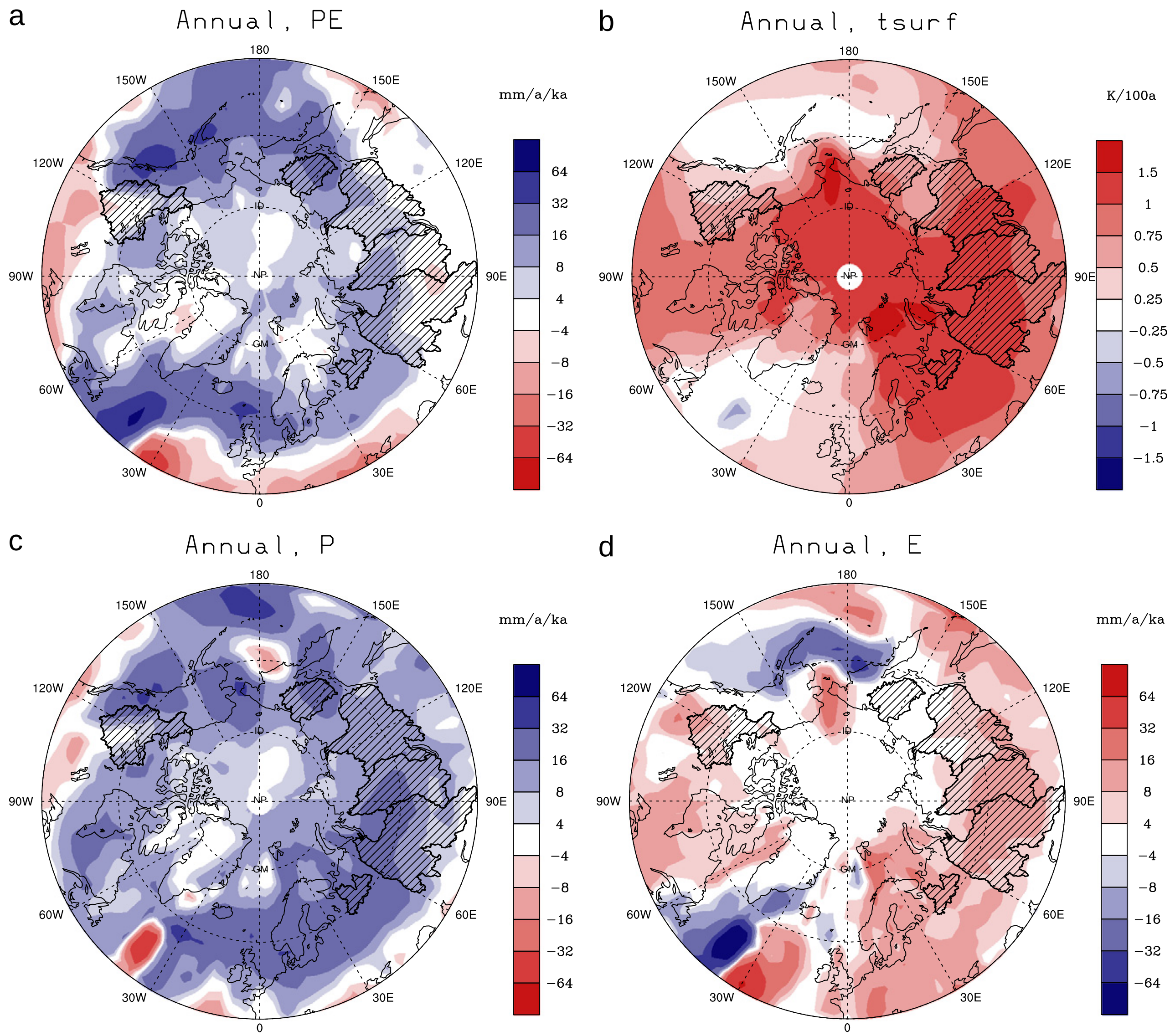

Fig. 8. ECHO-G model results showing industrial (1800 to 2000 years CE) precipitation minus evaporation trends [mm/a/100 a] (a), surface air temperature trends [K/100 a] (b), precipitation trends [mm/a/100 a] (c), and evaporation trends [mm/a/100 a] (d) for annual means. Domains shaped as white areas are masked out as they do not show significant trends. River catchment areas, except for the Pechora domain, are sketched in as striped patches.

In contrast, McClelland et al. (2006) identified decreasing annual discharge amounts for the North American Arctic area of around 15 km^3/37 a (~4.5%; 1964–2000 CE).

A multitude of potential agents, affecting river discharges, hinders a simple cause analysis: e.g. dams, thawing of permafrost, irrigation, farming, land use, glacier melting, changes in atmospheric oscillation pattern, variations in sea surface and land surface temperature, precipitation, and evaporation processes.

High-northern latitudes experienced a positive trend toward increasing land surface temperatures since the onset of the industrial era (beginning of the 19th century). For the Mackenzie domain, proxy reconstructions by D'Arrigo and Jacoby (1993), D'Arrigo et al. (2006), and Majorowicz and Skinner (2001) depict increasing land temperatures between 1 and 2.5 K for the time period between 1800 and 1990 CE. A spectrum of model-based simulations reveals a northern hemispheric warming trend of 1 to 1.5 K since the early 19th century (Jones and Mann, 2004). The investigation of instrumental time series for the Mackenzie shows an annual warming trend of 1.5 to 4.5 K during 1950–1998 CE (Gullett, 1992; Skinner and Maxwell, 1994; Zhang et al., 2000; Woo and Thorne, 2003). Analyses of climatic station data by Jones and Moberg (2003) and Jones et al. (2011) display a positive annual temperature trend of 1.4 K over the Arctic (60–90°N) domain.

Positive SST trends over the eastern North Pacific (1950–2004) have been investigated by Zhang et al. (1997) and Rayner et al. (2006). These SST changes are closely linked to ENSO (Zhang et al., 1997, 1998). The importance of ENSO to interdecadal climate variability over the North Pacific and parts of North America is emphasized by Trenberth (1990), Ebbesmeyer et al. (1991), Trenberth and Hurrell (1994), Graham (1994), and Weiss et al. (2009). A tendency to higher SST's is suggested to enhance the atmospheric water vapor transport (Arzel et al., 2008), and to increase the net precipitation over continental areas, resulting in an intensified hydrological cycle (Cubasch et al., 2001; Shiklomanov and Shiklomanov, 2003; Wu, 2005; Huntington, 2006). The analysis of instrumental precipitation data (1959–1998 CE) across the North American Arctic domain supports this argumentation, revealing positive changes in precipitation in the range of 5 to 20% (Groisman and Easterling, 1994; Vincent et al., 2004). Model-based precipitation data from the Mackenzie domain (latter half of the 20th century) shows a positive total precipitation trend by 5 to 35% (Zhang et al., 2000).

The construction of river dams in the second half of the 20th century affects Arctic discharges on a seasonal as well as on a multiannual scale

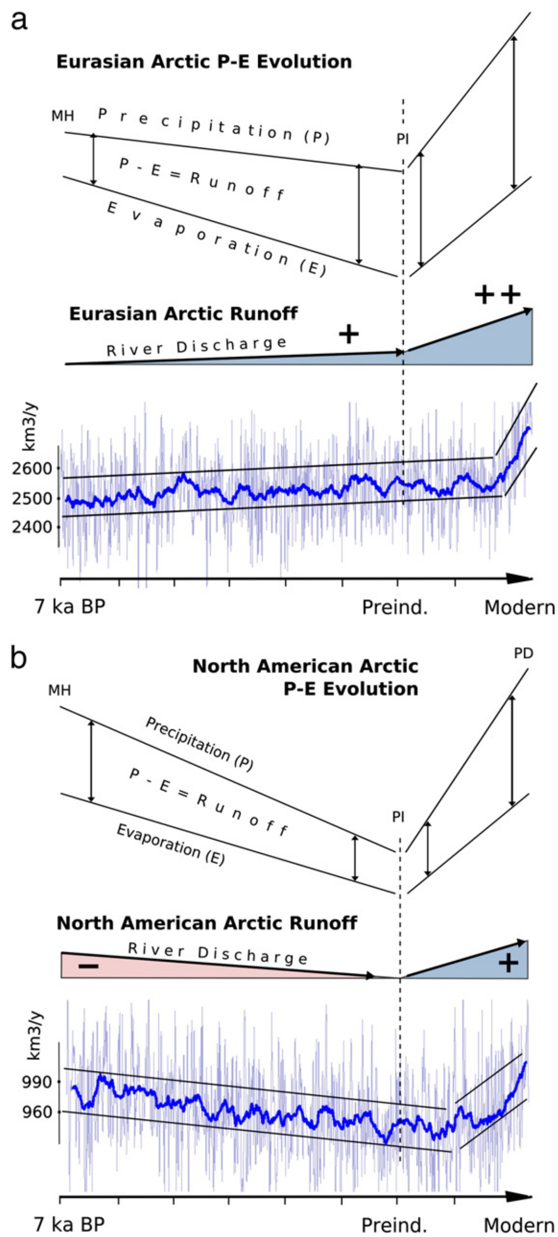

Fig. 9. Sketch of the (a) Eurasian and (b) North American discharge evolutions. Discharge trends are described as the result of P–E. The P–E evolutions throughout Eurasia and North America are contrasted in panels a and b. The time domain is subdivided into the mid-Holocene to preindustrial era with constant atmospheric gas concentrations and the following industrial era with a gradual increase of the most important greenhouse gasses.

(Peters and Prowse, 2001; Woo and Thorne, 2003; Ye et al., 2003; Yang et al., 2004a, 2004b; Liu et al., 2005; Woo et al., 2008). Modern Eurasian Arctic discharges are affected by, e.g., plant irrigation or hydroelectric stations, which lead to a decrease of total discharge amounts (Yang et al., 2004b). Regarding the ECHO-G model simulations of the industrial age, these dam-effects are not taken into account.

Melting of permafrost has been supposed to contribute to volumetric changes in Arctic runoff (Zhang et al., 2003). A volumetric integration and estimation of the Northern hemispheric permafrost layer result in a ground ice volume of approximately 6 to 15×10^3 km^3, alternative estimations lead to a volume range between 11 and 37×10^3 km^3 (Zhang et al., 2008). Around 70% of the Northern Hemisphere permafrost is situated within large parts of the Eurasian and North American Arctic river catchment areas between 45 and 67°N. Increasing Arctic temperatures could lead to ascending melting processes and hence to an increase in Arctic river discharges. Another calculation by McClelland et al. (2004) estimates the possible water equivalent of the Eurasian permafrost layer of approximately between 4 and 40 m thickness, which seems not very reasonable as a source for the amount of observed discharge changes (Holmes et al., 2003). A numerical modeling approach by Anisimov (1989) showed that an annual air temperature increase of approximately 2 K throughout Russia would cause a reduction of 15 to 20% of the continuous permafrost distribution. Further studies concerning global warming and permafrost thawing have been published by Woo (1986), Pavlov (1994), Osterkamp and Romanovsky (1999), and Romanovsky et al. (2007). Nevertheless, the results by Peterson et al. (2002) do fit very well with the ECHO-G model findings that exclude permafrost effects.

The reconstruction of spatial P patterns in northern high latitudes is difficult due to a lack of stations which were, moreover, reduced in the early 1990s (Serreze et al., 2002). Terrestrial P records of point measurements display several instrumental errors (Sevruk, 1982; Legates and Willmott, 1990; Groisman et al., 1991; Sevruk, 1993; Groisman and Easterling, 1994) which deteriorate the construction of a large-scale P pattern.

5. Conclusions

The simulated Arctic river discharges reveal heterogeneous trends during the Holocene. Throughout Arctic Eurasia discharges tend to increase, while across Arctic North America they tend to decrease. The Eurasian Arctic increase is induced by a negative P–E balance with more rapid decrease of E relative to P. Two mechanisms are responsible for this effect. The local mechanism, accountable for the high E decreases, is directly correlated to the high northern cooling trends across the Eurasian continent. The remote mechanism, responsible for smaller P decreases relative to E, is caused by an only minor reduction in moisture advection from the Atlantic Ocean to the Eurasian continent.

The moisture transport across the North American Arctic domain consistently decreased in a steeper way than in Eurasia. As a cause, the NE-Pacific temperatures decreased more rapidly than the NE-Atlantic temperatures. The smaller descent of oceanic E processes throughout the North Atlantic domain thus yielded a weaker decrease of P processes over Eurasia compared to the North American Arctic domains.

The model ECHO-G does not account for long-term (Holocene) storage changes (permafrost, glacier mass balance) of the terrestrial hydrological cycle. These storage changes could affect our findings, and hence, quantitative estimations of these storage changes are urgently needed. A qualitative study by Velichko et al. (1995) states a thawing of Holocene permafrost across northern and eastern Siberia. This finding substantiates our hypothesis of increasing Siberian river discharges during the Holocene.

The Holocene runoff describes relatively small changes throughout the preindustrial era with probably no noticeable effects on the Arctic Ocean sea-ice system. However during the last 100 years, in the course of global warming, runoff of all major Arctic river systems increased without precedent in the last 7 ka. The industrial warming is associated with a positive trend of terrestrial Arctic as well as North Atlantic and North Pacific surface temperatures. Consequently, moisture transports across the Eurasian Arctic and North American Arctic domains ascend significantly. As a result, P within the Eurasian and North American Arctic and river discharges tends to increase. The results are corroborated by analyzed gauging stations by e.g. Peterson et al. (2002, 2006), Shiklomanov (2010), Shiklomanov and Shiklomanov (2003), and Déry et al. (2009), precipitation trends (Wang and Cho, 1997; Vincent et al., 2004), land surface temperature trends (Woo and Thorne, 2003; Jones and Mann, 2004; D'Arrigo et al., 2006), and SST trends (Zhang et al., 1997; Rayner et al., 2006).

As a logical next step the robustness of our model findings should be tested with other model simulations. The experiments should include a permafrost sub-model as well as dynamic vegetation in order to simulate a more realistic water cycle of the terrestrial Arctic.

A further approach would be the use of regional hydrological models considering soil-type variations, grain size and pore volume distributions, bedrock structures, vegetation feedbacks as well as surface, intermediate and base flow processes with respect to discontinuous and continuous active layer existence. Isolated river catchment areas could be simulated by these regional models. The provided processes are beneficial for the improvement of the simulations.

Database access

Model datasets are archived in the PANGAEA database (http://www.pangaea.de)
(http://doi.pangaea.de/10.1594/PANGAEA.742984)

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