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Effect of increasing Arctic river runoff on the Atlantic meridional overturning circulation: a model study

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Abstract

An increasing amount of freshwater has been observed to enter the Arctic Ocean from the six largest Eurasian rivers over the past several decades. The increasing trend is projected to continue in the twenty-first century according to Coupled Model Intercomparison Project Phase 5 (CMIP5) coupled models. The present study found that water flux from rivers to the Arctic Ocean at the end of the century will be 1.4 times that in 1950 according to CMIP5 projection results under Representative Concentration Pathway 8.5. The effect of increasing Arctic river runoff on the Atlantic meridional overturning circulation (AMOC) was investigated using an ocean-ice coupled model. Results obtained from two numerical experiments show that 100, 150 and 200 years after the start of an increase in the Arctic river runoff at a rate of 0.22%/a, the AMOC will weaken by 0.6 (3%), 1.2 (7%) and 1.8 (11%) Sv. AMOC weakening is mainly caused by freshwater transported from increasing Arctic river runoff inhibiting the formation of North Atlantic Deep Water (NADW). As the AMOC weakens, the deep seawater age will become older throughout the Atlantic Basin owing to the increasing of Arctic runoff.

Key words: climate change, Arctic river runoff, Atlantic meridional overturning circulation

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1 Introduction

Observed vertical profiles of salinity in the Arctic Ocean always have a low-salinity surface layer. This low-salinity surface layer may cause strong stratification, constrain vertical mixing and promote sea ice formation in the Arctic Ocean. River inflow is important to maintain the fresh, low-density surface layer in the Arctic Ocean because the Arctic Ocean contains only about 1% of the global volume of seawater yet it receives about 11% of the world's river flow (Serreze and Barry, 2005). According to an estimation made by Serreze et al. (2006), river discharge makes the largest contribution (38%) to the freshwater input to the Arctic Ocean, whereas the percentages of fresh water inflow through the Bering Strait and from net precipitation are 30% and 24%, respectively.

River-monitoring data reveal that the flow of freshwater from the six largest Eurasian rivers to the Arctic Ocean has been increasing at an average annual rate of (2.0±0.7) km^3/a, and has increased by 7% from 1936 to 1999 (Peterson et al., 2002), while the freshwater discharge from North American rivers has decreased over the past 30 years (Sui et al., 2008). However, the discharge from Eurasian rivers is much greater than that from North American rivers, and the total river discharge into the Arctic Ocean is thus increasing (Sui et al., 2008). The increase in river discharge to the Arctic Ocean is considered to correlate with the North Atlantic Oscillation and a change in global mean surface air temperature (Peterson et al., 2002; Sui et al., 2008). Furthermore, Zhang et al. (2013) noted that an enhancement of poleward atmospheric moisture transport decisively contributes to the increasing Eurasian Arctic river discharges. In the twenty-first century, river discharge into the Arctic Ocean will increase according to the projections of Intergovernmental Panel on Climate Change (IPCC AR4) (Kattsov et al., 2007).

The increase in river discharge into the Arctic Ocean may affect the processes of seawater stratification, light attenuation, surface heating, gas exchange, biological productivity and carbon sequestration in the Arctic Ocean (Fichot et al., 2013). Besides these local effects in the Arctic Ocean, the increase in river discharge into the Arctic Ocean has potential remote effects on the Atlantic Ocean, such as the North Atlantic Deep Water (NADW) formation and Atlantic meridional overturning circulation (AMOC). The increasing runoff will freshen the Arctic Ocean, and more freshwater into the Arctic Ocean will be exported to the North Atlantic Ocean. Results of water-hosing experiments show that if additional 0.1 Sv freshwater input to the northern North Atlantic, the thermohaline circulation (THC) will weaken by 30% after 100 years (Stouffer et al., 2006). More freshwater input to the

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northern North Atlantic may strengthen stratification in the North Atlantic, inhibit the formation of NADW, and thus weaken AMOC. The increasing Arctic runoff has a potential effect on AMOC. AMOC plays important roles in the global climate system because it contributes to global heat transportation.

This potential remote effect has been discussed in many papers (Li, 2009; Morison et al., 2012; Fichot et al., 2013), but few studies have specifically investigated the effect. Rennermalm et al. (2006) studied the sensitivity of the THC to Arctic Ocean runoff and concluded that there is an inverse relationship between the THC strength and changes in riverine freshwater discharge. However, their study mainly focused on the steady state after more than 2 000 years simulations with idealized changes in Arctic runoff, yet the evolutionary processes of AMOC on a short time scale, which are also important in clarifying climate change, have not been included in the simulation.

Cheng et al. (2013) used CMIP5 projections to show that the weakening of AMOC by year 2100 is 15%–60% under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. However, whether and to what extent the AMOC will be weakened by increased Arctic runoff in the 21 century remain unknown. The present paper investigates the effect of increasing Arctic river runoff on AMOC by employing numerical experiments to answer these questions.

The remainder of the paper is organized as follows. Data and numerical experiments are introduced in Section 2. Section 3 presents the results of the numerical experiments, and Section 4 provides a discussion and draws conclusions from the results of the study.

2 Data and numerical experiments

To check the long-term trend of the river discharge into the Arctic Ocean, data of the annual mean river flow are taken from the Dai and Trenberth Global River Flow and Continental Discharge Dataset (Dai et al., 2009). Both the linear trend and Ensemble Empirical Mode Decomposition (EEMD) (Huang et al., 1998; Wu and Huang, 2009) non-linear trend of the annual mean river flow from 1950 to 2000 for the six largest Eurasian rivers are analysed. These six rivers are the Yenisey, Lena, Ob, Pechora, Severnaya Dvina and Kolyma.

To evaluate the future trend of the Arctic river runoff, the latest Coupled Model Intercomparison Project Phase 5 (CMIP5) coupled model simulation (1950–2005) and projection (2006–2100) results from 17 coupled models under the RCP8.5 scenario are used. The multi-model mean is used to reduce uncertainty due to large model spread on the results. The 17 CMIP5 coupled models are ACCESS1-0, ACCESS1-3, CNRM-CM5, CSIRO-Mk3.6.0, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M, and NorESM1-M.

To investigate the potential effect of river discharge on AMOC, two numerical experiments based on a global ocean-ice coupled model are designed. The ocean general circulation model used here is Modular Ocean Model version 5 (MOM5) (Griffies, 2012) developed by the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration, and the sea ice model is Sea Ice Simulator (SIS) (Winton, 2000). The zonal resolution of this global ocean-ice coupled model is 1° uniformly. The meridional resolution is (1/3)° at the equator and gradually decreases to 1° at 30°S and 30°N, beyond which the resolution is 1° uniformly. There are 50 levels in the vertical direction, and the thickness of the first layer is 10 m. The two numerical experiments are named Control_run and Runoff_increase, respectively. In the Control_run experiment, the ocean surface forcing data are taken from the corrected normal year forcing data of Coordinated Ocean-ice Reference Experiments version 2 (CORE2) (Large and Yeager, 2009) and the model is integrated for 3 000 years to reach an equilibrium state. To achieve the equilibrium state as quickly as possible, the surface salinity and temperature restoration time scale is 60 days (i.e., strong surface restoration) for the integration from 1 to 2 000 years and 219 days (i.e., moderate surface restoration) for the integration from 2 001 to 3 000 years. The Runoff_increase experiment is a 200-year (from 3 001 to 3 200) continuous run of the Control_run experiment, in which the ocean surface forcing is the same as that in the Control_run experiment. The difference between the two experiments is the river runoff into the Arctic Ocean. In the Control_run experiment, river runoff is also from the corrected normal year forcing data of CORE2. In the Runoff_increase experiment, however, river runoff into the Arctic Ocean increases at a rate of 0.22%/a, which is based on the projections of CMIP5 coupled models under the RCP8.5 scenario. After 150 years, the Arctic runoff will be 1.4 times its initial value. We mainly focus on the response of AMOC to the increase in the Arctic runoff. So different from water-hosing experiments where the hosing flux is applied uniformly over the Atlantic between 50°N and 70°N (Stouffer et al., 2006), additional freshwater in present study from the Arctic rivers is only applied around river mouths of the Arctic Ocean in our experiment.

3 Results

The annual mean river flow observed from 1950 to 2000 for the six largest Eurasian rivers is shown in Fig. 1. The annual mean total discharge of these six rivers is 1.85×10^3 km^3 and the linear trend is 2.8 km^3/a for the period from 1950 to 2000, which is greater than the value of 2.0 km^3/a for the period from 1936 to 1999 reported by Peterson et al. (2002). This indicates that increasing trend has been accelerating, which is shown more clearly by the EEMD trend in Fig. 1. There is no notable trend before 1970, but the EEMD trend gradually becomes large after 1970, and accelerates.

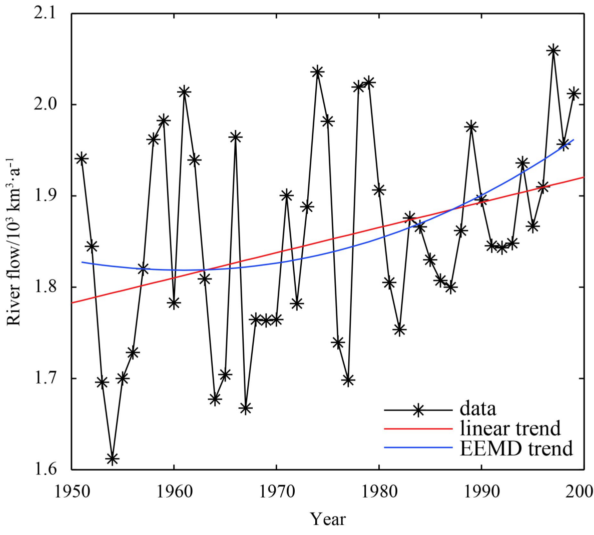

Fig. 1. Time series of the observed annual discharge (black) (10^3 km^3/a) of the six largest Eurasian rivers into the Arctic Ocean and its linear (red) and EEMD (blue) trends.

The multi-model mean water flux from rivers to the Arctic Ocean obtained using 17 CMIP5 coupled models is shown in Fig. 2. The water flux from rivers to the Arctic Ocean simulated with the CMIP5 coupled models has an increasing trend from 1950 to 2000 as shown in Fig. 1. The simulated linear trend of the annual mean discharge is 1.3 km^3/a. It is smaller than what was observed. Figure 2 also shows that water flux from rivers will have an increasing trend in the twenty-first century, and this is consistent with the result obtained using IPCC AR4 climate models (Kattsov et al., 2007). At the end of the twenty-first century, the water flux from rivers to the Arctic Ocean will be 1.4 times that in 1950. The increasing rate of Arctic river runoff in the Runoff_increase experiment is based on this rate.

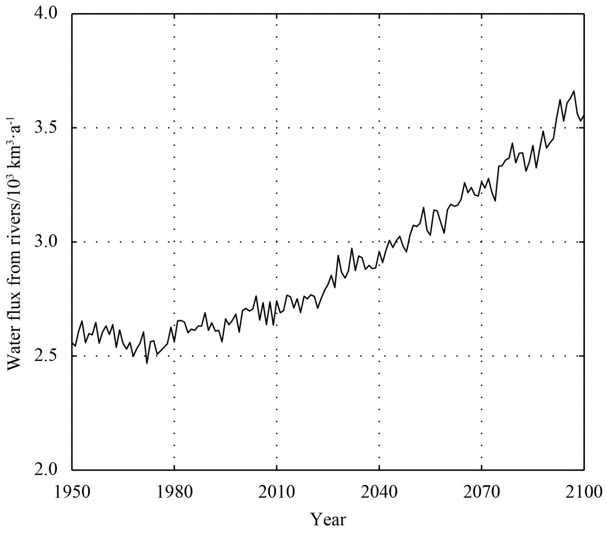

Fig. 2. Multi-model mean water flux (10^3 km^3/a) into the Arctic Ocean from rivers simulated and projected under the RCP8.5 scenario by CMIP5 coupled models.

The meridional overturning streamfunction of the Atlantic Basin and AMOC index time series for the last 100 years in the Control_run experiment are shown in Fig. 3. The AMOC index here is defined as the maximum meridional overturning streamfunction of the Atlantic Basin at 45°N, which is the same as that used by Griffies et al. (2009). The pattern and strength of the meridional overturning streamfunction of the Atlantic Basin in Fig. 3a are similar to those simulated by GFDL-MOM in Griffies et al. (2009). AMOC consists of two primary overturning cells (Survey, 2012). The upper cell transports warm upper water northward to compensate for the formation of NADW and returns southward. In the deep cell, Antarctic Bottom Water (AABW) flows northward and rises into the lower part of the southward-flowing NADW. Both cells are reproduced in the Control_run experiment (Fig. 3a). The simulated maximum AMOC is located at mid-latitude, and the NADW formation is mainly located at high latitude. The AMOC index in the Control_run experiment shown in Fig. 3b reveals that the AMOC strength is stable in the last 100 years simulation in the Control_run experiment, which means that the model has reached an equilibrium state after 3 000 years of integration. The average AMOC strength in the last 100 years of simulation in the Control_run experiment is 16.7 Sv according to the AMOC index in Fig. 3b. The AMOC strength in the Control_run experiment is a little lower than the average strength of 18.7 Sv observed from 2004 to 2014 by the Rapid Climate Change Program at 26.5°N (Srokosz and Bryden, 2015), but in the range of 15 to 23 Sv obtained in longer observations (Bryden et al., 2005). Although GFDL-MOM simulated the AMOC strength as being lower than the observations, GFDL-MOM has the most vigorous AMOC among several ocean-ice coupled models in the Coordinated Ocean-ice Reference Experiments (Griffies et al., 2009). The AMOC strength in the Runoff_increase experiment shown in Fig. 3b has a notable decreasing trend. This means that the AMOC will become weak when the river runoff increases in the Arctic Ocean. The AMOC strengths 100, 150 and 200 years after the start of the Runoff_increase experiment are 16.1, 15.5 and 14.9 Sv, corresponding to decreases of 0.6 (3%), 1.2 (7%) and 1.8 (11%) Sv, respectively.

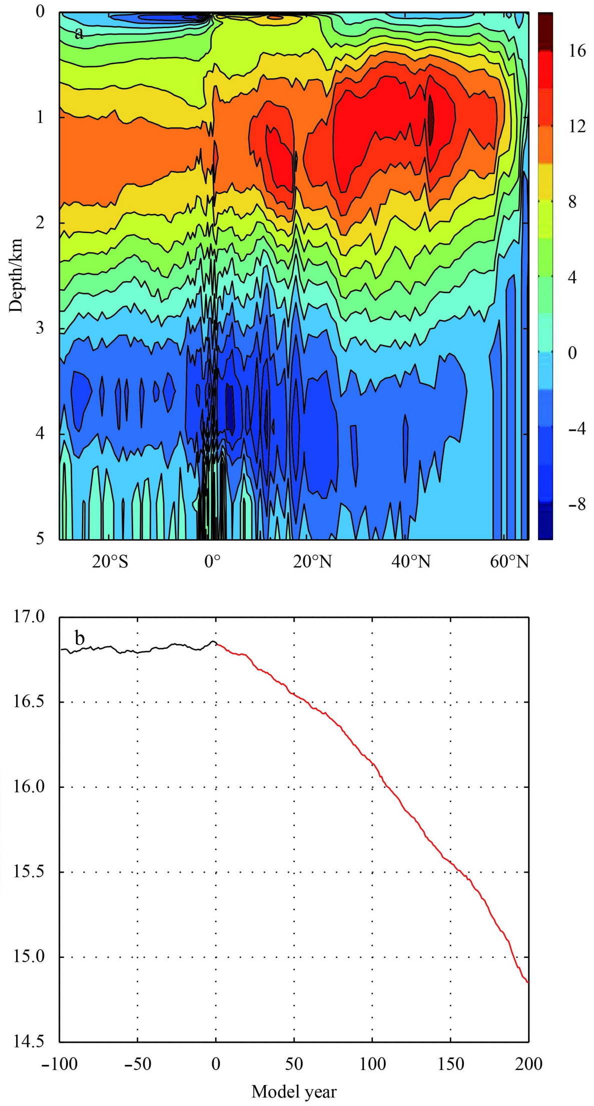

Fig. 3. Meridional overturning streamfunction of the Atlantic Basin (a) (Sv=10^6 m^3/s) simulated in the Control_run experiment and time series of AMOC index (b) in the Control_run (black line) and Runoff_increase (red line) experiments. The *x*-axis in Fig. 3b is the model year relative to the start of the Runoff_increase (red line) experiment.

The effect of increasing Arctic runoff on meridional overturning streamfunction of the Atlantic Basin is shown in Fig. 4. The meridional overturning streamfunction will decrease almost uniformly throughout the basin, and the strongest effect is located at depths between 1 500 m and 2 500 m and the latitudes between

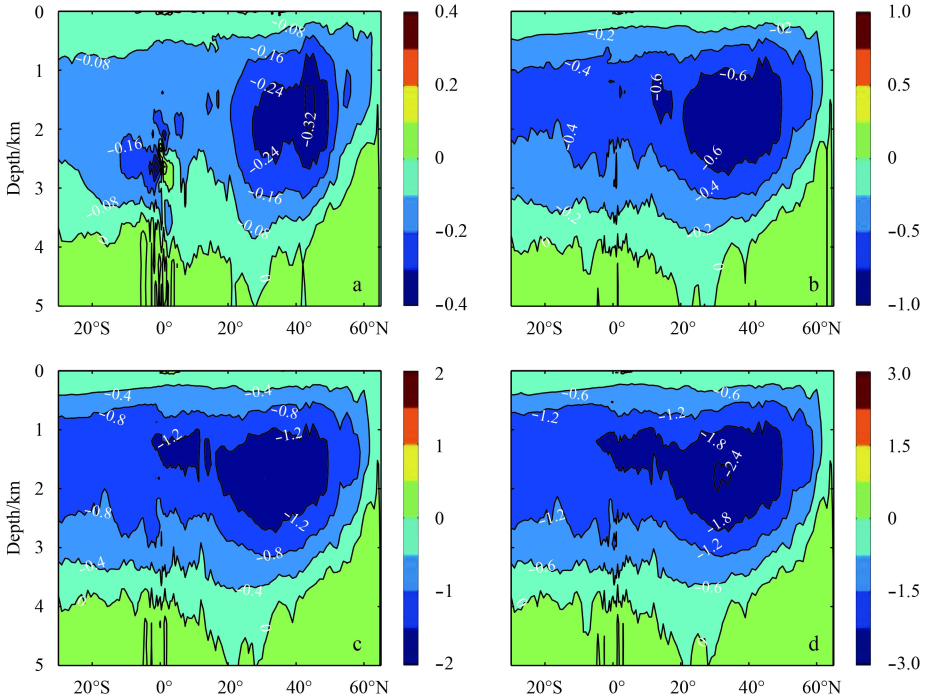

Fig. 4. Differences (Sv) in the meridional overturning streamfunction of the Atlantic Basin between the Runoff_increase and Control_run experiments. The model years in Figs 4a, b, c and d are 50, 100, 150 and 200 for the Runoff_increase experiment, respectively.

30°N and 50°N. The maximum changes 50, 100, 150 and 200 years after the start of the Runoff_increase experiment are –0.3, –0.8, –1.6 and –2.5 Sv, respectively.

The reason for the slowing of AMOC is that the increasing Arctic runoff inhibits the formation of NADW. The important process for NADW formation is deep ocean convection with a deep Mixed Layer Depth (MLD) in the North Atlantic during winter (Griffies et al., 2009). The annual mean MLD in the Control_run experiment shown in Fig. 5 reveals that NADW mainly forms in the Labrador Sea, Nordic seas and far North Atlantic on the south side of Iceland in numerical simulations. The freshwater from increasing Arctic runoff will be transported by ocean circulation to these important regions. Once there is more surface freshwater into these important regions, the upper ocean density will decrease and the stratification will strengthen. The MLD then becomes shallower and NADW formation is inhibited. Differences in the sea surface salinity (SSS) and MLD between the Runoff_increase and Control_run experiments are shown in Figs 6 and 7. Fifty years after the start of the Runoff_increase experiment, SSS in most of the Arctic Ocean and North Atlantic has a decreased trend (Fig. 6a). There are large differences caused by huge Eurasian Arctic river discharge into the Laptev Sea and Kara Sea. In other regions the differences are relatively small (no larger than 0.1). In the Labrador Sea, however, the MLD becomes markedly shallower owing to the SSS reduction (Fig. 7a). This means that NADW formation in the Labrador Sea is weakening. One-hundred years after the start of the Runoff_increase experiment, the regions with large SSS difference are expanded but mainly exist in the Arctic Ocean (Fig. 6b). In the Labrador Sea and Nordic seas, the maximum difference is SSS exceeds 0.1, and the annual mean mixed layer in the Nordic seas rises more than 150 m (Fig. 7b). Figure 6c shows that the freshening of the Arctic Ocean and North Atlantic expands continuously for 150 years after the start of the Runoff_increase experiment, but the large MLD differences are mainly in the Labrador Sea and Nordic seas (Fig. 7c). Figure 7d shows that a large MLD difference emerges in the far North Atlantic on the south side of Iceland, while the MLD differences become much larger in the Labrador Sea and Nordic seas.

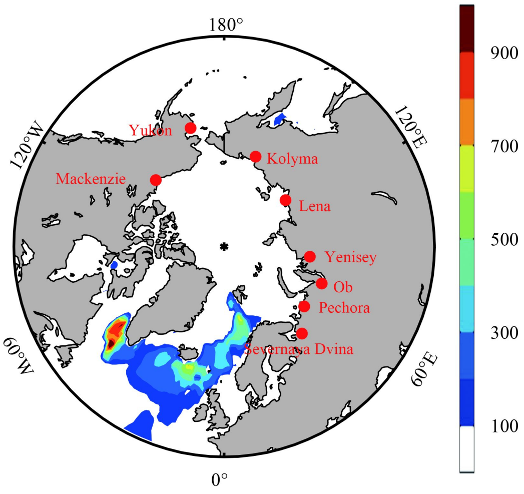

Fig. 5. Annual mean MLD (m) in the Control_run experiment. Red dots are the locations of main river mouths in the Arctic.

For investigating the stratification changes in the important regions of NADW formation, Fig. 8 shows salinity and density differences between the Runoff_increase and Control_run experiments at 60.5°N, 55.5°W in the Labrador Sea and 74°N, 9.5°E in the Nordic seas, respectively. There is no large differences in salinity and density for the first 50 years. This means the additional freshwater from the increase in the Arctic runoff has not been transported to these important regions yet. Salinity and density at

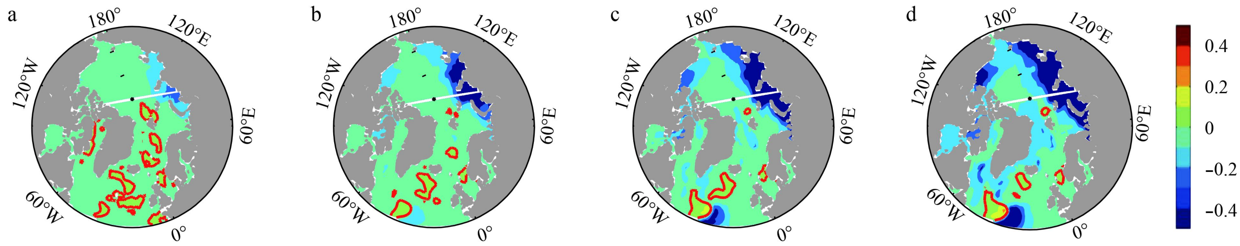

Fig. 6. Differences in the annual mean SSS between the Runoff_increase experiment and Control_run experiment. The model years in Figs 6a, b, c and d are 50, 100, 150 and 200 for the Runoff_increase experiment, respectively. The red line is the 0 isoline.

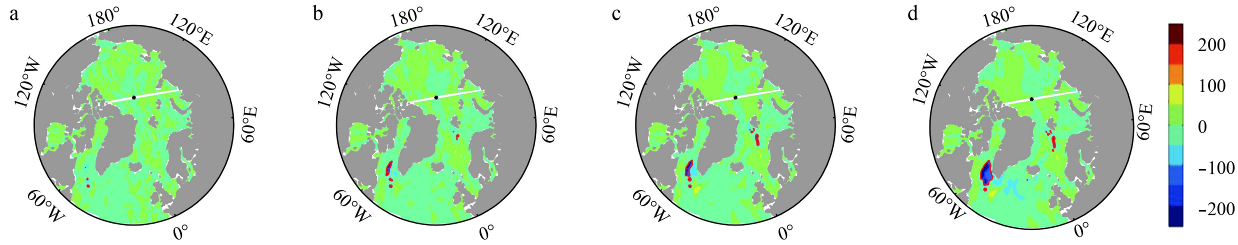

Fig. 7. Differences in the annual mean MLD (m) between the Runoff_increase and Control_run experiments. The model years in Figs 7a, b, c and d are 50, 100, 150 and 200 for the Runoff_increase experiment, respectively. The red line is the –100-m isoline.

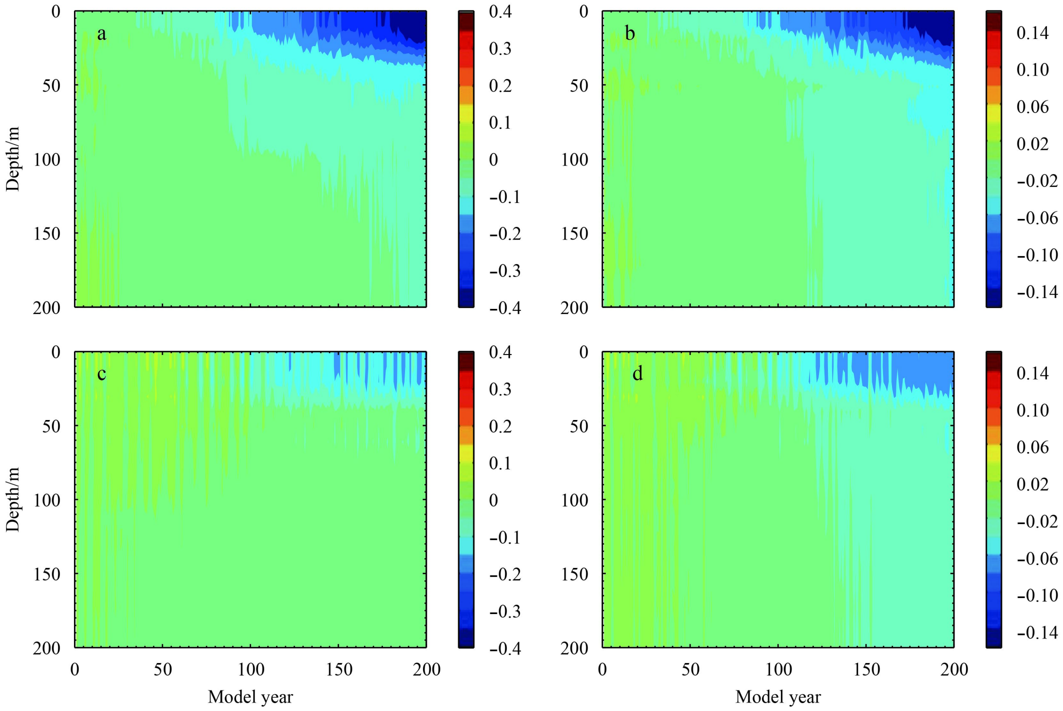

Fig. 8. Differences in annual mean salinity (a and c) and density (b and d) (kg/m^3) between the Runoff_increase and Control_run experiments at 60.5°N, 55.5°W in the Labrador Sea (a and b) and at 74°N, 9.5°E in the Nordic seas (c and d).

(60.5°N, 55.5°W) in the Labrador Sea begin to decrease after the 50th years, and change in the upper layer are much greater than those in the lower layer (Figs 8a and b). The significant decreases in upper-layer salinity and density indicate that the stratification strengthens in this important region. There are similar processes at (74°N, 9.5°E) in the Nordic seas (Figs 8c and d), but the differences are smaller and exist later than those in the Labrador Sea.

The above analysis reveals that an increase in the Arctic river runoff will inhibit the NADW formation in the Labrador Sea, Nordic seas and far North Atlantic on the south side of Iceland, but the strength and time of the effect are different in these three regions. The Labrador Sea is affected the most and earliest, while the far North Atlantic on the south side of Iceland is affected the least and latest. These differences are mainly due to ocean circulation in the Arctic Ocean and North Atlantic. To show the pathways of freshwater transport, Fig. 9 gives differences in the freshwater content between the Runoff_increase and Control_run experiments. The freshwater content is calculated as

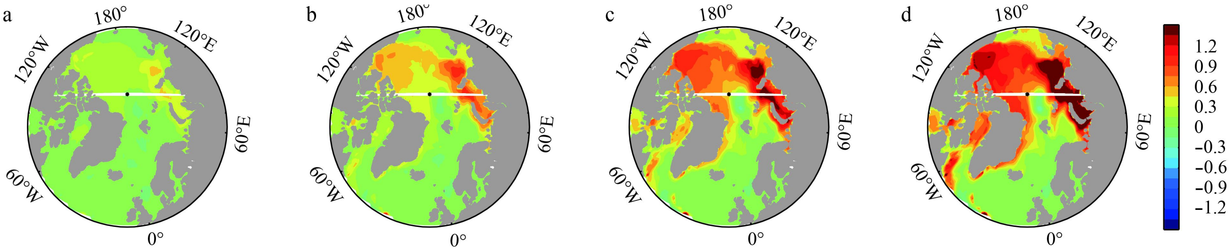

Fig. 9. Differences in the annual mean freshwater content (m) between the Runoff_increase and Control_run experiments. The model years in Figs 9a, b, c and d are 50, 100, 150 and 200 for the Runoff_increase experiment, respectively.

$$FWC = \int_{H}^{0} (1 - S(z)/S_{\text{ref}})\,\mathrm{d}z, \qquad (1)$$

where $S(z)$ is the salinity at depth z, S_{ref} is the reference salinity, and H is the depth at which the seawater salinity equals to the reference salinity. The reference salinity is 34.8, which is considered a reasonable estimate of average salinity for the Arctic Ocean (Serreze et al., 2006). Figure 9 shows that most freshwater from additional Arctic runoff is in the Kara Sea, Laptev Sea and Beaufort Sea, which are close to months of the Arctic rivers. Freshwater from Eurasian rivers will be transported to the Canadian Basin by ocean circulation. Additional freshwater from North American rivers will also accumulate in the Canadian Basin under the effect of the Beaufort Gyre. There are two freshwater transport pathways from the Arctic to the North Atlantic. The first pathway is along the eastern coast of Greenland through the Fram Strait and Denmark Strait to the Labrador Sea. The freshwater along this pathway is mainly transported by the Transpolar Drift and East Greenland Current. The second pathway is along the Baffin Current through Baffin Bay and Davis Strait to the Labrador Sea. The additional freshwater along these two pathways will affect the formation of deep water directly in the Labrador Sea. Part of the additional freshwater along the East Greenland Current will be split off to the east by the Jan Mayen Current owing to the bathymetry, and will affect the formation of deep water in the Nordic seas.

Increasing Arctic river runoff will affect the properties of NADW. Differences in seawater salinity at a depth of 3 000 m between the Runoff_increase experiment and Control_run experiment are shown in Fig. 10. NADW salinity decreases gradually as the surface water freshens and the AMOC weakens. NADW starts freshening in the North Atlantic (Fig. 10a) and then extends to the South Atlantic. One-hundred and fifty years after the start of the Runoff_increase experiment, the seawater salinity at a depth of 3 000 m will decrease (Fig. 10c). The NADW will become older because the NADW formation is inhibited and the AMOC is slowed by increasing Arctic runoff. Here, the age of seawater is defined as the time that has elapsed since a given water parcel was last exposed to the atmosphere (England, 1995). Figure 11 shows that NADW at a depth of 3 000 m throughout the Atlantic will become older after the start of the Runoff_increase experiment (Fig. 11c). The largest age differences exist in the tropical Atlantic, mid-latitude North Atlantic and Nordic seas. In these regions, the age changes exceed 20 years. Sea surface temperature (SST) and extent of sea ice will also be affected by increasing Arctic runoff. SST in the Labrador Sea and Nordic seas has a cooling trend in the Runoff_increase experiment. This cooling trend is mainly due to a decrease in heat transport from tropical regions by AMOC. Consistent with the decreasing SST, winter sea ice in the Labrador Sea and Nordic seas has an increasing trend in the Runoff_increase experiment.

4 Conclusions and discussion

In this paper, two numerical experiments were designed to study the effect of increasing Arctic runoff on AMOC. The increasing rate of Arctic runoff in the numerical experiment was given according to the projections of CMIP5 coupled models under the RCP8.5 scenario. Results of the numerical experiments show that the Atlantic meridional overturning streamfunction will slow almost throughout the basin because of increasing Arctic runoff. The largest decrease is at depths between 1 500 and 2 500 m and latitudes between 30°N and 50°N. The mechanism of the effect of increasing Arctic runoff is that ocean surface circulation transports freshwater from increasing Arctic runoff into where NADW has formed, and the stratification then strengthens in these important regions and the MLD becomes shallower, which inhibits the formation of NADW. Numerical results also

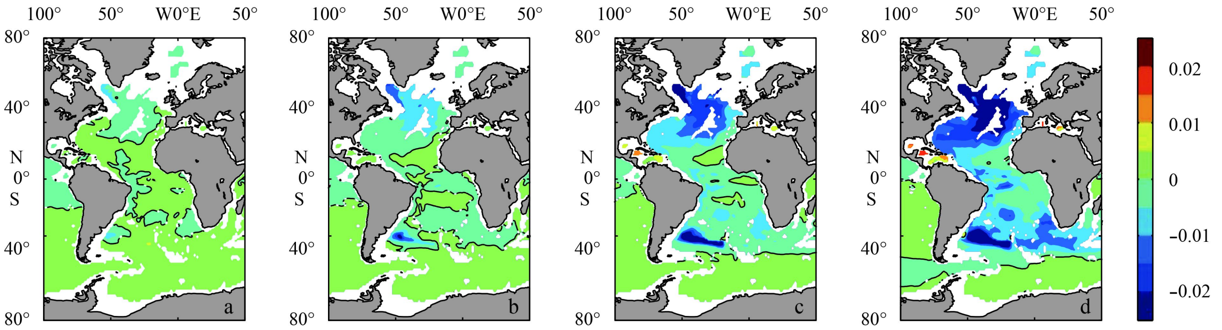

Fig. 10. Differences in the seawater salinity at a depth of 3 000 m between the Runoff_increase and Control_run experiments. The model years in Figs 10a, b, c and d are 50, 100, 150 and 200 for the Runoff_increase experiment, respectively. The black line is the 0 isoline.

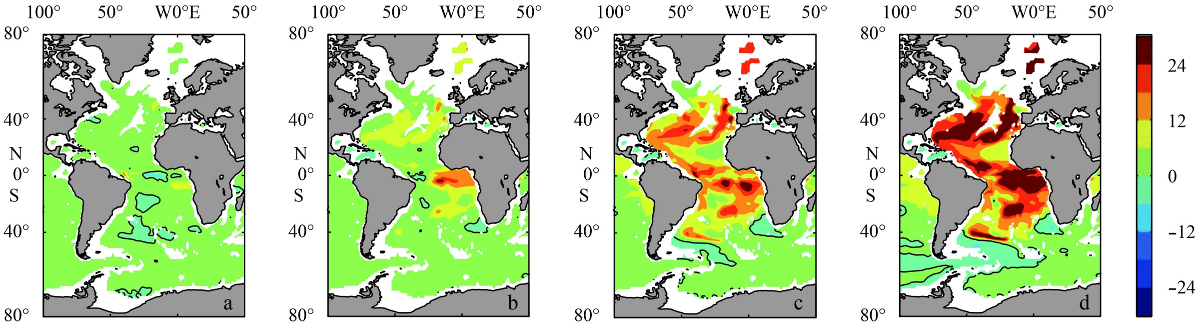

Fig. 11. Differences in seawater age (a) at a depth of 3 000 m between the Runoff_increase and Control_run experiments. The model years in Figs 11a, b, c and d are 50, 100, 150 and 200 for the Runoff_increase experiment, respectively. The black line is the 0-year isoline.

show that this process affects the age of NADW. NADW will become older at a depth of 3 000 m in the Atlantic 150 years after the start of the increase in Arctic runoff.

The surface salinity restoration in the model may introduce uncertainty to the numerical experiments. Salinity restoration method is necessary for long-term simulation using ocean-ice coupled models to prevent climate drifts. However, salinity restoration method will lead to unphysical negative feedback (Griffies et al., 2009). For the results that we analyzed here, the piston velocity for salinity restoration is 10 m per 219 days (i.e., 50 m per 3 years), which is moderate salinity restoration. The uncertainty related to salinity restoration can be eliminated using fully coupled climate simulations (Griffies et al., 2009). The effect of increasing Arctic river runoff on AMOC will therefore be further studied employing fully coupled climate simulations.

Acknowledgements

The observed annual flow of Eurasian rivers are from http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/index.html, and the model forcing data are download from http://data1.gfdl.noaa.gov/nomads/forms/mom4/COREv2.html. The authors thank the above data providers.

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