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Atlantic Meridional Overturning Circulation Decline: Tipping Small Scales under Global Warming

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The Atlantic circulation is a key component of the global ocean conveyor that transports heat and nutrients worldwide. Its likely weakening due to global warming has implications for climate and ecology. However, the expected changes remain largely uncertain as low-resolution climate models currently in use do not resolve small scales. Although the large-scale circulation tends to weaken uniformly in both the low-resolution and our high-resolution climate model version, we find that the small-scale circulation in the North Atlantic changes abruptly under global warming and exhibits pronounced spatial heterogeneity. Furthermore, the future Atlantic Ocean circulation in the high-resolution model version expands in conjunction with a sea ice retreat and strengthening toward the Arctic. Finally, the cutting-edge climate model indicates sensitive shifts in the eddies and circulation on regional scales for future warming and thus provides a benchmark for next-generation climate models that can get rid of parametrizations of unresolved scales.

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Introduction.—The Atlantic Meridional Overturning Circulation (AMOC), an important part of the global ocean conveyor, is projected to slow in the warming 21st century [1,2], as carbon dioxide emissions continue to increase and melting of the Greenland ice sheet accelerates [3]. Its decline would affect the Northern Hemisphere [4] and decelerate global carbon cycle [5]. Although a collapse of the large-scale AMOC (large scale means basin scale in this context) is unlikely in the near future [1,2], the regional scales are not investigated so far.

The small scales (in this context, ocean eddies and convection) are also crucial in climate and ecology. For example, the mesoscale eddies transport considerable heat [6] and nutrients [7]. Satellite observations have shown a global acceleration of eddy activity over the course of altimetry records [8]. Ocean convection, which forms deep water and transforms the upper limb of AMOC into lower limb, acts as heat [9] and carbon [10,11] pump. They have undergone some changes over the last decades [12–14]. Small-scale eddies play an important role in preconditioning and restratifying the water column before and after convection events, influencing the variability of deep water formation [15]. Simulations using high-resolution ocean and climate models, as well as measurements in key regions of the AMOC, indicate that the decline in AMOC over the past 20 years is primarily the result of weakened deep-water formation in the subarctic Atlantic [16]. Since the AMOC characterizes the zonally integrated circulation (Fig. 1), the small scales might hold the key in understanding its changes [17–19].

However, projecting these small scales under future climate is challenging due to the low resolution of climate models [20]. The subarctic Atlantic, where convection and the overturning occur, is very rich in eddy activity. However, eddies are not resolved due to their small spatial scale. Simulation of convection is generally problematic, in part because it is modulated by misrepresented small-scale boundary currents and eddies [21]. In addition, the complex topography determines the dynamics of boundary currents and overflows. These small scales are not properly resolved in the current generation of climate models, so even AMOC predictions remain largely uncertain [17]. The projected AMOC collapse has a certain threshold [22,23], but the small scales could have different thresholds to collapse. The AMOC collapse is also suggested to be resolution dependent—the AMOC in higher-resolution model might be less sensitive to freshwater forcing and driven predominantly by internal feedbacks [22].

Climate model.—With the development of a high-resolution climate model [24], it is possible to assess how the AMOC and eddies may change [20]. Here, we use a cutting-edge high-resolution climate model [24] (hereinafter abbreviated as HR), which has been used for studying small scales and corresponding regional climate and ecology in the other ocean basins [25–27] to examine AMOC and small scales in the subarctic Atlantic under

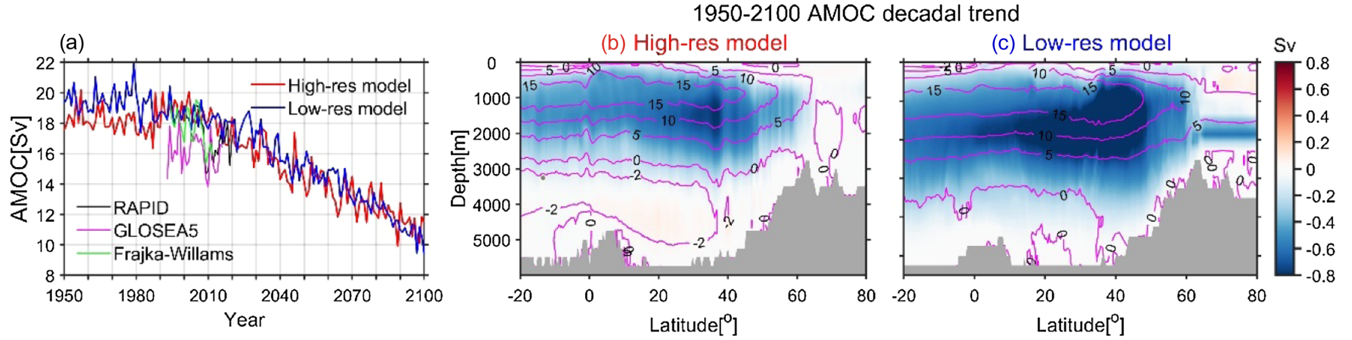

FIG. 1. Atlantic Meridional Overturning Circulation under global warming. (a) Its annual-mean indices in HR (red line) and LR (blue line). The black, magenta, green lines, respectively, represent AMOC at 26 °N observed by RAPID project (2005–2020) [32], a reconstruction from the GloSea5 reanalysis (1993–2016) [33], a reconstruction from satellite altimetry and cable measurements (1994–2012) [34]. (b),(c) Linear decadal trend over 1950–2100 in the stream function of HR (b) and LR (c). The solid magenta contours denote the long-term mean stream functions.

global warming. We also use a low-resolution analog model version [24] to compare results (hereinafter abbreviated as LR).

The models used in this study are based on CESM1.3 [28]. HR has a nominal horizontal resolution of 0.1° in the ocean and sea ice components and 0.25° in the atmosphere and land components. LR has a nominal horizontal resolution of 1°, which is consistent with most current generation climate models [29]. The oceanic eddies are parametrized in LR [30]. The time period of both versions is 1950–2100, with 1950–2005 and 2006–2100, respectively, applied with historical forcing and representative concentration pathway 8.5 forcing (high CO_2 emission scenario) [1,2]. The spin-up time is 250 years, with a climate forcing fixed to preindustrial (year 1850) conditions. The detailed setup of the models can be found in an overview paper [24].

Atlantic Meridional Overturning Circulation.—The AMOC stream function Ψ in the model [31] is defined as

$$\Psi(y, z) = \int_0^z \int_{x_w}^{x_e} v(x, y, \tilde{z}) dx d\tilde{z},$$

where x_e and x_w are the eastern and western boundaries of the Atlantic basin, v is the meridional velocity. The AMOC index is defined as the spatial maximum of Ψ at 26 °N.

The AMOC indices are surprisingly consistent between HR and LR [Fig. 1(a)]. Their magnitude is comparable to the observation [32] and reconstructions [33,34] of AMOC at 26 °N. The AMOC indices in both models similarly decline by ~8 Sv from 2000 to 2100 CE with the sharpest decline beginning in ~2020. The AMOC decline reflected in the spatial distributions of the trends is somewhat weaker in HR [Figs. 1(b) and 1(c)]. It is suggested to be modulated by the resolved processes in HR: the better resolved Labrador Current limits the offshore transport of freshwater from Arctic Ocean into the convection region, and thereby the decline in Labrador Sea overturning is weaker in HR [35]. The mean states of AMOC show larger differences [Figs. 1(b) and 1(c) magenta lines]. In HR, the upper limb of North Atlantic deep water is shallower. This is attributed to the no longer necessary parametrization for the Nordic Sea overflows and stronger Antarctica Bottom Water flow in HR [24]. Although the large-scale AMOC indices are very similar between the model versions, the changes in the spatial structure of AMOC are more evident in the high-resolution model. The AMOC indices cannot reflect regional-scale changes either [31,36,37], which is detected in other basins of HR [25,27].

The overturning stream function across sections (MOC_σ) is defined as [38]

$$MOC_\sigma(\sigma, t) = \int_{\sigma_{\min}}^{\sigma} d\sigma \int_{s_w}^{s_e} v(s, \sigma, t) ds,$$

where s_w and s_e are the western and eastern boundaries of the sections, s is the distance coordinate along the sections, v is the velocity perpendicular to the sections, σ is the potential density referenced to 0 m. The integral of density is taken from the surface density ($\sigma_{\min}$) across all density surfaces. The maximum of MOC_σ at a certain time is recognized as the magnitude of AMOC at the sections.

The Subpolar North Atlantic Program (OSNAP) sections [Fig. 2(a)] are designed to observe the western and eastern overturning in the subarctic Atlantic since 2014 [38]. In HR, the overturning in the subarctic Atlantic compares better with the observations, in terms of magnitude and variability (Fig. 2 in [39], Fig. S1). The detailed analysis is provided in Supplemental Material [40] (see also Refs. [41–54] therein). Further north at the Greenland-Scotland Ridge [GSR; Fig. 2(a)], an overflow parametrization is not used for HR, in contrast to LR. Here, we see an increase of AMOC in HR [Fig. 2(b)], which is the opposite to the decline at 26 °N and OSNAP sections. While in LR, there is almost no overturning and also no increase [Fig. 2(c)].

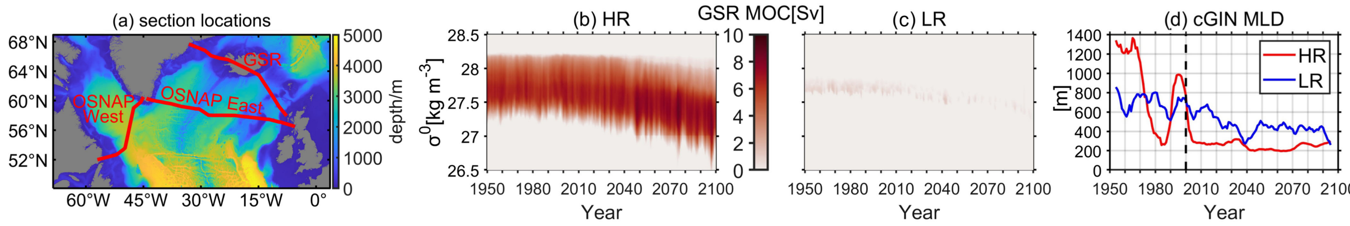

FIG. 2. Meridional Overturning Circulation in the North Atlantic. (a) The locations of the three sections—OSNAP West, OSNAP East, and Greenland-Scotland Ridge (GSR). Color shading denotes the ocean depth. (b),(c) Hovmöller diagram of MOC_σ at GSR during 1950–2100 in HR (b) and LR (c). (d) Area-mean March mixed layer depth in the Nordic Sea (averaging areas are shown in Fig. S3 [40]), smoothed by a 10-year running mean. The vertical dashed line denotes a tipping point.

This amplification of AMOC suggests that ventilation and subduction north of the GSR is increasing under global warming. As sea ice retreats and open-ocean area increases, air-sea interaction enhances ocean mixing. This leads to an strengthening of AMOC toward the Arctic, as projected by climate modeling [48] that indicates sites of convection and subduction moving northward to the central Arctic with global warming. Reference [55] also found AMOC emerges beyond the GSR, which strengthens as the areas of deep mixing move northward toward the central Arctic following sea ice retreat. In addition, there is observational evidence supporting increased mixing and convection as the sea ice edge retreats [56,57]. Our results in HR support the hypothesis that the AMOC intensifies toward the Arctic under global warming.

Following the decline in sea ice, several locations show weakly increasing trends of march mixed layer depth (MLD, representing the convection strength [48], definition written in Supplemental Material) (Fig. S3d [40]). The convection in the Nordic Sea shows a tipping point at the year 2000 for both models [Fig. 2(d)]. In HR, the MLD strongly declines to a minimum of ∼300 m in the 1980s, and then rising abruptly to 1000 m in 1990s. A similar decline was observed in the 1980s [58] and recovery in the 1990s [59]. After 2000, it drops to ∼200 m and then remains stable, indicating that convection has almost collapsed. In LR, the MLD begins to decline in 2000 and remains ∼400 m since 2020 CE. The variability in HR is more abrupt and step-wise. Regarding the convection in the other seas, one can refer to Supplemental Material [40]. To summarize, at the regional scale in the North Atlantic, HR outperforms LR in simulating local circulations and shows a completely different response of the AMOC to global warming. When representing regional ocean circulations, the small scales should be key.

Eddy kinetic energy.—The eddy kinetic energy (E_{EK}) reflects the strength of eddy activity in the ocean. The eddy activity is not resolved and parametrized in LR [30]. The detailed discussion of regional E_{EK} changes in HR is written in Supplemental Material [40]. The E_{EK} is calculated based on sea surface height from HR, which will be referred as η hereinafter. First, the daily surface geostrophic velocity (u_g, v_g) is calculated as

$$u_g = \frac{-g}{f}\frac{\partial \eta}{\partial x}, \qquad v_g = \frac{g}{f}\frac{\partial \eta}{\partial y},$$

where the gravitational acceleration $g = 9.81\ \mathrm{m\,s^{-2}}$, Coriolis frequency $f = 2\Omega \sin\varphi$ with the angular speed of Earth $\Omega = 7.292 \times 10^{-5}\ \mathrm{rad\,s^{-1}}$ and latitude φ. Afterward the perturbation (u'_g, v'_g) is defined as

$$u'_g = u_g - \overline{u_g}, \qquad v'_g = v_g - \overline{v_g},$$

where the overbar denotes annual mean. (u'_g, v'_g) does not contain interannual variability and is recognized as eddy velocity [60]. Therefore, the E_{EK} is calculated as

$$E_{\mathrm{EK}} = \frac{1}{2}(u'^2_g + v'^2_g).$$

Prominent shifts in the eddy activity, which are key to regional climate change, occur under the background of a moderately declining AMOC [Fig. 3(b) and Fig. S2 [40]]. The enhanced E_{EK} near Fram Strait is related to the increasing freshwater outflow (due to sea ice retreat) that increases barotropic instability, as well as the increasing freshwater presence inshore that increases the horizontal density gradient and thus baroclinic instability. The eddy activity causes freshwater spread into the convection region in the GIN sea and thus its variability could be partly related to the HR shifts in the convection. Given the lateral freshwater spread, the E_{EK} decrease as seen in the following east greenland current (EGC) could be due to a decreased velocity and density gradient. This further leads to a stable (and even increasing) density in the EGC [Fig. 3(c)] in HR. While in LR, the density decrease across the GSR section is generally uniform [Fig. 3(d)]. In HR, the contrast in the west-east density change [Fig. 3(c)] causes a regional AMOC increase at the GSR section.

Discussion.—Eddies are ubiquitous in the world ocean and alter seawater properties, ocean circulation, biogeochemical fluxes, and mixed-layer properties [61]. In the North Atlantic, GIN Sea and Barents Sea, pronounced mixed layer anomalies and very energetic mesoscale eddies are observed [62], suggesting a robust relationship between eddy amplitude and mixed layer variations [15]. In

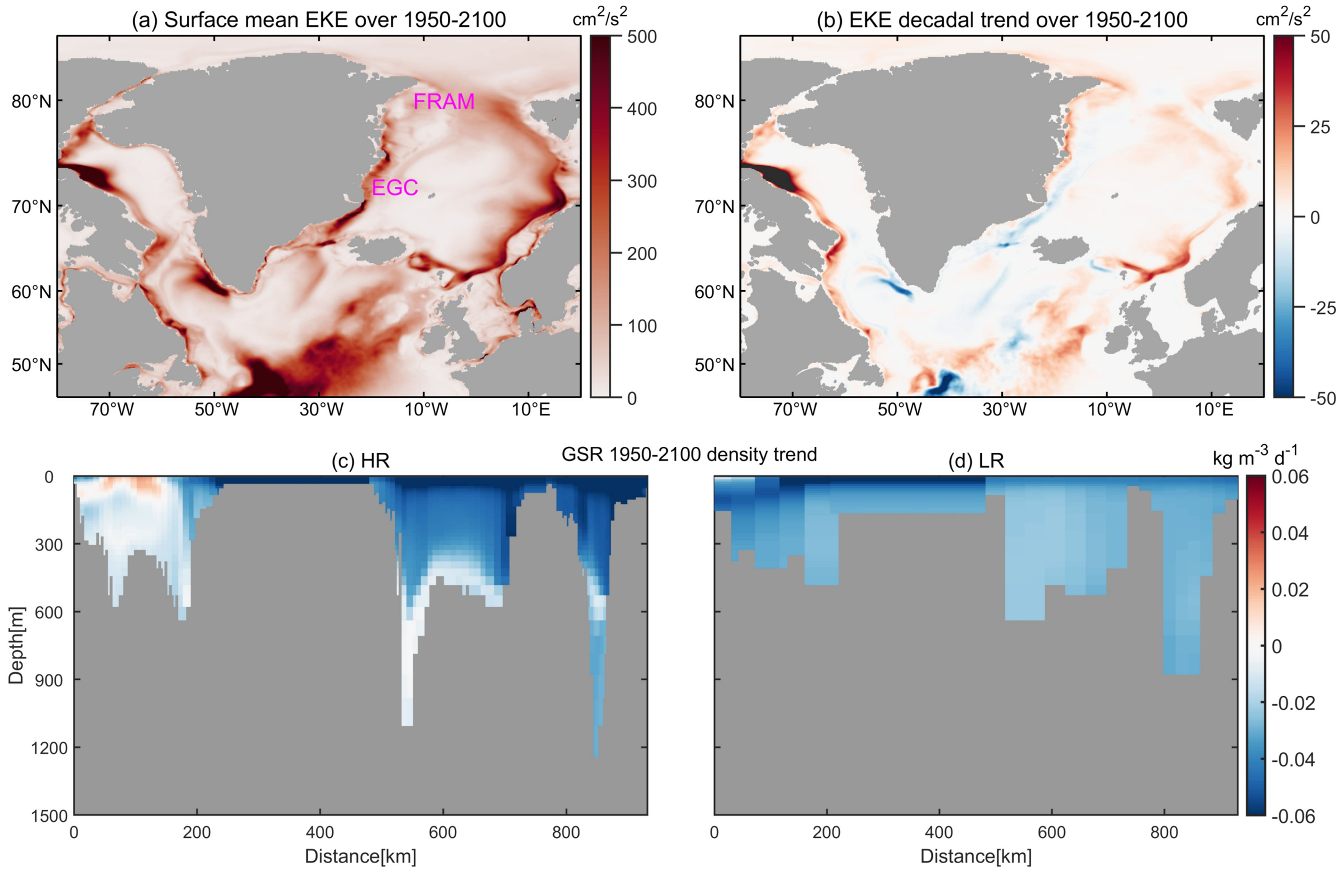

FIG. 3. Surface eddy kinetic energy and density distribution in the subarctic Atlantic under global warming. (a),(b) Mean (a) and linear decadal trend (b) of E_{EK} over 1950–2100 in HR. FRAM and EGC, respectively represent East Greenland Current and Fram Strait. (c),(d) Linear decadal trend over 1950–2100 of density at the GSR section in HR (c) and LR (d).

addition, eddies near deep convection and boundary currents cause flattening of steep isopycnals [63], affecting directly deep-water formation and thus AMOC. Given the slowing of AMOC and the potential crossing of a tipping point in the future [64], our study suggests that the feedback between AMOC and small scales could change in the future. High-resolution climate modeling provides new opportunities to study the links between eddies, convection, and AMOC under climate change.

Although the decrease in the AMOC index under global warming is basically the same in HR and LR, HR changes the AMOC structure and eddy activity significantly. In HR, abrupt shifts in regional circulation and eddy activity are detected under global warming: the AMOC shows a strengthening trend at GSR, suggesting enhanced ventilation toward the Arctic, which is only seen in HR. Convection nearly ceases after 2000 CE in the eastern subpolar gyre, in contrast to a moderately decreasing convection in LR. The change in eddy activity indicates significant spatial heterogeneity: substantial increase around Fram Strait and decrease in the EGC induce the AMOC increase at GSR by altering the density distribution. To summarize, it is likely that the small and regional scales of AMOC have different tipping points compared to the general AMOC.

Consequently, the upper-ocean variability and water mass properties can strongly differ between high and low resolution [65]. The shifts in the eddy activity imply an abrupt change in the pattern of horizontal movement of heat and nutrients under global warming. The resulting convection shifts imply the transition in the vertical movement of heat and nutrients. Although the AMOC is uniformly decreasing, the regional redistribution of heat and nutrients may be transitioning to a different state because of the small-scale shifts. This can be crucial when we try to reconstruct large-scale AMOC shifts that have occurred in the past, based on limited spacial information [66].

We conclude that the interplay between convection, eddy activity, and AMOC is scale dependent, posing a challenge for the large-scale circulation and mesoscale features in a warming ocean. In the 1970s, the framework for climate models was established [67,68], and a prototype climate model was used to demonstrate that anthropogenic CO_2 is causing global warming [69]. Since then, given the limitation of model resolution, the focus of research has been on large-scale climate pattern that are externally driven. With the developing computing capacities, it is time to "think big and model small" [18], to understand the mesoscale changes which can hold a key for surprises [70]. Regional high-resolution climate models like Med-CORDEX aiming at Mediterranean climate [71] have shown series of impacts from model resolution and resolved processes on regional climate. Incorporating the interplay of small-scale processes is key to assess the large-scale ocean evolution, but also requires direct observations at critical locations. On the other hand, the observed decline in AMOC at 26 °N over the past two decades [72,73] is now placed in the context of actual small-scale shifts that cannot be simply inferred from the AMOC decline at a certain latitude.

The data that support the findings of this study are available upon request.

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R. G. performed the analysis, G. L. proposed the central idea, R. G. and G. L. wrote the paper, L. W. conceived the project, and all authors contributed to improving the manuscript.

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