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Past and possible future influence of the Atlantic Meridional Overturning Circulation on the climate responsible for concentration of geopolitical power and wealth in the North Atlantic region

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Abstract

Previous research has shown that nations that controlled global-scale empires over the most recent centuries and presently possess great per-capita wealth are in Earth's two largest regions of regular moderate rainfall. That rainfall regime is the pattern of atmospheric precipitation most supportive of agriculture and water-wheel-powered industry, both of which presumably contributed to those nations' advancement. Those regions of regular moderate rainfall ring the North Atlantic, and this article reviews the evidence that the Gulf Stream delivers warm vapor-releasing water in the upper limb of the Atlantic Meridional Overturning Circulation, generating the distinctive climate of western Europe and eastern North America. Ocean circulation's control on continental climate has thus contributed significantly to the Euro-American concentration of wealth and geopolitical power that has dominated the last few centuries of human history. However, comparison of the present apparent weakening or failure of the Atlantic Meridional Overturning Circulation with both the early Holocene 8.2 ka event and modeling of the Atlantic Meridional Overturning Circulation's diminished generation of water vapor suggests that Europe and eastern North America may lose their beneficent climate pattern as rainfall there lessens.

Keywords

Atlantic Meridional Overturning Circulation, global overturning circulation, climate, atmospheric precipitation, rainfall, Europe, North Atlantic, Gulf Stream, oceanography, empire, wealth

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Introduction

The influence of climate on civilization, and conversely of civilization on climate, has been a topic of great interest over the past few decades. Examples of climate's impact on civilization(s) range in space and time from the Arabian Peninsula at 5.9 ka BP (Parker et al., 2006) to China at 4.1 ka BP (Liu and Feng, 2012) to Namibia at 1.8 ka BP (Sletten et al., 2013) to Belize at 850 BP (Akers et al., 2016). However, humans' impact on climate may have begun more than 6000 years ago (Ruddiman et al., 2015) and is widely recognized today (e.g. IPCC, 2014). Most proposed examples of the influence of climate on civilization were decadal in scale and thus were "events" that had impacts on human history well before the present. One long-term and contemporaneous example has been the concentration of wealth and geopolitical power in the North Atlantic basin attributed by Railsback (2017) to that region's coincidence with Earth's two largest areas of regular moderate rainfall (Figure 1).

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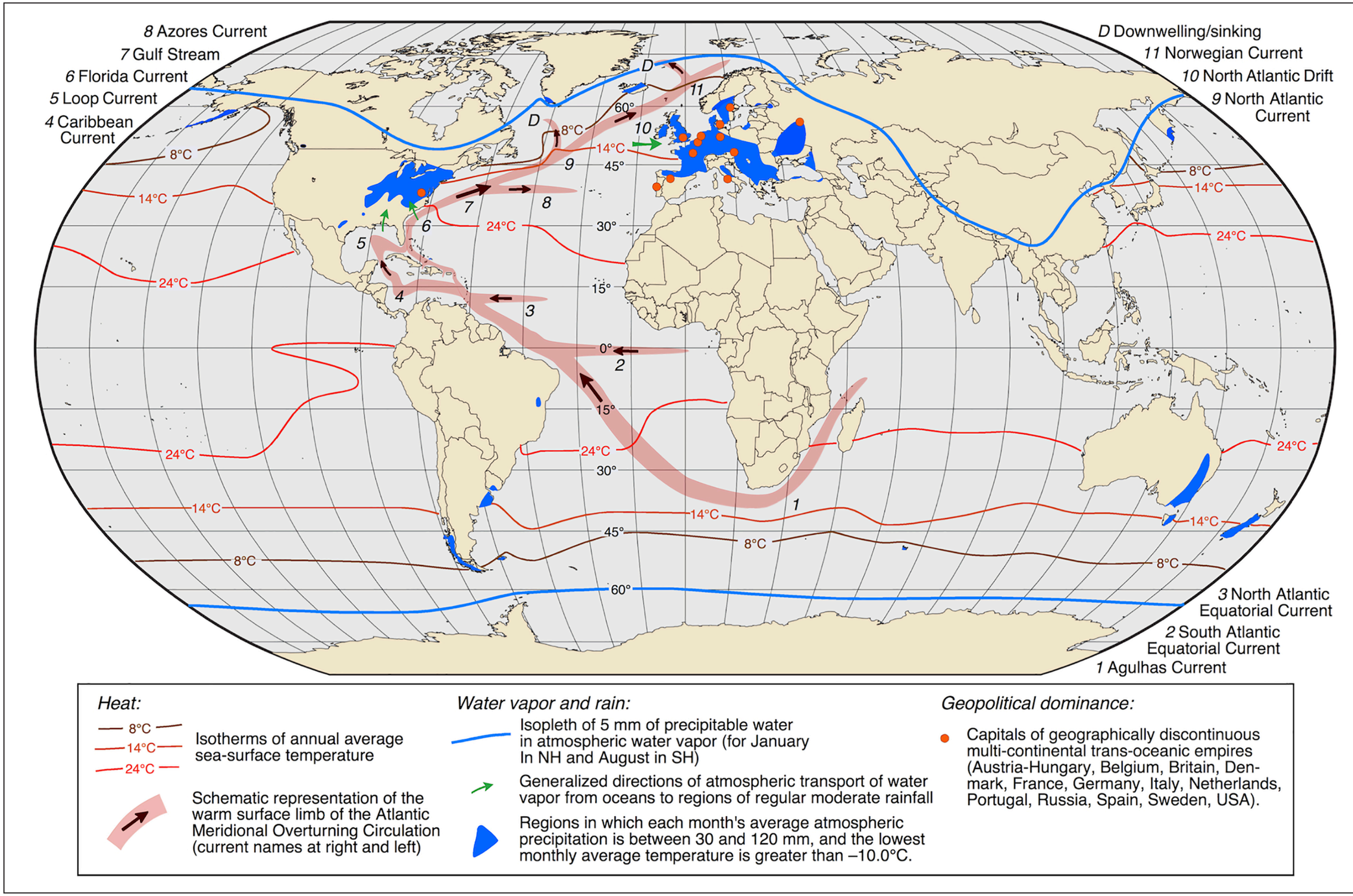

Figure 1. World map showing oceanographic, climatic, and geopolitical features discussed in sections "The AMOC, atmospheric water vapor, and regular moderate rainfall" and "Warming, meltwater, and weakening of the AMOC." Isotherms are from the map of annual mean sea-surface temperature (1982–1995) produced by the US National Weather Service Climate Prediction Center as presented at http://app.earth-observer.org/data/basemaps/images/global/ModernSST_512/ModernSST_512.html (accessed 29 November 2017). Schematic portrayal of AMOC is from Rahmstorf (2000, 2006), Curry and Mauritzen (2005), Richardson (2008), and Rasmussen et al. (2016), from Figure 2, and from NASA visualizations of Global Sea-Surface Currents and Temperature at https://svs.gsfc.nasa.gov/vis/a000000/a003900/a003912/. Isopleths for precipitable water are from the NCEP/NCAR Reanalysis Project of 1959–1997 climatologies as animated by the Department of Geography of the University of Oregon as presented at http://climvis.org/anim/maps/global/pwat.html. The three green arrows are from Oort (1983) and Akers (2016). Areas of rainfall and national capitals are from Figure 2 of Railsback (2017). The underlying map is a Robinson projection made available by the University of Alabama Cartographic Research Laboratory.

Railsback (2017) focused solely on land and rainfall in making the argument that nations holding geographically discontinuous multicontinental transoceanic empires coincided remarkably with Earth's largest regions where each month's average atmospheric precipitation is between 30 and 120 mm/month. This article moves forward from Railsback (2017) in two ways. First, it reviews evidence connecting the hydroclimate of the North Atlantic region to ocean circulation in the North Atlantic itself, and specifically to the Atlantic Meridional Overturning Circulation (AMOC). Second, it considers the possible impact of changes in the AMOC on the North Atlantic region's historically unique hydroclimate.

The AMOC, atmospheric water vapor, and regular moderate rainfall

The presence of Earth's two largest regions of regular moderate rainfall around the North Atlantic (Figure 1) is not the only respect in which the latter is climatologically unique. Regular moderate rainfall requires a constant poleward transfer of warm seawater from the equatorial and tropical zones to generate abundant atmospheric water vapor in an extra-tropical region. The North Atlantic is climatologically unique in being the region in which significant precipitable water vapor (defined here as $\geqslant$5 mm of precipitable water) reaches farthest poleward in winter, as shown by the blue isopleths in Figure 1. Meteorological patterns (e.g. Oort, 1983, as presented in Broecker, 1991; NASA, 2014) and isotopic data (e.g. Akers, 2016; Harvey and Welker, 2000) indicate that vapor moves eastward from the greater North Atlantic to generate the atmospheric precipitation that makes Europe exceptional in terms of regular moderate rainfall, and vapor moves northward from the Gulf of Mexico and western North Atlantic to similarly generate the regular moderate precipitation of eastern North America.

Evaporation to generate water vapor in turn depends on a warm sea surface (Faizal and Ahmed, 2011), and the North Atlantic is also exceptionally warm. For example, the only part of the world's oceans where the 24°C isotherm of annual average sea-surface temperature goes poleward of 30° latitude is the North Atlantic, the only part of the world's oceans where the 14°C isotherm goes poleward of 45° latitude is the North Atlantic, and likewise, the only part of the world's oceans where the 8°C isotherm goes poleward of 60° latitude is the North Atlantic (as is shown by the brown to red isotherms in Figure 1).

The exceptional warmth of the North Atlantic results from the exceptional warmth and jet-like flow of the Florida Current along the coasts of Florida, Georgia, and South Carolina (Shoosmith et al., 2005) into the Gulf Stream (Figure 2). Like all western boundary currents, the Gulf Stream *sensu lato* (the Florida Current, Gulf Stream *sensu stricto*, and North Atlantic Current) moves water previously warmed in the equatorial zone poleward (Imawaki et al., 2013), but it is the strongest western boundary current, with flow estimated to be as much as 150 Sv (Sverdrups, 10^6 m/s; Hogg, 1992). It thereby induces the greatest poleward heat flow of the oceans (Figure 1 of Ganachaud and Wunsch, 2000). The Gulf Stream's contribution to Europe's exceptional warmth has long been recognized (e.g. Maury, 1855; Rahmstorf, 2000, but see also Seager et al., 2002), but the Gulf Stream's responsibility for Europe's exceptional pattern of atmospheric precipitation has gone largely unappreciated (e.g. Link and Tol, 2004). The Gulf Stream's linkage to atmospheric vapor is, however, apparent from maps of sea-surface evaporation, in that regions of great evaporation extend farther poleward in the North Atlantic than in any other ocean basin (Yu, 2007; Figure 3).

The Gulf Stream is the most recognizable component of the AMOC, the surface limb of which brings warm and saline water to the far North Atlantic from the South Atlantic, which in turn receives such water from the Indian Ocean (Richardson, 2007) and perhaps even the tropical Pacific (Gordon, 1986; Box 1 of Marshall and Speer, 2012) (Figure 1). The AMOC thus distinguishes the entire Atlantic as the ocean in which heat transfer is from south to north across the equator, rather than from the equator toward the polar regions, as in the Pacific (Vellinga and Wood, 2002). This northward transfer of warm water is favored by a series of geographic coincidences that include the low latitude of Cape Agulhas at the southern tip of Africa (allowing warm water to move from the Indian Ocean to the South Atlantic), the location at 5°S of the Ponta do Calcanhar, the northeastern tip of South America (favoring splitting of warm equatorial currents toward the northern rather than southern Atlantic), and the partial enclosure of the Caribbean Sea and Gulf of Mexico (basins in which waters warm and become more saline with evaporation during a tropical detour on their trip to the North Atlantic) (Figure 1). The later Holocene regular moderate rainfall at the margins of the North Atlantic, which Railsback (2017) suggested may have facilitated the development of overseas empires, is thus favored by a series of geographic coincidences thousands of kilometers to the south that are ultimately rooted in the breakup of Gondwanaland beginning about 160 million years ago (Norton and Sclater, 1979; Xu et al., 2012) and in the closure of the Tropical American Seaway (Collins et al., 1996) or Pacific-Caribbean Seaway (Coates et al., 2004) in the last 10 million years.

The AMOC's warm saline water in the Florida Current moves into the northern Atlantic as (in succession) the Gulf Stream, the North Atlantic Current, the North Atlantic Drift, and finally the Norwegian Current (Figure 1). Cooling, and perhaps mixing with cold seawater moving

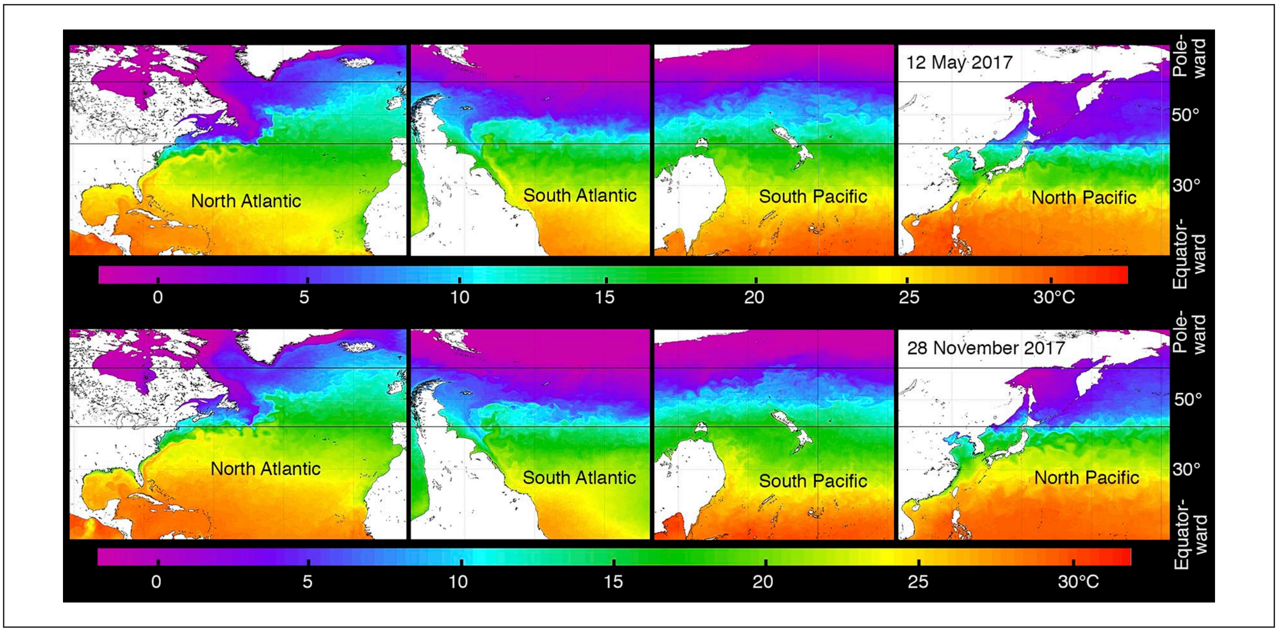

Figure 2. Maps of sea-surface temperature in and around the western boundary currents on days in 2017 approximating the climatic equinoxes in May (upper four panels) and November (lower four panels). The middle panels, for the Southern Hemisphere, are inverted so that all panels have poleward to the top and warm currents on the left. Poleward streams of orange and yellow (T ⩾ 24°C) are the most visible expressions of western boundary currents; note that the Gulf Stream (leftmost panels) is the most distinct such plume and extends farthest poleward (the lower black line in each row provides a comparator). Note that the poleward limit of ~10°C water in the North Atlantic, which results from Gulf Stream transport, is similarly the most poleward such water (the upper black line in each row is a comparator). Maps are from US National Oceanographic and Atmospheric Administration (NOAA) Sea-Surface Temperature (SST) Contour Charts webpage at http://www.ospo.noaa.gov/Products/ocean/sst/contour/index.html as accessed on the days shown.

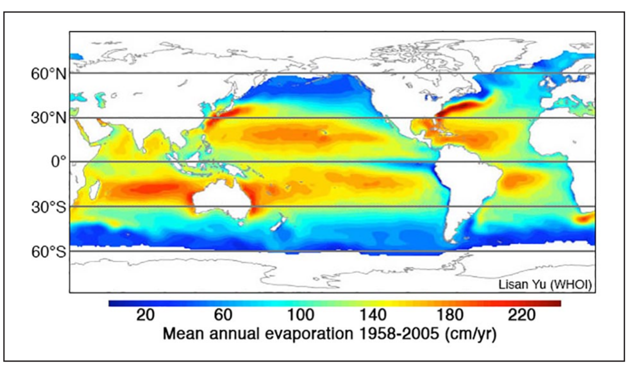

Figure 3. Map of mean annual sea-surface evaporation for the period from AD 1958 to AD 2005. Note that the areas of considerable evaporation extended farther poleward in the North Atlantic than in other ocean basins, and that the most poleward areas of greater evaporation (light blue at 45–75°N) follow the paths of the North Atlantic Drift and Norwegian Current in Figure 1. Image is modified from the COMET website, which requires the statement that "The source of this material is the COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR), sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce (DOC). ©1997–2017 University Corporation for Atmospheric Research. All Rights Reserved." See also Yu (2007).

south from the Arctic, causes that saline water to sink largely if variably in the Labrador Sea and in the Nordic Seas between Iceland, Greenland, Svalbard, and Norway (Bailey et al., 2005; Broecker, 1991; Rahmstorf, 2006). The resulting deep water, mostly North Atlantic Deep Water (NADW), then moves southward as the cold deep limb of the AMOC, and it remains recognizable into the South Atlantic to at least 45°S (Figure 2 of Broecker, 1991). The sinking in the North Atlantic is believed to drive the surface system, "drawing [warm] water northward like the plug-hole of a bath" (Rahmstorf, 2000). The supply of water vapor to Europe thus depends on northward movement of warm water from the central and southern Atlantic that in turns depends on the AMOC's sinking of cooled saline seawater in the North Atlantic.

Warming, meltwater, and weakening of the AMOC

Broecker (1991) observed that influx of fresh water to the North Atlantic can weaken or stop the AMOC. Pleistocene examples may include both in-situ generation of meltwater from abundant icebergs during Heinrich events and, in contrast, diversion of Laurentide Ice Sheet meltwater from the Mississippi River to the St. Lawrence Seaway and thus

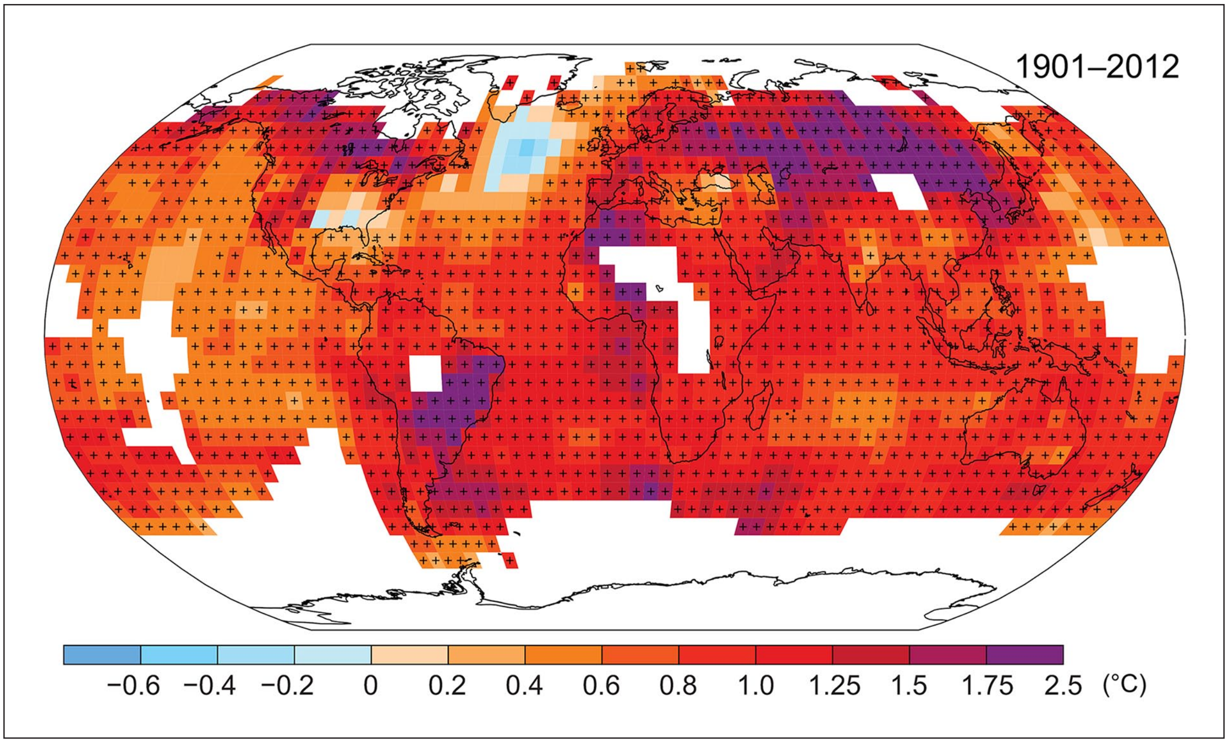

Figure 4. Map showing temperature change from 1901 to 2012 in 5° cells across Earth's surface (IPCC, 2013). "+" indicates cells with most robust results; white indicates cells for which acceptable records were not available. Note that the only regions with decreases were the North Atlantic and the US coast of the Gulf of Mexico.

to the North Atlantic during the Younger Dryas (Lynch-Stieglitz, 2017, and sources cited therein). The most striking Holocene example is the 8.2-ka event, in which meltwater from Lake Agassiz abruptly drained through Hudson Bay (Clarke et al., 2004) and briefly stopped the AMOC (Hoffman et al., 2012), leading to drought across much of the Northern Hemisphere (Alley et al., 1997).

This linkage of meltwater, AMOC failure, and drought is relevant to present and future rainfall around the North Atlantic because the AMOC appears to be failing in response to greenhouse-gas-induced warming and secondarily (Bakker et al., 2016) to dilution of the far North Atlantic with glacial meltwater (Curry and Mauritzen, 2005). Modeling studies suggest that meltwater, especially from the Greenland Ice Sheet, would slow the AMOC significantly (Gierz et al., 2015), and bias-corrected modeling by Liu et al. (2017) suggests that a doubling of atmospheric P_{CO_2} relative to that of 1990 would lead to collapse of the AMOC. Observations of flow confirm that hypothesis, in that Toole et al. (2017) reported a lessening of transport in the deep limb of the AMOC that carries NADW equatorward, and Rahmstorf et al. (2015) concluded that the extent of slowing of the AMOC in past few decades is unprecedented in the context of the most recent millennium.

Failure of the AMOC is relevant to the previous section of this article because it will lessen transport of warm water to the North Atlantic. Evidence of that trend is already apparent: in the IPCC (2013) map of temperature change across the entire Earth, the only two regions of cooling were a large part of the North Atlantic (the "cold blob" of Rhein et al., 2017, a region spanning at least 20° of longitude by 15° of latitude) and a smaller region in the southeastern United States just north of the path of the Loop Current in the Gulf of Mexico (Figure 4) (see also Figure 1(d) and (e) of Robson et al., 2016). These observations suggest a slowing of oceanic heat transport (as seen in the Gulf of Mexico) and lessened delivery of heat (in the North Atlantic). Because of the dependence of sea-surface evaporation on warming of the overlying air (Faizal and Ahmed, 2011), a cooler sea surface in an otherwise warming atmosphere (e.g. Figure 3(b) of Rahmstorf et al., 2015) would presumably cause decreased evaporation (the Atacama and Namib deserts in warm-latitude regions adjacent to cold coastal currents provide extreme examples). Diminished evaporation in the North Atlantic would presumably lead to less atmospheric precipitation in Europe and perhaps eastern North America and thus to a likely end of the regular moderate rainfall to which Railsback (2017) attributed that region's prosperity. This inference is supported by modeling studies, in that models of a failure of the AMOC as the result of input of freshwater to the North Atlantic indeed predict diminished precipitation, diminished precipitation surplus, and diminished net primary productivity across much of Europe (e.g. Figure 5 of Rahmstorf and Ganopolski, 1999; Figure 4 of Vellinga and Wood, 2002; Figure 6(a) of Lorenzo et al., 2009; Figures 3 and 7 of Jackson et al., 2015). Figure 4(d) and (f) of Liu et al. (2017) shows that their bias-corrected modeling suggests that diminished rainfall in Europe would accompany the AMOC collapse caused by a doubling of atmospheric P_{CO_2} relative to that of 1990.

The inference of diminished rainfall is also supported by paleoclimatological research from the Little Ice Age (LIA) and the 8.2-ka event. With regard to the former, decrease in precipitation around the North Atlantic with modern sea-surface cooling there is suggested by studies inferring diminished precipitation during the LIA in Europe (Büntgen et al., 2011; Rumsby and Macklin, 1996) and eastern North America (Thirumalai et al., 2018). However, the 8.2-ka event is probably a better analog for the coming ocean-climate configuration, both because that event's sea-surface cooling was driven by meltwater influx to the North Atlantic (rather than the sustained negative North Atlantic Oscillation of the LIA; Fohlmeister et al., 2012) and because the 8.2-ka event occurred during the early-to-middle Holocene era of relatively warm climate like that expected of the future, rather than during the widespread if not global cool phase that characterized the LIA. Considerable evidence in fact suggests a drying of climate in northern and western Europe during the 8.2-ka event (Magny et al., 2003; Prasad et al., 2009; Wicks and Mithen, 2014), although wetter conditions may have prevailed in Alpine regions where snowfall was favored (Figure 2 of Magny et al., 2003).

The prospect of diminished rainfall around the North Atlantic in the coming decades to centuries implies the end of the regular moderate rainfall to which Railsback (2017) attributed a role in the development of European or Euro-American wealth and geopolitical power. This does not dictate that oceanographic processes will cause a reversal of distribution of wealth. However, it does mean that northern Europeans, or at least those inland from rising seas, may find that global climate change initiated by their ancestors' Industrial Revolution brings not only welcome warmer winters but also drier conditions that could lead to water shortages and agricultural failures among Broecker's (1987) "surprises in the greenhouse."

Conclusion

The North Atlantic region that ruled far-flung empires in the past few centuries and that has exceptional wealth at present coincides with Earth's two largest areas of regular moderate rainfall. Regular moderate rainfall requires poleward transport of warm seawater from the equatorial and tropical zones to generate abundant atmospheric water vapor in an extra-tropical region. The upper limb of the AMOC has accomplished that transport in recent millennia, but the AMOC's weakening with global warming and meltwater influx appears likely to diminish rainfall in the region around the North Atlantic, with the effect that the region that initiated the Industrial Revolution and its transfer of carbon to the atmosphere may lose the regular moderate rainfall that seemingly facilitated its prosperity and power. The oceans have thus influenced human cultural development in the North Atlantic region in the past and may influence its sustainability in the future.

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