The Role of the Gulf Stream in European Climate

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Abstract

The Gulf Stream carries the warm, poleward return flow of the wind-driven North Atlantic subtropical gyre and the Atlantic Meridional Overturning Circulation. This northward flow drives a significant meridional heat transport. Various lines of evidence suggest that Gulf Stream heat transport profoundly influences the climate of the entire Northern Hemisphere and, thus, Europe's climate on timescales of decades and longer. The Gulf Stream's influence is mediated through feedback processes between the ocean, atmosphere, and cryosphere. This review synthesizes paleoclimate archives, model simulations, and the instrumental record, which collectively suggest that decadal and longer-scale variability of the Gulf Stream's heat transport manifests in changes in European temperature, precipitation, and storminess. Given that anthropogenic climate change is projected to weaken the Atlantic Meridional Overturning Circulation, associated changes in European climate are expected. However, large uncertainty in the magnitude of the anticipated weakening undermines the predictability of the future climate in Europe.

1. INTRODUCTION

Sverdrup balance: a theoretical angular momentum balance whereby a torque provided by wind stress causes ocean meridional transport

Winter surface air temperatures in western Europe are up to 10°C higher than the zonal mean at equivalent latitudes (**Figure 1*a***). A common assumption is that this relative warmth stems from westerly winds extracting heat from the warm Gulf Stream and its North Atlantic Current extension (**Figure 1*b***). Although there is no controversy that a maritime climate contributes greatly to the moderate winter temperatures in western Europe and that the Gulf Stream plays an important role in Northern Hemisphere climate in general, the importance of the Gulf Stream in establishing Europe's warmth relative to the zonal mean has evoked strenuous debate among oceanographers and climate scientists for more than a decade. Some have argued that Europe's moderate winter temperatures relative to the zonal mean can be explained largely by the winter release of heat accumulated during summer warming of the North Atlantic's shallow surface layer, and these scientists have inferred a subordinate role for ocean heat transport relative to the predominant southwesterly winds blowing toward Europe (Seager et al. 2002). Evidence from climate simulations led Seager (2006) to argue that it is time to toss the "urban legend" of a Gulf Stream control on Europe's anomalously warm winter climate in the rubbish bin. Others have contended that a view that underplays the role of Gulf Stream heat transport in the climate system misses fundamental processes of the coupled ocean-atmosphere system (Rhines et al. 2008). Although some controversy remains with respect to the Gulf Stream's role in setting the zonal asymmetry in Northern Hemisphere climate, neither perspective dismisses the part that the Gulf Stream plays in influencing Northern Hemisphere climate relative to a world with a more sluggish current.

The Gulf Stream heat transport is responsible for 20–30% of the total meridional heat transport at 26°N (Bryden & Imawaki 2001, Ganachaud & Wunsch 2003, Trenberth & Caron 2001) (**Figure 2**). This fraction of the total heat transport drops considerably to the north, yet there is ample evidence of an association between slowdowns of Gulf Stream transport and synchronous periods of anomalous European cooling over geological timescales. These associations are often assumed to be causally linked, although the chain of cause and effect is hardly straightforward. The aim of this review is to evaluate the question of how changes in the Gulf Stream and European climate are associated, with an emphasis on the mechanisms at play and the sensitivity of the answer to timescale.

Most of the European temperature anomaly occurs north of 40°N, where the ocean is responsible for only approximately 10% of the total meridional heat transport (**Figure 2**). Thus, it may be tempting to assume that the atmosphere and its variability exert the dominant control on Europe's climate. However, there are at least two problems with this assumption. The first is that the atmospheric transport of heat at middle and high latitudes of the North Atlantic is determined partly by upwind turbulent transfer from the ocean to the atmosphere. The second is that the strength of the Gulf Stream's heat and salt transport is linked to feedback effects in the atmosphere and other components of the climate system (Herweijer et al. 2005; Rugenstein et al. 2012; Winton 2003; Winton et al. 2009, 2013). A well-known example of these feedback effects involves the Gulf Stream's northward transport of salty waters, which prevents the buildup of freshwater at high latitudes, the expansion of sea ice, and an increase in albedo (Rhines et al. 2008).

Before exploring recent progress in understanding the role of the Gulf Stream in setting European climate, it is useful to define both halves of this relation: What is included in Gulf Stream transport, and what metrics pertaining to western European climate are within the scope of this review? The Gulf Stream provides the return flow of two circulation regimes: the North Atlantic subtropical gyre and the Atlantic Meridional Overturning Circulation (AMOC). The subtropical gyre is principally wind driven: The large-scale wind stress drives southward transport, which is approximately in Sverdrup balance in the gyre interior, and the Gulf Stream provides

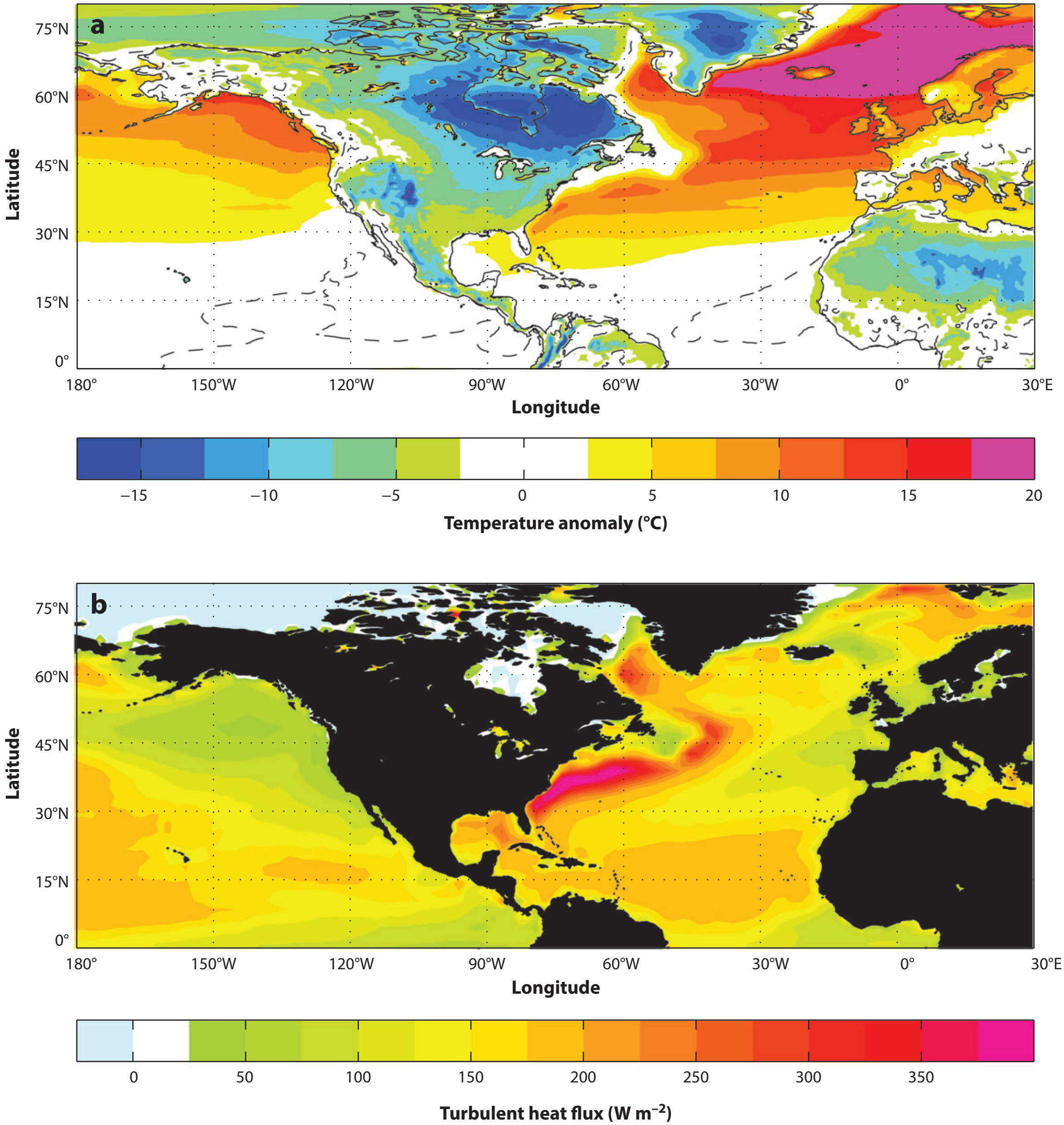


Figure 1

January climatology of the North Atlantic, Europe, and North America. (*a*) January climatological surface temperature anomalies relative to the global zonal mean, constructed from reanalysis data for the years 1981–2009 from the US National Centers for Environmental Prediction (Saha et al. 2010). (*b*) The January climatological turbulent heat flux (latent plus sensible) across the ocean-atmosphere interface calculated from the same data as in panel *a*. The sign convention is such that a positive flux indicates a warming of the atmosphere.

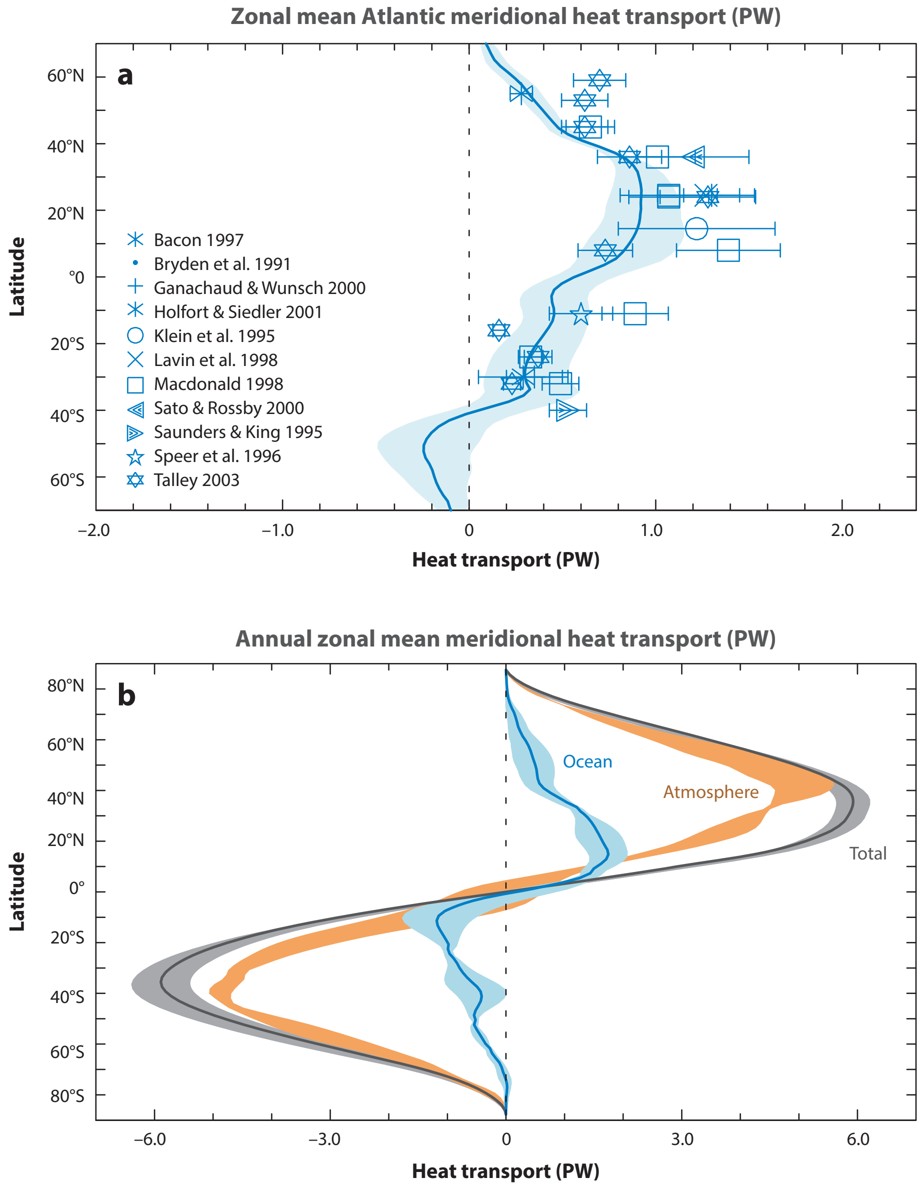


Figure 2

Integrated meridional heat transports and their uncertainty: (*a*) annual zonal mean for the Atlantic and (*b*) annual global zonal median for the ocean, the atmosphere, and the total. The associated ranges in both panels are shaded. The solid line in panel *a* is the median annual mean transport by latitude from observation-based estimates made using a combination of satellite and reanalysis products. Symbols show independent estimates of heat transport made using hydrographic section data and inverse methods. Panel *a* adapted from Trenberth & Fasullo (2008); panel *b* adapted from Fasullo & Trenberth (2008).

the poleward closure for this equatorward transport (Stommel 1958). In this respect, the Gulf Stream is similar to all subtropical western boundary currents, which provide a poleward return flow for their gyres' wind-driven transport; however, the Gulf Stream is exceptional in that it also includes a flow-through component that does not recirculate at subtropical latitudes but rather continues poleward as the shallow return branch of the AMOC (e.g., Rayner et al. 2011, Schmitz & McCartney 1993, Worthington 1976). These relatively warm throughput waters eventually reach subpolar latitudes and the Nordic Seas, where heat and freshwater exchange with the atmosphere and sea ice transform them into the North Atlantic Deep Water, which is exported in the deep limb of the AMOC (Hansen & Østerhus 2000, Schmitz & McCartney 1993, Smethie & Fine 2001). Because the Gulf Stream carries the shallow limb of the AMOC, I consider any influence of AMOC variability on European climate to be within the scope of this review.

Radiative forcing: a net imbalance between the energy received by Earth and that radiated back to space

As for European climate metrics, this review focuses on surface air temperature, with precipitation and storminess addressed to the degree that observational and modeling studies permit. It addresses the time period spanning the transition to the current interglacial through projections out to the year 2100. Variability in European climate and the Gulf Stream are likely more dramatic on timescales even longer than those discussed here. For instance, the existence of the Gulf Stream in the early Cenozoic (65–56 Mya) is recorded in sedimentary strata (Kaneps 1979, Pinet et al. 1981), the Northern Hemisphere was strikingly warmer at that time than it is now (Greenwood & Wing 1995), and idealized models have suggested that ocean heat transport played an important role in establishing this warm northern climate (Rose & Ferreira 2012). Because quantitative assessments of European climate anomalies, Gulf Stream heat transport, and the synchrony of their timing degrade with increasing time before present (Wunsch 2006), I emphasize here the more recent past, the present, and predictions of the near future.

To date, scientists exploring questions related to the influence of ocean heat transport on climate have used a diversity of resources, including in situ, satellite, and proxy observations of the ocean and atmosphere; numerical models of varying complexity; and blends of models and data provided by ocean and atmosphere reanalysis products. This review seeks to synthesize the insights provided by these tools and is organized by timescale rather than by method of investigation. The next section discusses hypotheses about the Gulf Stream's influence on European climate on millennial to centennial timescales, starting at the transition to the current interglacial climate. The remainder of the review explores the Gulf Stream's contribution to European climate variability at interannual to decadal scales (Section 3) and in response to anthropogenic climate change over the coming decades (Section 4). Section 5 summarizes and offers an outlook for the future.

2. GULF STREAM–EUROPEAN CLIMATE ASSOCIATIONS SINCE THE TRANSITION TO THE CURRENT INTERGLACIAL

The ocean acts as the flywheel of the global climate, its large mass and heat capacity tempering the rapidity of global swings in surface air temperatures during transient anomalies of radiative forcing. However, it is the ocean's potential to cause rapid climate change that has often captured the scientific and public imagination, with the most famous example provided by the hypothesis that variations of Gulf Stream heat transport cause abrupt climate fluctuations in northern latitudes (Broecker et al. 1990). Such fluctuations in Northern Hemisphere climate were common throughout the last glacial period (Dansgaard et al. 1982), and they have occurred several times since the Last Glacial Maximum (Masson-Delmotte et al. 2013). There is a vast literature exploring the connection between the AMOC component of Gulf Stream heat transport and Northern Hemisphere climate anomalies during the current interglacial period and last glacial period as well as on even longer timescales (for a review, see Rahmstorf 2002). Here, I emphasize the more recent period, during which the absolute dates of the sedimentary proxies used to reconstruct ocean circulation and climate are abundantly available and remove one element of uncertainty linking these phenomena.

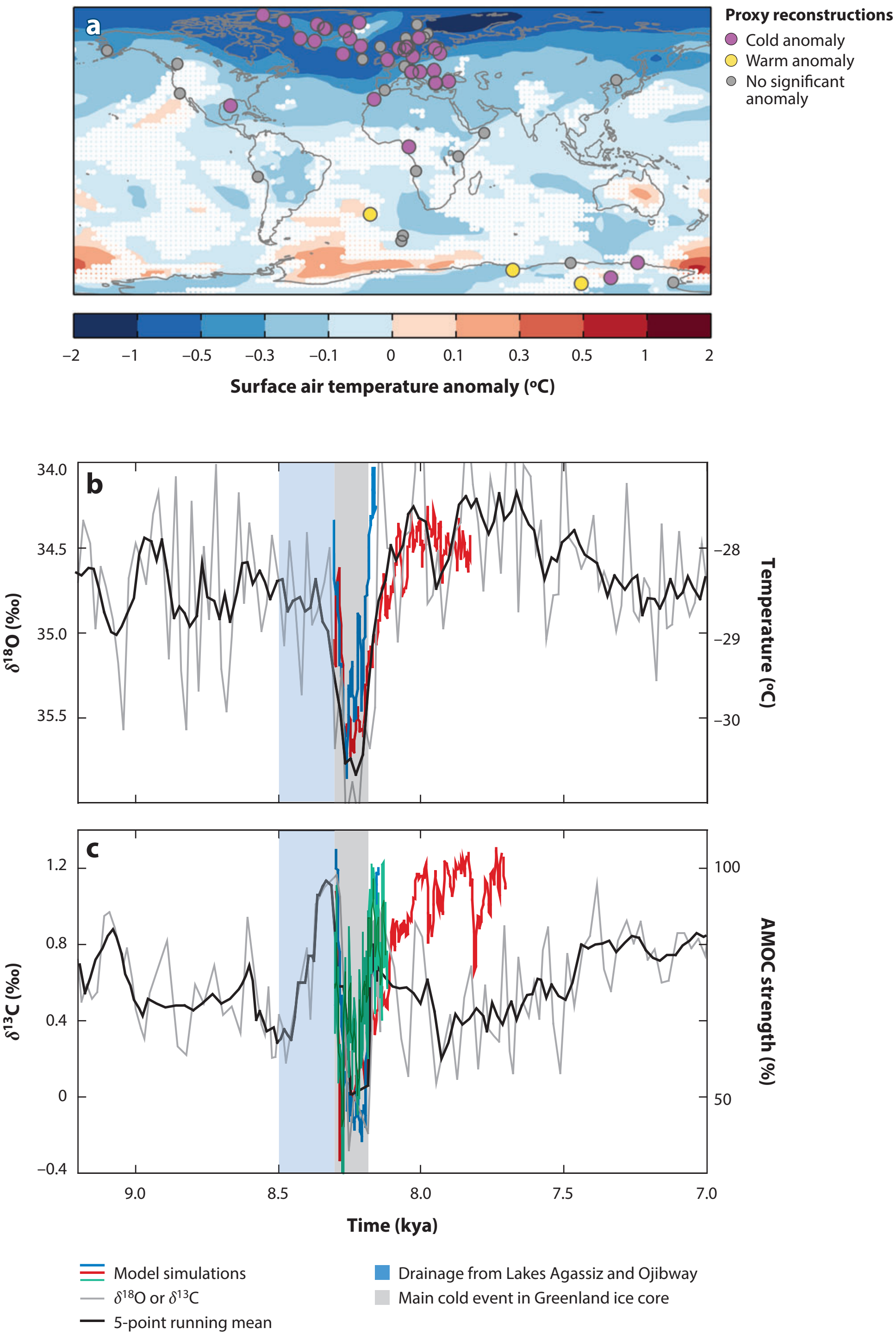
Holocene: a geological epoch that began approximately 12 kya and is identified with the warm period of the current interglacial

The long-term melting of the North American and Eurasian ice caps in the transition to the current interglacial lasted from approximately 15 to 8 kya. This period was marked by two abrupt transitions between relatively warm and near-glacial conditions in the North Atlantic and Europe. Each climate swing began in a matter of decades, lasted for several hundred years to a millennium, and ended as abruptly as it began. The first and more severe of these cold events, the Younger Dryas, started approximately 12.8 kya and ended about 1,000 years later with an abrupt warming of several degrees over a few decades (Berger 1990, McManus et al. 2004). A compilation of more than 100 high-resolution proxy records during the Younger Dryas revealed the Northern Hemisphere–wide geographic extent of the cooling, which ranged from 2°C to 5°C below the temperatures of the preceding Allerød warm period (Shakun & Carlson 2010). Recent high-resolution proxies spanning the Younger Dryas event added subtlety to the record, suggesting that approximately 170 years after the initial cooling of northern Europe, which was synchronous with cooling around Greenland, a dramatic aridification of northern Europe occurred (Rach et al. 2014). The lagged drying of Europe is thought to be caused by the southward expansion of sea ice following the initial cooling, which changed the atmospheric circulation and associated rainfall patterns. The warm period following the Younger Dryas period was again interrupted by a weaker cooling event 8.2 kya (Barber et al. 1999). The European climate fingerprint of the 8.2-kya event is also well established: For approximately 150 years, Greenland and European mean temperatures plummeted by more than 1°C below the background Holocene climate (**Figure 3*a***).

Myriad proxies from sediment cores suggest that variations in Gulf Stream transport are coincident with swings in European climate over the past 15,000 years (for a review of these proxy records and their relationship with transport rates in the ocean, with an emphasis on the Last Glacial Maximum, see Huybers & Wunsch 2010). For example, ^{231}Pa/^{230}Th ratios suggest that the rate of North Atlantic Deep Water export in the deep branch of the AMOC was reduced during Younger Dryas cooling, implying an equal reduction in the mass flux of the shallow branch of the AMOC (McManus et al. 2004). Oxygen isotopes of benthic foraminifera straddling the Gulf Stream on either side of the Florida Straits are consistent with a smaller temperature contrast across the

Figure 3

Signatures of the 8.2-kya cooling event from sediment proxies and model reconstructions. Model simulations were initialized with preindustrial conditions and perturbed with a prescribed 2.5-Sv meltwater pulse (1 Sv = 10^6 m^3 s^{-1}) applied for 1 year, based on best estimates of the flux from Lakes Agassiz and Ojibway from Clarke et al. (2004). (*a*) Multimodel mean surface air temperature anomalies relative to a control simulation without the prescribed meltwater pulse, averaged over the first 50 years following the pulse. White squares indicate regions where fewer than three models agree on the sign of change. Colored circles show paleoclimate data from records resolving the 8.2-kya event. (*b*) North Greenland Ice Core Project δ^{18}O (a temperature proxy) from the Greenland Summit Station. The blue and red lines represent simulated Greenland temperatures in two model ensembles with the prescribed meltwater pulse, the shaded blue area shows the published age constraints for the period of freshwater release from Lakes Agassiz and Ojibway, and the shaded gray area shows the time of the main cold event as found in Greenland ice core records (Thomas et al. 2007). (*c*) *Cibicides wuellerstorfi* δ^{13}C (a deepwater ventilation proxy) at 3.4-km water depth south of Greenland. The colored lines represent modeled changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) in three coupled climate models subjected to the prescribed meltwater pulse. The observational (*black*) curve and simulated (*colored*) curves are subjectively aligned at the first decrease in the time series. Figure adapted from Masson-Delmotte et al. (2013).


a
Proxy reconstructions
Cold anomaly
Warm anomaly
No significant anomaly
−2
−1
−0.5
−0.3
−0.1
0
0.1
0.3
0.5
1
2
Surface air temperature anomaly (°C)
b
34.0
34.5
35.0
35.5
δ18O (‰)
−28
−29
−30
Temperature (°C)
c
1.2
0.8
0.4
0
−0.4
δ13C (‰)
100
50
AMOC strength (%)
9.0
8.5
8.0
7.5
7.0
Time (kya)
Model simulations
δ18O or δ13C
5-point running mean
Drainage from Lakes Agassiz and Ojibway
Main cold event in Greenland ice core

straits during the Younger Dryas, which is interpreted as a reduced density gradient and smaller geostrophic Gulf Stream transport (Lynch-Stieglitz et al. 2014). This reduced geostrophic Gulf Stream transport could be associated with a slowdown in either the AMOC or wind-driven components of the Gulf Stream. Nutrient proxies from carbon isotopes and cadmium suggest that during the Younger Dryas the deep North Atlantic was filled with high-nutrient waters (Boyle & Keigwin 1987), an indicator that this area of the ocean was more sluggishly ventilated and, thus, that AMOC transport was reduced. Many of these proxies show similar anomalies during the 8.2-kya cold event (**Figure 3*b*,*c***).

No consensus has emerged on what triggered the Gulf Stream slowdown during the Younger Dryas. The slowdown has long been attributed to a stratifying pulse of meltwater flowing from the disintegrating Laurentide Ice Sheet that prevented the formation and export of North Atlantic Deep Water and the associated import of warm surface waters (Fairbanks 1989), but direct evidence for the flooding mechanism is lacking (Broecker 2006). Alternative triggers include a perturbation to the jet stream position in response to the change in ice sheet configuration, which may have enhanced precipitation and stabilized the water column in the North Atlantic (Eisenman et al. 2009). By contrast, the 8.2-kya event was clearly preceded by the drainage of freshwater from Lakes Agassiz and Ojibway in North America (Barber et al. 1999). After the AMOC slows, a self-amplifying feedback may take hold whereby the reduced advection of salty water in the AMOC's shallow limb further freshens the high-latitude ocean and leads to the prolonged suppression of convection (Rahmstorf 1996, Stommel 1961). A sluggish AMOC also reduces the transport of warm waters, ostensibly destabilizing the water column and balancing the stratification owing to freshwater buildup. However, at low seawater temperatures, salinity variations dominate density variations, and the buildup of a halocline is not easily overcome by a reduction in heat transport convergence in these high latitudes. Moreover, any ocean heat transport convergence anomaly tends to be damped by altered air-sea heat fluxes; as such, a sluggish heat transport is unlikely to help initiate convective heat loss to the atmosphere.

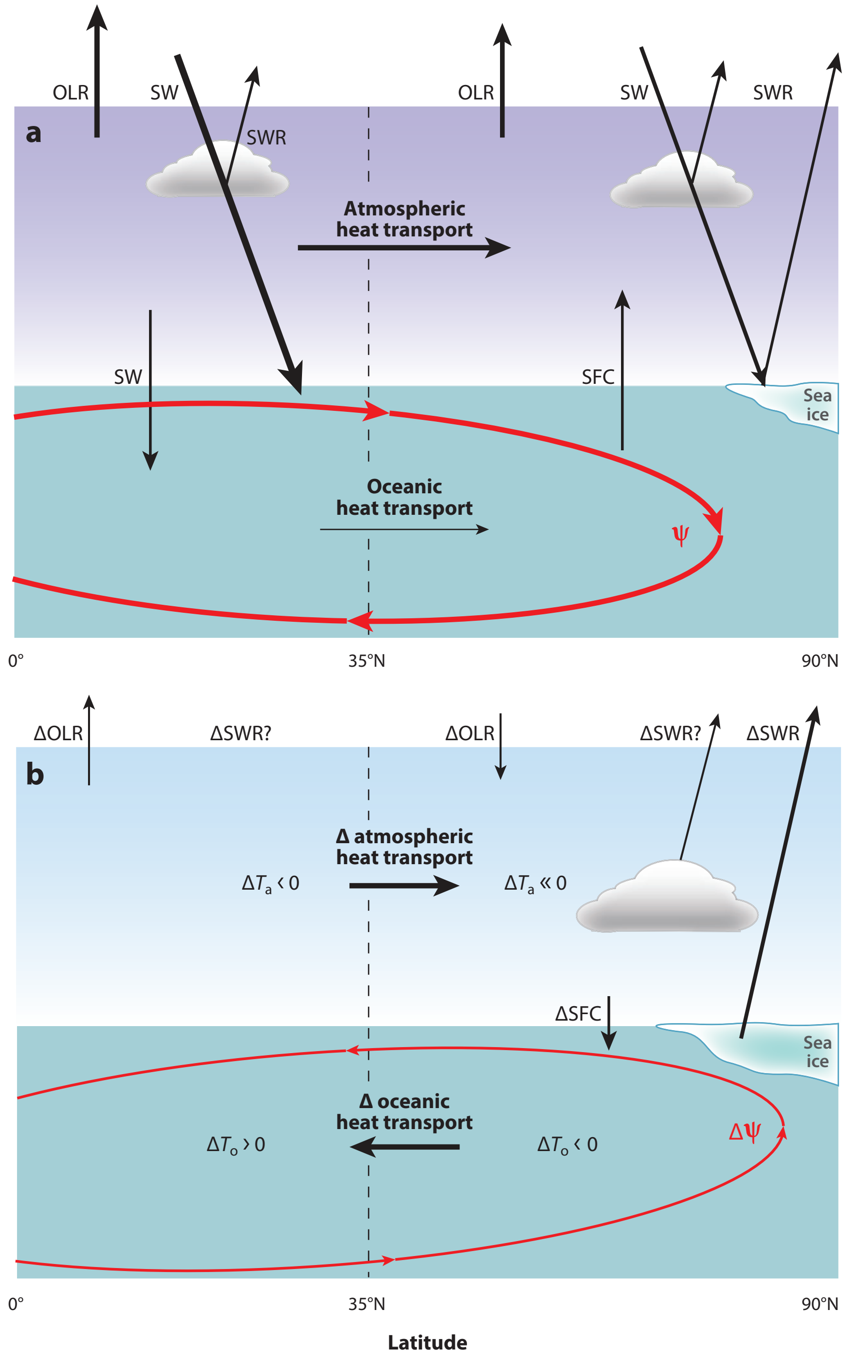
Although the precise trigger for an AMOC slowdown during the Younger Dryas period remains controversial, the remarkable consistency among independent proxies has led to consensus that AMOC variations and abrupt climate change in the Northern Hemisphere are coincident in time for the dramatic Younger Dryas and 8.2-kya events. In turn, climate model simulations offer a framework for evaluating whether these phenomena are causally linked. One simple test is to compare atmospheric general circulation model simulations with and without a representation of meridional ocean heat transport in the oceanic boundary condition. The results of such simulations led Seager et al. (2002) to their conclusion that heat transport by the Gulf Stream is not the cause of the zonal asymmetry in winter temperatures, as the cooling associated with their idealized removal of AMOC heat transport was to some extent zonally symmetric.

However, these same simulations clearly showed that ocean heat transport does exert an important control on Europe via its influence on the entire Northern Hemisphere climate: The absence of ocean heat transport cooled the region north of 35°N by an average of 4.5°C in a model in which the sea ice cover was fixed and by 6.5°C in a model in which sea ice responded thermodynamically to the heat transport difference (Clement & Seager 1999). Similar results have been reproduced in more comprehensive global climate models employing different methods to remove or reduce ocean heat transport (Herweijer et al. 2005). Moreover, although Seager et al. (2002) emphasized a large degree of zonal symmetry in the response to the removal of AMOC heat transport, the largest cooling was indeed zonally asymmetric: In the simulation that allowed for a thermodynamic sea ice response, the Nordic Seas and parts of northern Europe (i.e., the Scandinavian Peninsula) cooled by more than 20°C, more than any other locale at the same latitude. This region is located precisely where the modern zonal winter temperature anomaly is maximized (**Figure 1**), and it coincides with the region of maximum cooling in response to freshwater perturbation simulations mimicking the 8.2-kya event (**Figure 3**). Therefore, it is wrong to use these model results as a basis for entirely dismissing the role of ocean heat transport in establishing northern Europe's temperature departure from the zonal mean.

That the effect of the ocean heat transport on air temperatures is mediated through climate feedbacks is clear from the large differences in the extent of the surface air temperature cooling between simulations with fixed sea ice and those with thermodynamically responsive sea ice (Seager et al. 2002). When the simulated ocean transports a large amount of heat and salt to northern high latitudes, the effect is to push the sea ice edge further north, thereby reducing the planetary albedo, resulting in enhanced warming at high northern latitudes, a reduction in the area of snow on land, and a consequent warming of the global mean climate (Herweijer et al. 2005, Stouffer et al. 2006). Such feedback effects are essential in explaining the difference between Northern Hemisphere climate conditions in models in which ocean heat transport is suppressed and those in which it is included, because a strengthening of the atmospheric heat transport efficiently compensates for the reduction in oceanic heat transport (**Figure 4**). General circulation models have repeatedly demonstrated this compensation (Herweijer et al. 2005, Rose & Ferreira 2012, van der Swaluw et al. 2007, Zelinka & Hartmann 2012).

In addition to the amplifying effect of the sea ice–albedo feedback, water vapor and cloud feedbacks are likely key factors in explaining why a small reduction in total meridional heat transport can trigger a relatively large cooling in Northern Hemisphere climate. A cooler atmosphere has a lower water-holding capacity, so absolute humidity decreases in response to the cooling effect of the albedo increase. Because the absorption of long-wave radiation (i.e., greenhouse trapping) increases roughly logarithmically with atmospheric water vapor content, this humidity decrease leads to a net cooling in simulations with reduced or eliminated ocean heat transport (Herweijer et al. 2005). In the models, the reduction or elimination of meridional ocean heat transport also leads to an expansion of the dry subtropical regions, introducing a dynamical mechanism to reduce greenhouse trapping in addition to the thermodynamical response to the overall cooling (Herweijer et al. 2005). In contrast to the global mean decrease in water vapor caused by cooling, temperatures in the deep tropical ocean (and the overlying atmosphere) rise in response to diminished export of heat out of these latitudes in the models analyzed by Herweijer et al. (2005). However, here, the atmosphere is nearly saturated in water vapor regardless of the strength of the meridional ocean heat transport, so the warming increases simulated convective precipitation while producing little change in the greenhouse trapping caused by water vapor. Hence, in the Northern Hemisphere mean, the water vapor content of the atmosphere and its opacity to outgoing long-wave radiation decreases with a more sluggish ocean overturning circulation.

The cloud feedback in response to changes to the overturning circulation is more model dependent and meridionally variable than the water vapor feedback. Indeed, even the sign of the cloud-albedo feedback is sensitive to model configuration (Herweijer et al. 2005, Rugenstein et al. 2012). However, the change to the radiative balance is typically dominated at low latitudes by water vapor feedbacks (Herweijer et al. 2005, Zelinka & Hartmann 2012) and at high latitudes by changes in the surface albedo, such that the uncertainty in the cloud feedback does not disturb the overall picture of cooling associated with weakened ocean heat transport. At higher latitudes (40–60°N), models generally agree that reduced meridional ocean heat transport leads to enhanced cloud cover at lower levels of the atmosphere. This enhanced low cloud cover may result from a strengthened lower-atmospheric stability caused by a greater meridional sea surface temperature (SST) gradient (Winton 2003). This mechanism is consistent with observational analyses that have shown that the amount of low cloud cover increases with the static stability of the lower troposphere at the seasonal timescale, because the more stable atmosphere suppresses entrainment of drier air from


OLR
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Latitude

above the boundary layer (Klein & Hartmann 1993). The low clouds reflect a greater proportion of incoming shortwave radiation back to space (**Figure 4*b***) while changing the greenhouse trapping little and therefore cooling the climate.

In sum, models suggest that the combined effect of cloud, water vapor, and sea ice feedbacks leads to a dramatic cooling of the high latitudes under a weaker or collapsed meridional ocean heat transport. This cooling, in turn, reduces the total outgoing long-wave radiation. Although many of the studies that have elucidated these processes have compared simulations without any ocean heat transport to those with a prescribed heat transport similar to modern observational values (Herweijer et al. 2005, Seager et al. 2002), the same general picture holds when the AMOC heat transport is perturbed in a more isolated way (Rugenstein et al. 2012, Stouffer et al. 2006). Thus, paleoclimate reconstructions and model simulations collectively indicate that changes in meridional ocean heat transport in general, and in AMOC heat transport more specifically, can trigger large changes to Northern Hemisphere climate on centennial to millennial timescales. These changes are mediated through multiple complex feedback effects with the atmosphere and sea ice, as depicted schematically in **Figure 4**. Some of the feedbacks, such as those related to water vapor and clouds, may be activated quickly, whereas changes in sea ice cover may take decades or longer. Because paleoclimate data and models suggest that transitions between warm and cold states have happened abruptly (i.e., over periods as short as a single decade), one might expect to observe Northern Hemisphere climate variability responding to short-term variations in Gulf Stream dynamics in the instrumental record. The next section evaluates this expectation.

3. INTERANNUAL TO MULTIDECADAL GULF STREAM–EUROPEAN CLIMATE CONNECTIONS DURING THE OBSERVATIONAL ERA

Speculation on the causes of interannual to decadal atmospheric variability over the North Atlantic has a long lineage that can be traced to Hasselmann (1976) and Bjerknes (1964). Hasselmann (1976) surmised that low-frequency variations in climate arise when random fluctuations in weather are integrated via interaction with the ocean mixed layer. Indeed, atmospheric models can simulate realistic statistics of interannual to decadal climate variability when coupled to a slab ocean with no dynamic circulation (e.g., Hansen & Lebedeff 1987). In contrast to this minimalistic, one-dimensional view of the oceanic influence on atmospheric variability, which would preclude a role for ocean heat transport in climate variability in Europe and elsewhere, Bjerknes (1964) surmised that decadal variability in ocean circulation could lead to anomalous heat transport and an active

Figure 4

Schematic of heat budget terms in the Northern Hemisphere ocean and atmosphere. (*a*) Modern climatological conditions. (*b*) The change in these budgets when the Atlantic Meridional Overturning Circulation (AMOC) component of the Gulf Stream heat transport weakens. Note the compensation: When the meridional oceanic heat transport weakens, the atmospheric heat transport strengthens. However, the Northern Hemisphere still cools because sea ice, cloud, and water vapor feedbacks collectively increase the planetary albedo and reduce greenhouse trapping (the latter of which is depicted by the lighter color of the atmospheric box in panel *b*). At low latitudes, slight atmospheric cooling under reduced meridional ocean heat transport is, counterintuitively, paired with increased outgoing long-wave radiation. This surprising combination arises because of decreased greenhouse trapping resulting from water vapor feedbacks. Abbreviations: OLR, outgoing long-wave radiation; SFC, air-sea turbulent heat flux; SW, shortwave radiation; SWR, reflected shortwave radiation; ψ, ocean meridional stream function. Figure inspired by Herweijer et al. (2005) and Rugenstein et al. (2012), with additional insights from Rose & Ferreira (2012) and Winton et al. (2013).

role for the ocean in setting climate variability. However, given the shortness of the observational record and the multidecadal timescale for the hypothesized coupled interactions, evaluations of Bjerknes's hypothesis were limited to numerical simulations until recently. As the length of ocean reanalysis products now extends beyond the century mark (Gulev et al. 2013), observation-based evidence in support of an active role for ocean dynamics in setting atmospheric variability on decadal timescales is accumulating.

Ocean Rossby wave: a large-scale wave, often generated by wind forcing, whose restoring force depends on Earth's curvature

3.1. Interannual Variability

Recently, Gulev et al. (2013) produced a long observation-based reconstruction of SST and air-sea heat fluxes. With these data, they showed that the heat fluxes and SST are anticorrelated on a subdecadal timescale over much of the North Atlantic—i.e., cool SSTs are associated with large fluxes from the ocean to the atmosphere. This anticorrelation seems to confirm that the atmosphere sets the strength of air-sea heat fluxes on these short timescales, thus cooling the oceanic mixed layer. On decadal timescales, the correlation between heat fluxes and SST switches sign, and warm SSTs are correlated with larger fluxes. These positive correlations are consistent with ocean dynamics exerting an important influence on the sizes of the fluxes on multidecadal timescales (as is explored in Section 3.2).

If subdecadal variability in the surface ocean were at the whim of the atmosphere everywhere, then there would be no mechanism for the ocean to induce significant high-frequency climate variability. However, the atmospheric control on interannual heat flux variability postulated by Hasselmann (1976) and demonstrated statistically by Gulev et al. (2013) holds only at a distance from the Gulf Stream. In the Gulf Stream region, upper-ocean heat content anomalies are determined largely by the convergence of oceanic heat transport and are damped by air-sea turbulent exchange at interannual and shorter timescales (Buckley et al. 2014, Dong & Kelly 2004, Dong et al. 2007). These interannual variations in heat transport convergence are driven in part by the ocean's Rossby wave adjustment to fluctuations in the curl of the wind stress (DiNezio et al. 2009; for a review, see Kwon et al. 2010). Hence, the Gulf Stream stands as an exception to the nondynamic mixed-layer oceanic response proposed by Hasselmann (1976) on these short timescales. A strong influence of ocean heat flux convergence on air-sea heat fluxes was likewise suggested in a modeling study in which the Kuroshio heat transport was perturbed over a 10-year period (Yulaeva et al. 2001).

During the past 20–30 years, an increasing number of direct observations has allowed an unprecedented view of this interannual Gulf Stream variability. A bottom-mounted current meter on the container ship *Oleander* collected velocity data across the Gulf Stream at a nominal latitude of 37°N more than 750 times from 1992 to 2012 (Rossby et al. 2014); these data showed that interannual variability in the Gulf Stream transport amounts to 4.5% of the long-term mean transport, with excursions in individual years reaching 10% (Rossby et al. 2014) (**Figure 5**). Upstream, at 26°N, electromagnetically induced voltages on several undersea telephone cables have been used to produce daily estimates of the total volume transport of seawater through the Florida Straits (DiNezio et al. 2009, Larsen & Sanford 1985), and these data also show peak-to-peak variability of roughly 10% of the mean value of 31 Sv (1 Sv $= 10^6$ m^3 s^{-1}) (**Figure 5**). The coherence between anomalies in upstream and downstream transports in the Gulf Stream is not obvious over these records, although this lack of coherence is perhaps not surprising, given that recirculating streamlines of the North Atlantic subtropical gyre triple the Gulf Stream transport between the upstream and downstream monitoring sites. Any temporal anomaly in the recirculating transport may easily swamp the anomaly stemming from upstream transport. Perhaps relatedly, changes in heat content in the subpolar and subtropical North Atlantic are often out

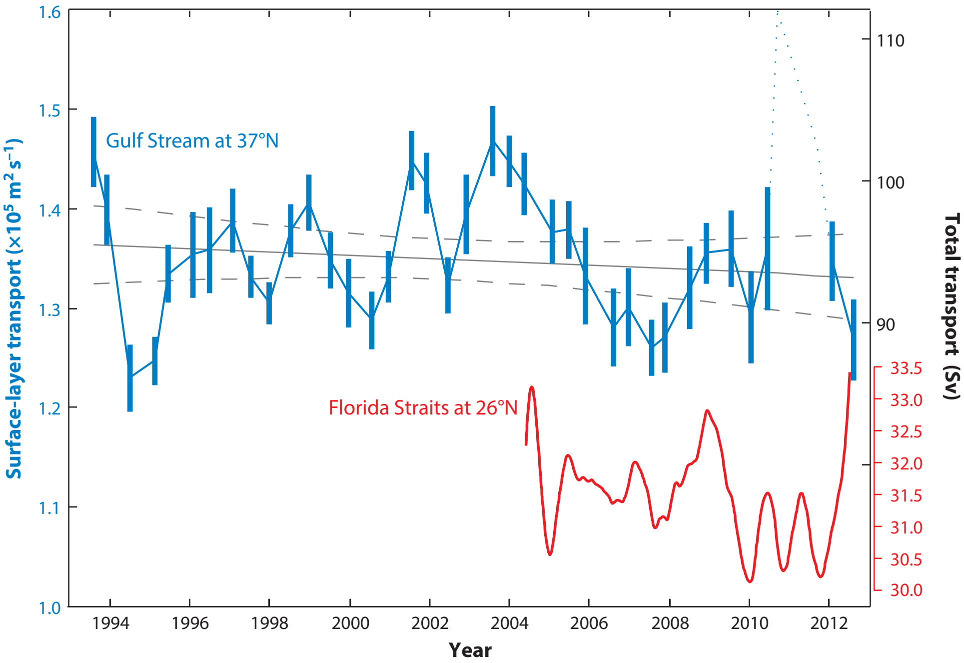

Figure 5

Direct observations of Gulf Stream transport. The blue line and bars show the Gulf Stream transport measured by the container ship *Oleander* from 1992 to 2012, nominally at 37°N (*right y-axis*; 1 Sv $=10^6$ m^3 s^{-1}) (adapted from Rossby et al. 2014). The data were annually averaged and stepped every half year. The solid gray line shows the slope of the linear least squares regression against time; the dashed gray lines indicate the 95% confidence intervals. The dotted line in 2011 reflects a scarcity of data. The red line shows Gulf Stream transport through the Florida Straits (26°N) (data from Natl. Oceanogr. Cent. et al. 2013). These data, which were reported every 12 h from April 1, 2004, to October 1, 2012, were smoothed with a six-month, shape-preserving recursive filter, with the first and last three months of filtered data excluded.

of phase (Lozier et al. 2010, Williams et al. 2014). Thus, one question that may be resolved as our observational record extends further into the future is how anomalies in Gulf Stream heat transport propagate through the North Atlantic.

The question closer to the heart of this review—to what degree the oceanic control on interannual heat flux variability over the Gulf Stream influences downwind climate variability in Europe—remains relatively little explored. Ocean-to-atmosphere heat loss over the Gulf Stream has been directly observed to reach 1,000 W m^{-2} in winter, during which time the boundary-layer height can rise by 2 km (Marshall et al. 2009). This turbulent air-sea exchange is among the strongest anywhere in the world ocean. Cloudiness, the depth of the planetary boundary layer, and the intensity of storms are all linked to these vigorous fluxes at the frontal scale of the Gulf Stream (Kelly et al. 2010). Yet drawing clear connections between this frontal-scale exchange and the basin-scale impacts that would be required to communicate Gulf Stream anomalies downstream to Europe has been extraordinarily difficult (Kwon et al. 2010). Can a 10% change in Gulf Stream transport persisting for about a year noticeably influence European climate?

Previous studies have touched on this question by characterizing the statistical relationship between European temperature and the leading modes of interannual variability in North Atlantic SST, which are tied to the North Atlantic Oscillation (Gámiz-Fortis et al. 2011, Junge &

Stephenson 2003). The implicit assumption of these studies is that oceanic variability, including that of the Gulf Stream, is communicated to the atmosphere via SST anomalies. Their conclusion is that knowledge of the SST variance yields little predictive skill for European climate on an interannual timescale. Likewise, a recent study tracking Lagrangian air parcels for 10 days preceding their arrival at the surface of four western European cities suggests that SST variability on interannual timescales contributes little to downwind climate variability in Europe, even though many of these air parcel trajectories pass over the Gulf Stream extension (A. Yamamoto, J.B. Palter, M.S. Lozier, M. Borqui & S. Leadbetter, manuscript in review). In sum, there is presently no compelling evidence that oceanic variability in the North Atlantic exerts a strong control on European climate at interannual and shorter timescales. However, many studies suggest that the ocean plays a more active role at decadal timescales.

Internal variability: variability resulting solely from the coupled dynamics of the atmosphere-ocean-biosphere-cryosphere system, independent of a forcing agent

3.2. Multidecadal Variability

The hypothesis that Gulf Stream variability influences European climate on multidecadal timescales requires that three conditions be met, each of which is challenging to observe. First, the existence of an internal multidecadal oscillatory signal in the North Atlantic must be detected. An obstacle to this detection is the relatively short instrumental record and the likelihood that this record is contaminated by anthropogenic and natural radiative forcing (Booth et al. 2012, Mann et al. 2014, Zhang et al. 2013). Such external forcing could cause coordinated climate responses in both the North Atlantic and Europe, bypassing any causal link between the ocean circulation and climate response. Second, a role for the Gulf Stream in establishing this multidecadal signal must be determined. The short length of the instrumental record of Gulf Stream transport also hampers this determination. Third, oceanic variability must be shown to induce large-scale changes in atmospheric dynamics and/or thermodynamics, the influence of which extends to Europe. Next, each of these conditions is examined in turn.

3.2.1. Detecting multidecadal variability in the North Atlantic. Multidecadal (50–70-year) variability has been repeatedly demonstrated in time series of North Atlantic SST observations (Folland et al. 1984, Kushnir 1994) and is often referred to as the Atlantic Multidecadal Oscillation (AMO). Because direct SST observations extend back just beyond the turn of the twentieth century, only one and a half cycles of the oscillation have been directly observed (**Figure 6*a***), taking place at a time of nonmonotonic change to the large-scale radiative forcing (Booth et al. 2012, Mann et al. 2014). Thus, a diversity of statistical techniques, ensembles of climate models, and extensions of the instrumental record to include paleoclimate data have been used to characterize North Atlantic internal variability (DelSole et al. 2011, Delworth & Mann 2000, Kravtsov & Spannagle 2008, Mann et al. 2014, Schlesinger & Ramankutty 1994, Terray 2012, Ting et al. 2009). Despite subtle differences among their techniques and results, each of these studies clearly shows that internal variability plays an important role in setting multidecadal North Atlantic SST variability.

3.2.2. The role of the Gulf Stream in establishing multidecadal North Atlantic sea surface temperature anomalies. It is natural to hypothesize that the detected internal variability in North Atlantic SST is caused by anomalies in AMOC heat transport that are carried by the Gulf Stream. This causality has been established in several climate models, each of which has a North Atlantic mean SST temporal variability similar to that in the observational record (Delworth & Mann 2000, Latif et al. 2004). **Figure 6*b*** shows the striking correspondence between AMOC transport anomalies and North Atlantic mean SST for one such climate model. A recent study questioned the earlier separation of internal and forced variability, arguing that aerosol forcing was the primary

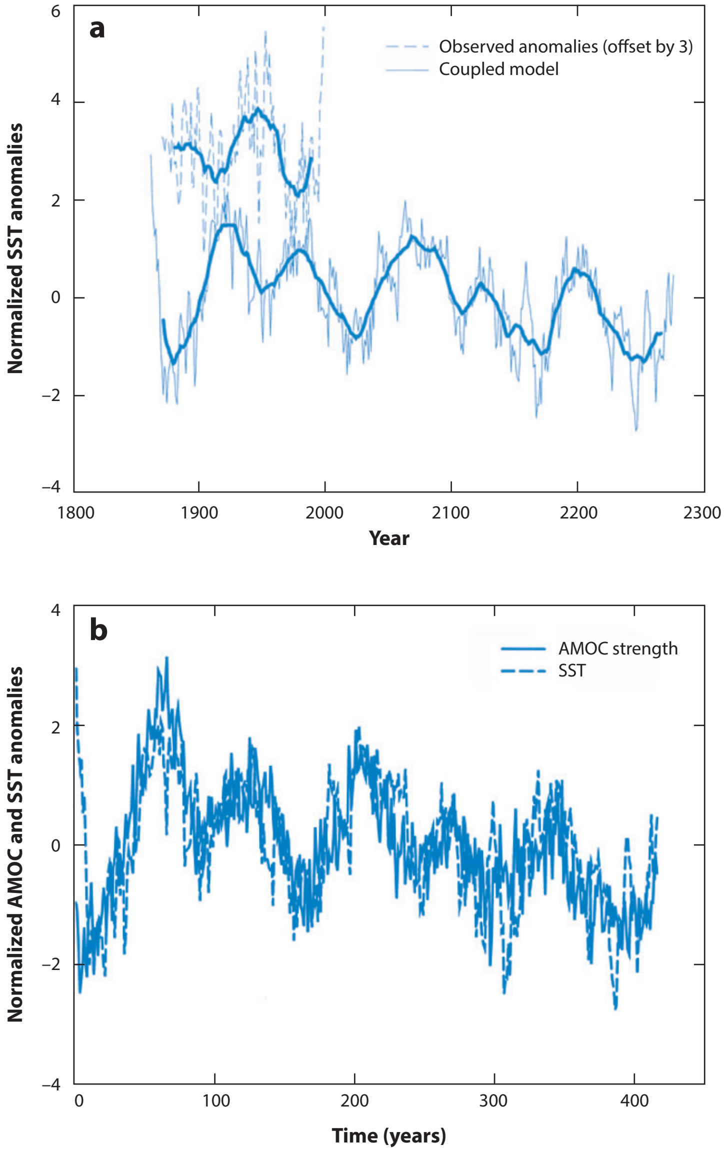

Figure 6

Multidecadal variability in the North Atlantic (40°–60°N, 50°–10°W). (*a*) Observed North Atlantic sea surface temperature (SST) anomalies (*thin dashed line*) and the corresponding Max Planck Institute for Meteorology Global Climate Model time series (*thin solid line*). The thick lines show the 21-year running means. (*b*) Anomalies of the maximum simulated overturning stream function at 30°N [a measure of Atlantic Meridional Overturning Circulation (AMOC) strength] plotted with the simulated temperature anomalies from panel *a* to emphasize the coherence between the ocean circulation and North Atlantic SST response. All anomalies have been normalized by their respective standard deviations. Figure adapted from Latif et al. (2004).

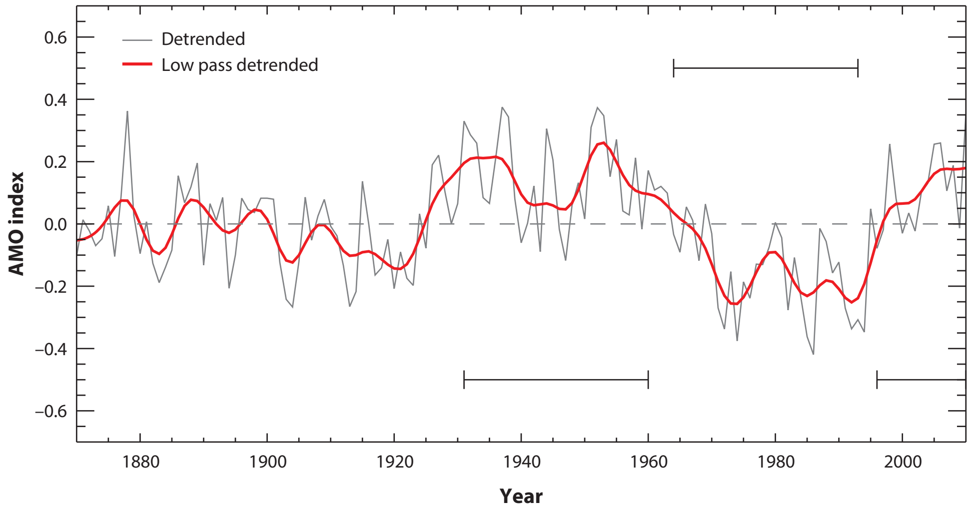

Figure 7

The detrended Atlantic Multidecadal Oscillation (AMO) index, calculated by taking the annual mean global sea surface temperature (SST) anomaly when excluding the North Atlantic (0°–60°N, 75°W–7.5°W) and subtracting it from the annual mean SST anomaly averaged over the North Atlantic only. The black bars indicate the two warm periods and intervening cool period used to construct **Figure 8**. Figure adapted from Sutton & Dong (2012).

driver of observed North Atlantic SST variability in the twentieth century (Booth et al. 2012). However, the concerns raised by Booth et al. (2012) have been largely dismissed because their model had an exaggerated response to aerosol forcing and could not faithfully simulate observed tropical Atlantic subsurface heat content and subpolar salinity (Zhang et al. 2013), both telltale fingerprints of AMOC variability (Zhang 2008). Thus, a clear link between multidecadal North Atlantic SST anomalies and AMOC variability is becoming more firmly established in climate models and is consistent with multiple metrics found in existing observations.

3.2.3. The link between North Atlantic multidecadal variability and European climate. Statistical correlations between North Atlantic SST, as characterized by the AMO index (**Figure 7**) and European climate variability, have long been noted (Delworth & Mann 2000, Kushnir 1994, Schlesinger & Ramankutty 1994). Warm phases of the AMO tend to be associated with wet anomalies across northern and central Europe and warm/dry anomalies over the Iberian Peninsula, particularly in summer (Sutton & Dong 2012, Ting et al. 2014) (**Figure 8**). Atmospheric models successfully reproduce European summer precipitation anomalies when forced with idealized AMO-like extratropical (30°–70°N) North Atlantic SST anomalies (Sutton & Hodson 2005). These higher latitudes encompass the region where SST anomalies are closely tied to AMOC variations (Terray 2012, Williams et al. 2014). Collectively, these results suggest that observed correlations between the AMO and European summer precipitation could be a consequence of SST-induced variability in sea level pressure and a shift of the storm track, as originally posited by Kushnir (1994) and more recently explored by Häkkinen et al. (2011).

Taken as a whole, these studies provide ample evidence that the variability of AMOC heat transport, which is carried by the Gulf Stream, has a detectable influence on Europe's summer climate on multidecadal timescales. The same cannot be said for Europe's winter climate (Arguez et al. 2009, Sutton & Dong 2012) or for European climate variability on shorter timescales (see

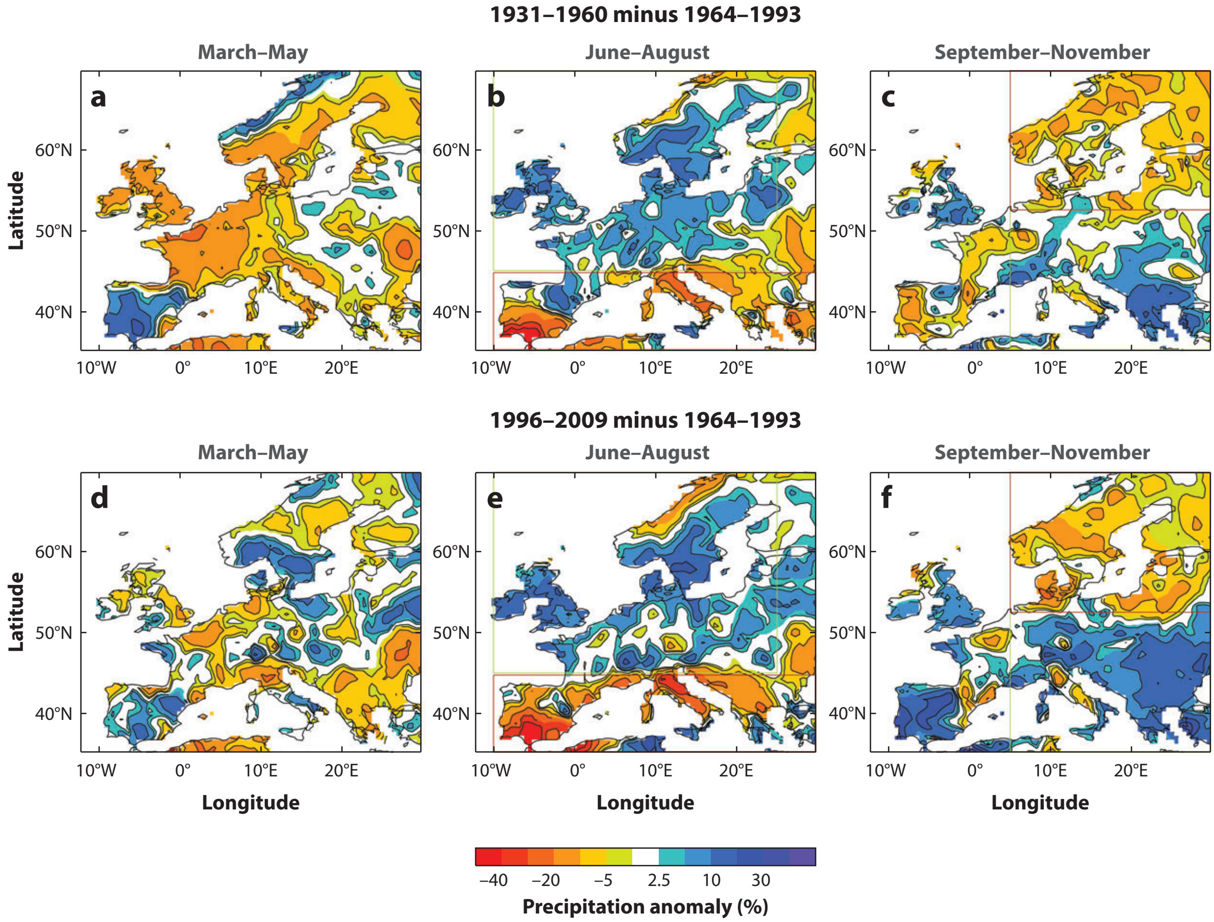

Figure 8

Anomalies in precipitation (as percentages of their climatological mean value) in two recent warm phases of the Atlantic Multidecadal Oscillation (AMO) minus those in the intervening cold phase. Panels *a–c* show seasonal mean anomalies for 1931–1960 minus those for 1964–1993; panels *d–f* show the same, but for 1996–2009 minus 1964–1993. The seasonal data at each grid point were detrended by removing the linear regression to the low-pass-filtered global sea surface temperature anomalies before calculating the anomalies. Figure adapted from Sutton & Dong (2012).

Section 3.1). The lack of a winter AMO signal in Europe despite the persistence of SST anomalies throughout all seasons remains unexplained. In addition, debate persists about the best approach to separate forced and internal climate variability. The subtle details of the technique used in this separation can change the phasing and amplitude of the resultant AMO index, particularly in the most recent years (Mann et al. 2014, Terray 2012, Ting et al. 2009). These phase differences have implications for the attribution of recent Northern Hemisphere climate change to internal as opposed to anthropogenic climate change.

In addition, the reliance on climate models for diagnosing the mechanistic relationship between Gulf Stream variability and climate impacts creates uncertainty that urgently needs to be addressed. For instance, numerical costs have mandated that the global climate models integrated on timescales relevant for understanding deep ocean circulation (which takes hundreds to thousands of years to reach equilibrium) use resolutions that are too coarse to accurately represent the jet-like structure of the Gulf Stream and the overflows of dense waters that may drive variability in the AMOC. At present, many of our conclusions may be sensitive to the parameterizations used to represent these processes in climate models, and an active field of research is devoted to evaluating these parameterizations. One hope is that an enhanced understanding of the causes and consequences of variability in North Atlantic circulation will lead to greater decadal predictability for Europe's climate.

4. ANTHROPOGENIC CLIMATE CHANGE, THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION, AND EUROPEAN CLIMATE

One of the priorities of climate change research has been to understand the risk of a tipping element in the climate system. Tipping elements have been defined as "regional-scale features of the climate that could exhibit a threshold behavior in response to climate change—that is, a small shift in background climate can trigger a large-scale shift towards a qualitatively different state of the system" (Levermann et al. 2011, p. 846). The AMOC has been considered one possible tipping element with important consequences for Europe, given its demonstrated propensity for abrupt slowdowns in the paleoclimate record and its strong influence on Northern Hemisphere climate (discussed in Section 2). Importantly, the expert view embraced in both of the most recent assessment reports from the Intergovernmental Panel on Climate Change is that the probability of a full AMOC collapse by the end of the twenty-first century is less than 10% (Stocker et al. 2013). Yet, given the small but finite probability of collapse, it is worth considering what its effects would be in the context of global warming. Do the climate responses to an AMOC collapse in the context of global warming differ from those indicated in the paleoclimate record and simulated in preindustrial climate simulations?

Vellinga & Wood (2007) probed this question using a climate model with prescribed greenhouse gas buildup in the atmosphere meant to represent twenty-first-century anthropogenic emissions. In addition to the rising greenhouse gas simulation, they ran a further simulation that introduced a large, instantaneous freshwater flux into the North Atlantic in the year 2049 to suppress the AMOC. In the 10 years following the freshwater perturbation, the AMOC slowed to less than 30% of its unperturbed values, and Northern Hemisphere surface air temperatures dropped on average by almost 2°C relative to the simulation with greenhouse forcing alone. **Figure 9** shows the spatial pattern in surface air temperature differences for these two simulations in the first decade after the freshwater perturbation. The cooling is intensified over the Nordic Seas and the Scandinavian Peninsula, which is similar to results from the freshwater forcing simulations meant to mimic the flooding of the North Atlantic at the onset of the 8.2-kya cooling event (see **Figure 3** and the discussion in Section 2). These simulations suggest that a collapse of the AMOC could cause abrupt, short-term (<50 years) cooling of Europe to temperatures below those experienced in the preindustrial mean climate, even in the context of global warming. Model snow and frost conditions were more prevalent in the years immediately following the AMOC perturbation, when the average simulated winter was as cold as the most extreme winter from the preindustrial period. Even so, the response is smaller than that simulated when the AMOC weakens in the context of preindustrial greenhouse warming, largely because global warming suppresses sea ice growth in the Greenland and Norwegian Seas.

These dramatic consequences of a rapid and severe suppression of AMOC transport under global warming are unlikely to be realized in the twenty-first century. However, in almost all climate models, global warming causes a freshening and warming of the high-latitude surface ocean, enhanced water column stability, and a suppressed sinking branch of the AMOC. The

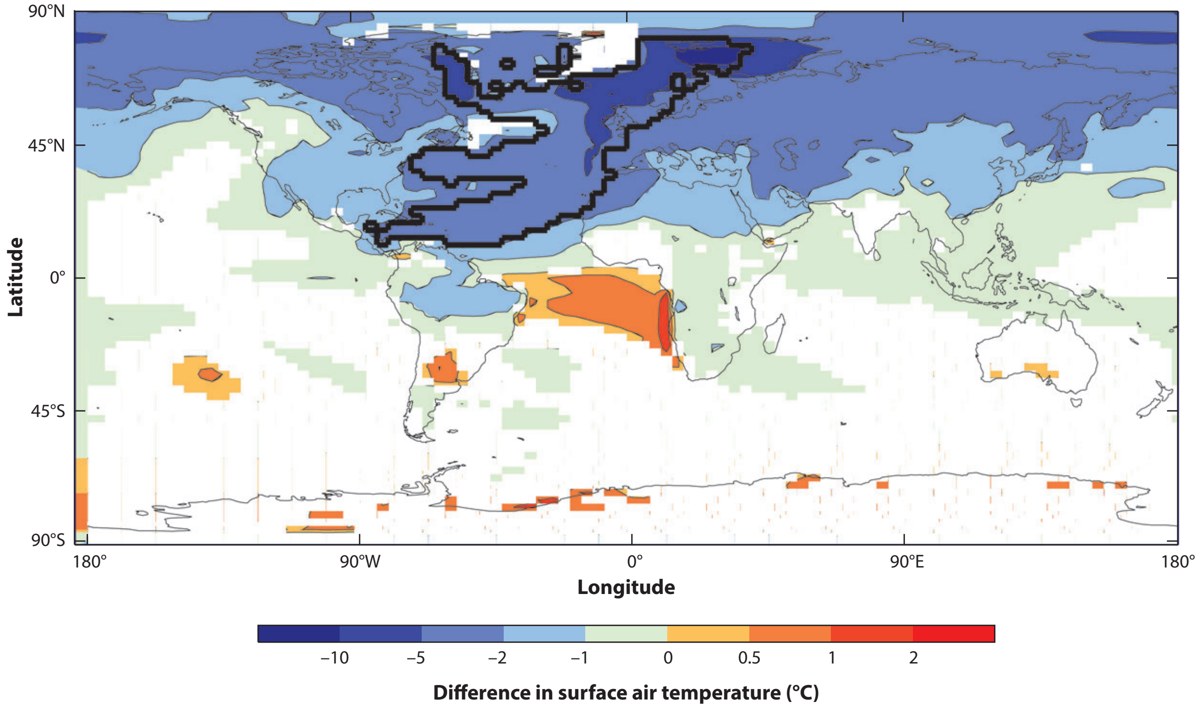

Figure 9

Surface air temperatures in a coupled climate model simulation with a 70% weakening of the Atlantic Meridional Overturning Circulation (AMOC) due to a prescribed freshwater flux at the ocean's surface minus those in a simulation with no prescribed freshwater flux. Both models have prescribed rising concentrations of atmospheric greenhouse gases as projected for the twenty-first century. In the first simulation, an idealized freshwater flux imposed in 2049 triggers the AMOC weakening; the results in both simulations were then averaged over the years 2049–2059. A thick solid line outlines the area where cooling causes temperatures to fall below preindustrial conditions (as determined by a separate simulation with constant preindustrial greenhouse gas concentrations). Areas where the difference is not significant have been masked. Figure adapted from Vellinga & Wood (2007).

degree of expected AMOC weakening remains highly uncertain and is sensitive both to the rate at which atmospheric concentrations of greenhouse gases grow and to the model used to simulate the climate (Stocker et al. 2013).

As would be expected from paleoclimate records and model simulations and the association of the cool AMO phase with cooler Northern Hemisphere surface air temperatures, the projected twenty-first-century AMOC decline caused by anthropogenic climate change partially offsets the warming over the North Atlantic and Europe (Drijfhout et al. 2012, Rugenstein et al. 2012, Woollings et al. 2012). This so-called warming hole is seen in the multimodel mean projection of surface air temperatures at the end of this century and is statistically associated with the weakening of the AMOC (Drijfhout et al. 2012). Slower warming of the Northern Hemisphere under a doubling of atmospheric CO_2 has been more precisely attributed to the AMOC's weakening poleward heat transport, which, in turn, slows the retreat of sea ice and the associated surface albedo change (Rugenstein et al. 2012). It is intriguing that this warming hole is apparent in observations from the twentieth century, although no AMOC slowdown can be discerned from background variability in the observational record (Drijfhout et al. 2012).

The implications of the warming hole associated with an AMOC decline extend beyond the simple slowing of European warming. Models suggest that an AMOC decline will intensify and

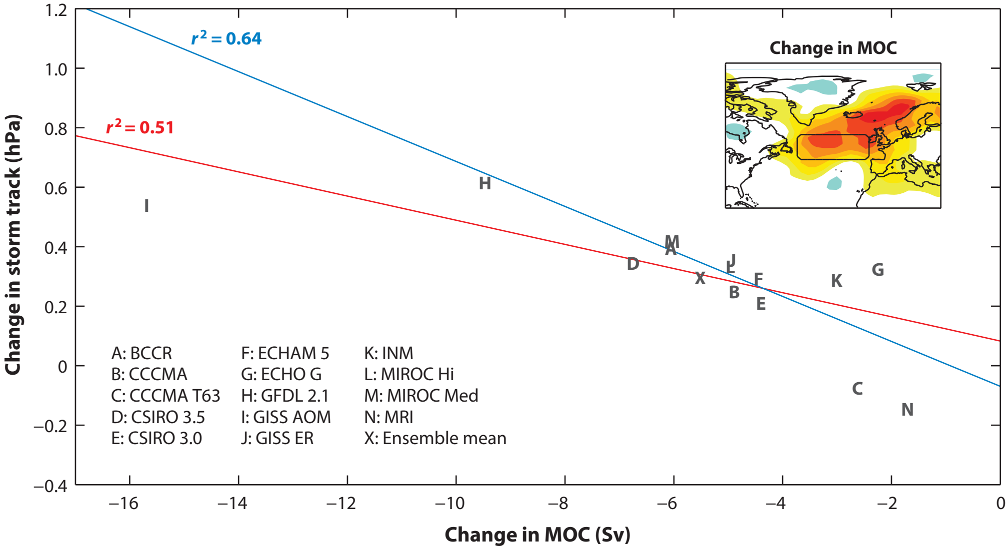

Figure 10

The relationship between storm track and Atlantic Meridional Overturning Circulation (AMOC) change under anthropogenic warming. The scatterplot shows the storm-track response averaged over the region outlined in the inset (45°–55°N, 10°–50°W) against the AMOC response in 14 climate models. Both the storm track and AMOC changes are calculated as the 20-year average from the end of a climate change scenario (2081–2100) minus the 40-year average from the end of a historical simulation (1961–2000). Regression lines are shown both including (*red*) and excluding (*blue*) the outlier model I. The AMOC is characterized by the maximum value of the meridional stream function (1 Sv $= 10^6$ m^3 s^{-1}) at 45°N. The storm track is diagnosed using the standard deviation of 2–6-day band-pass-filtered sea level pressure. The inset shows the linear regression between the AMOC change and the storm-track change for climate models simulating the historical period and twenty-first-century climate change. At each point, a linear regression between the AMOC change and the storm track is calculated over the longest available period for each model, with the multimodel average then plotted. Figure adapted from Woollings et al. (2012).

extend eastward the midlatitude storm track that governs storminess in Europe (Woollings et al. 2012). **Figure 10** shows the mean modeled pattern of the storm track change regressed on the AMOC decline at the end of the twenty-first century as well as the spread of the storm track response versus the AMOC decline among 14 models. The large range of the predicted AMOC decline is indicative of the uncertainty in the near-term future of the Atlantic circulation, which, in turn, creates uncertainty in predictions of future changes in European storminess. This underscores the potential for the AMOC to impact European climate in the near future and the pressing need to reduce uncertainty in predictions of AMOC transport.

5. SUMMARY

The connection between the Gulf Stream and climate has long fascinated scientists and led to an astounding breadth and depth of research. The studies reviewed here represent only a small sample of what has been done. Any one piece of evidence connecting a change in Gulf Stream transport with a response in Northern Hemisphere climate—for instance, from a single paleoclimate proxy, a coarse-resolution climate model, or the short and undersampled instrumental record—could seem tenuous and circumstantial. Yet, synthesized as a whole, the preponderance of evidence supports the notion that heat carried poleward by the Gulf Stream critically influences European and Northern Hemisphere climate. Because of feedbacks between the ocean, atmosphere, and cryosphere, a change in oceanic heat transport can alter climate, even when largely compensated for by a change in atmospheric heat transport.

However, there are situations in which the Gulf Stream's influence on Europe's climate may not live up to expectations. First, on timescales shorter than roughly a decade, variability in the atmosphere seems to swamp any oceanic signal in setting basin-scale climate patterns. Second, Europe's warmth relative to the zonal mean cannot be attributed simply to westerly winds extracting heat from the warm current. Stationary waves in the atmospheric midlatitude jet contribute to zonal anomalies of both signs, with the Rocky Mountains playing an important role in establishing the southwesterly winds that bring warm air masses to Europe. Thus, when the ocean heat transport is eliminated in model simulations, Europe's zonal temperature anomaly is not entirely erased, though it is diminished (Seager et al. 2002). In a fun twist, recent research has implicated the Gulf Stream even in setting up these stationary waves and contributing to the frigid winters on North America's east coast (Kaspi & Schneider 2011), against which Europe's warmth is often contrasted.

In conclusion, on timescales longer than a decade, the Gulf Stream's influence on climate is of paramount importance. Models indicate that a slowdown in the AMOC transport, which is assumed to manifest in a more sluggish Gulf Stream, is likely to occur by the end of this century. This change in ocean circulation and the associated feedback effects are likely to influence ocean heat uptake, the rate of Northern Hemisphere warming, and even the rate of warming globally (Winton et al. 2013). The consequences for Europe will depend in part on the rate of AMOC weakening, which remains highly uncertain. Our ability to diagnose AMOC changes continues to be hampered by the large natural variability of the current system. AMOC monitoring is now expanding from the efforts of the RAPID program at 26°N (**http://www.rapid.ac.uk/rapidmoc**) to include monitoring across the subpolar North Atlantic (**http://www.o-snap.org**) and in the South Atlantic (**http://www.aoml.noaa.gov/phod/research/moc/samoc**). The hope is that, collectively, such programs will enhance our understanding of the mechanisms governing the Gulf Stream dynamics and provide a window to observe the current system if it begins to change as predicted.

DISCLOSURE STATEMENT

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