

## RESEARCH LETTER

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## Key Points:

- We investigate subpolar decadal temperature variability associated with the North Atlantic Current
- This variability covaries with Atlantic and Pacific Ocean decadal climate modes
- Atlantic climate variability leads/amplifies that of the Pacific and its associated teleconnections

## Supporting Information:

- Supporting Information S1
- Data Set S1

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## Global linkages originating from decadal oceanic variability in the subpolar North Atlantic

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**Abstract** The anomalous decadal warming of the subpolar North Atlantic Ocean (SPNA), and the northward spreading of this warm water, has been linked to rapid Arctic sea ice loss and more frequent cold European winters. Recently, variations in this heat transport have also been reported to covary with global warming slowdown/acceleration periods via a Pacific climate response. We here examine the role of SPNA temperature variability in this Atlantic-Pacific climate connectivity. We find that the evolution of ocean heat content anomalies from the subtropics to the subpolar region, likely due to ocean circulation changes, coincides with a basin-wide Atlantic warming/cooling. This induces an Atlantic-Pacific sea surface temperature seesaw, which in turn, strengthens/weakens the Walker circulation and amplifies the Pacific decadal variability that triggers pronounced global-scale atmospheric circulation anomalies. We conclude that the decadal oceanic variability in the SPNA is an essential component of the tropical interactions between the Atlantic and Pacific Oceans.

## 1. Introduction

The multidecadal variability of the North Atlantic Ocean has a strong signal in the sea surface temperature with many global climate linkages [Enfield *et al.*, 2001; Knight *et al.*, 2006]. An even stronger multidecadal signal can be found in the subpolar temperatures and salinities, where the Atlantic Water inflow variations constitute an essential part in the variability [Hátún *et al.*, 2005; Häkkinen *et al.*, 2011a; Reverdin, 2010]. The atmospheric forcing in the subpolar North Atlantic Ocean is dominated by the variability of the North Atlantic Oscillation (NAO), i.e., the leading mode of atmospheric variability in the North Atlantic sector, which modulates the atmosphere-ocean momentum and heat exchanges on a range of temporal scales. The subpolar ocean variability thus appears to be tightly connected to atmospheric forcing and associated basin-scale circulation changes, which together force the subpolar ocean properties toward extremes [Lozier *et al.*, 2008, 2010], either to warm-saline or cold-fresh conditions on multidecadal scales. These regime changes have recently been argued to be important for global mean surface temperature warming acceleration and hiatus [Chen and Tung, 2014; Drijfhout *et al.*, 2014] (Figure S1 in the supporting information).

The temporary decadal-long global warming slowdown just after the turn of the century has received much attention from the climate community [Meehl *et al.*, 2011; Trenberth and Fasullo, 2013; Kosaka and Xie, 2013; Watanabe *et al.*, 2014; Trenberth *et al.*, 2014; England *et al.*, 2014; McGregor *et al.*, 2014; Song *et al.*, 2014; Maher *et al.*, 2014; Steinman *et al.*, 2015; Fyfe *et al.*, 2016]. Natural internal variability can temporarily influence and cause a “pause” in an otherwise upward global mean air temperature trend [Held, 2013; Trenberth, 2015]. Numerous reasons, mainly centered around the low-frequency Pacific climate variability, have been offered [Kosaka and Xie, 2013; Watanabe *et al.*, 2014; Trenberth *et al.*, 2014; England *et al.*, 2014; McGregor *et al.*, 2014; Maher *et al.*, 2014]. Other studies [Katsman and van Oldenborgh, 2011; Balmaseda *et al.*, 2013; Chen and Tung, 2014; Drijfhout *et al.*, 2014] have also suggested the redistribution of heat across multiple basins and into the depths of the oceans as alternate explanations for the missing heat offsetting the global warming acceleration.

A growing number of studies have highlighted the importance of the tropical Atlantic warming trend since the mid-1990s in generating the pronounced eastern Pacific cooling and negative Interdecadal Pacific Oscillation trend that dominated for more than a decade since around 2001 [Kucharski *et al.*, 2011; Chikamoto *et al.*, 2012; McGregor *et al.*, 2014; Kucharski *et al.*, 2015; Li *et al.*, 2015]. Chikamoto *et al.* [2012], for example, pointed out that the stepwise climate shifts in the Pacific are a lagged response to the basin-scale warming/cooling of the North Atlantic. A warming of the Atlantic Ocean induces a basin-scale sea surface temperature seesaw with the Pacific [Wang, 2006], which in turn reorganizes the position of the Walker circulation, strengthens the easterly trade winds [Lindzen and Nigam, 1987; England *et al.*, 2014], and influences the Pacific decadal variability, as suggested recently by McGregor *et al.* [2014]. The latter study further finds that East Pacific cooling can induce a tropical warming response in the Atlantic, suggesting two-way interbasin coupling. The Atlantic and Pacific are thus linked through this large-scale transbasin variability that may, initially, be induced by North Atlantic Ocean dynamics via a slowdown, or spin-up, of the Atlantic meridional circulation and the associated northward heat transport [Timmermann *et al.*, 2007; McCarthy *et al.*, 2015; Robson *et al.*, 2016; Zhang *et al.*, 2016].

We focus the present study on understanding the role of the subpolar North Atlantic Ocean (SPNA) in driving this Atlantic-Pacific interconnection. Our approach is to identify the potential source leading to a regime shift of Atlantic Water subsurface temperatures in the SPNA. These shifts are found to be associated with a decadal-scale progression of heat anomalies from the Gulf Stream region and revealed to coincide with sea surface temperatures extending to cover most of the subpolar and tropical North Atlantic. As a result of this basin-wide climate change, a large-scale Atlantic-Pacific surface temperature gradient, which correlates well with the strength of the Walker circulation, is generated and the Pacific decadal variability is amplified. These results are discussed in detail below and derived from several observational data sets as described in the next section.

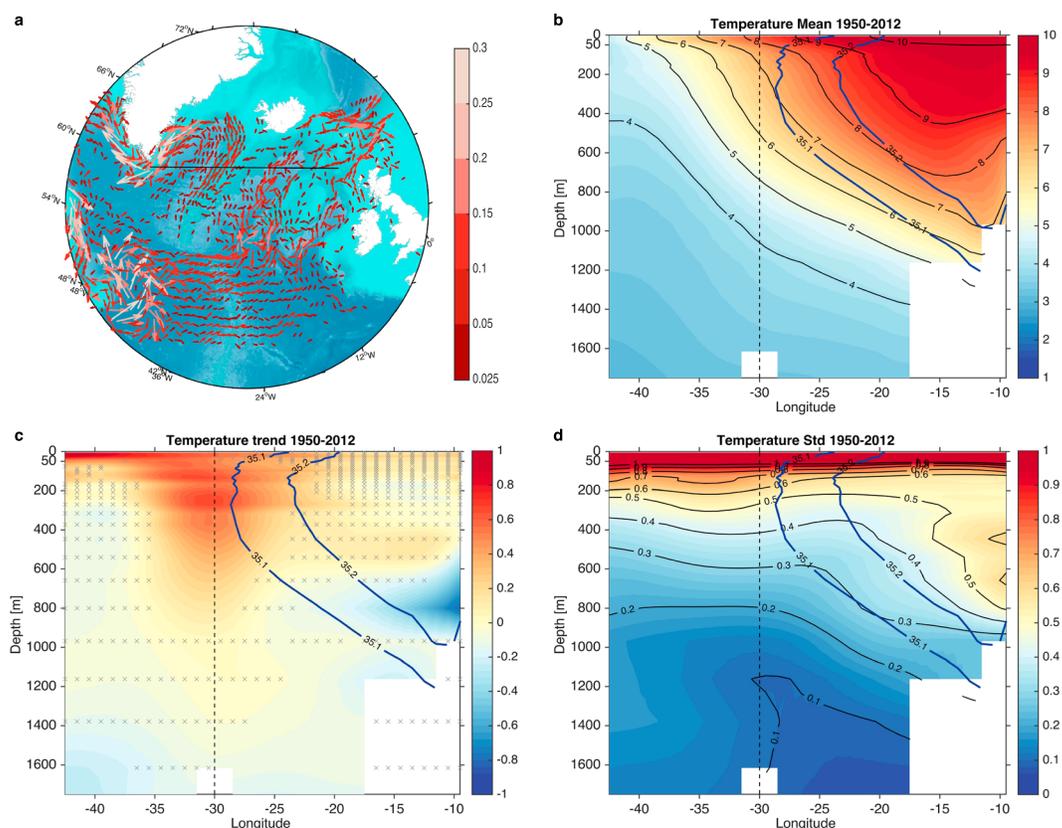
## 2. Data and Methods

To better understand the low-frequency temperature variability in the SPNA, we construct a subsurface temperature index in the SPNA that is colocated with the core of the North Atlantic Current (see Figure 1). To do this, we first construct a temperature cross section centered along 59.5°N by averaging associated grid points latitudinally between 58°N and 61°N. These are averaged along a line parallel to the Reykjanes Ridge and not in the north-south direction [Chafik *et al.*, 2014]. Second, we omit the upper 300 m, partly due to the large month-to-month variability, to ensure that the temperature variability captured is associated with that of the North Atlantic Current. Third, at every time step, we area average temperature corresponding to salinity larger than the 35.1 climatological isohaline. The resulting index, termed Atlantic Water Temperature (AWT), is thus a volumetrically averaged subsurface temperature of Atlantic Water along the pathway of the North Atlantic Current in the SPNA.

The temperature data are based on the monthly mean objectively analyzed hydrographic data from the UK Met Office, EN4 [Good *et al.*, 2013]. This data set is also used to calculate ocean heat content (OHC) in the upper 657 m of the water column:

$$\text{OHC} = \rho_0 c_p \int_5^{657} T(z) dz, \quad (1)$$

where  $\rho_0$  and  $c_p$  are the seawater density and specific heat capacity, respectively. In situ observations were rather sparse before the 1950s and mostly relax to climatology. We therefore rely on the period between 1950 and 2012 for our analyses. Complementary to OHC, we also use sea surface temperatures (SSTs) from the ERSSTv4 data set [Huang *et al.*, 2016]. Geopotential height and tropical Pacific winds are based on the twentieth century National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis [Compo *et al.*, 2011]. OHC, SSTs, geopotential heights, and winds have been deseasoned and linearly detrended before the analyses. We also use several climate indices publicly available on the NOAA website. These are based on similar data sets as all other variables. The indices are the NAO, Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation (PDO). All variables and indices have been smoothed using a 25 month running mean prior to the analyses, unless otherwise stated. Given this low-pass filtering, the significance of the Atlantic-Pacific lag-lead SST correlations is assessed using 5000 Monte Carlo simulations



**Figure 1.** Temperature climatology, trend, and variability in the SPNA between Scotland and Greenland. (a) Time-mean surface currents ( $\text{m s}^{-1}$ ) derived from altimetry. The 1950–2012 (b) climatology, (c) trend, and (d) standard deviation of potential temperature ( $^{\circ}\text{C}$ ) from EN4 in depth-longitude coordinates. The 35.1 and 35.2 climatological isohalines are indicated by the blue contours. The cross section used to construct Figures 1c and 1d is shown in black in Figure 1a and is a result of averaging over latitude bands between 59 and 61 $^{\circ}$ N. The latitudinal averaging of the potential temperature is performed along a slope parallel to that of the Reykjanes Ridge following the orientation of the currents. The dashed line at 30 $^{\circ}$ W represents the Reykjanes Ridge. The gray stipplings in Figure 1c denote nonsignificant grid points at the 99% confidence level based on the modified Mann-Kendall test [Hamed and Rao, 1998].

[Ebisuzaki, 1997] at the 99% confidence level. The random-phase method in the Monte Carlo significance test resamples the data in the frequency domain, which preserves its autocorrelation and power spectrum, but generally is as robust as a two-sided  $t$ -test [Von Storch and Zwiers, 2001].

### 3. Results

#### 3.1. Climatology and Long-Term Changes Across the SPNA

The time-mean surface currents from satellite altimetry (Figure 1a) reveal the flow toward the Nordic Seas and the Labrador Sea, respectively, following the upper limb of the Atlantic meridional overturning circulation [Chafik et al., 2015; Buckley and Marshall, 2016]. In the upper 400 m, equal amounts of water ( $\sim 8 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ) are transported by these branches [Chafik et al., 2014], which are effectively separated and topographically organized by the Reykjanes Ridge at 30 $^{\circ}$ W. East of this ridge, the isotherms reach deeper due to the presence of warm Atlantic Water associated with the North Atlantic Current as indicated by the gradual shoaling and cooling toward the west (Figure 1b). The Mann-Kendall test [Hamed and Rao, 1998] indicates a significant upward temperature trend in the SPNA (Figure 1c). The strong warming of the subpolar region is likely associated with the weakening of the gyre circulation [Häkkinen and Rhines, 2004; Lohmann et al., 2009; Häkkinen et al., 2013] but may also be partly anthropogenically forced [Stocker et al., 2013]. The standard deviation of the monthly data shows that the largest temperature variability between Scotland and Greenland during the past 63 years is found near the surface and also subsurface in the Iceland Basin (Figure 1d), which is consistent with the path of the North Atlantic Current.

### 3.2. North Atlantic Decadal Climate Shifts

The subsurface temperature index corresponding to Atlantic Water in the SPNA captures the largest variability associated with the core of the North Atlantic Current (Figure 1). It exhibits pronounced decadal climatic shifts (Figure 2a) associated with warm and cold periods lasting for about 17 years as confirmed by its power spectrum (Figure 2b) and projects onto an ocean heat content dipole pattern between the subpolar gyre and the Gulf Stream region (Figure 2c). This pattern is remarkably similar to that based on subsurface temperatures reported to be induced by the meridional overturning circulation [Zhang, 2008]. In the SPNA, the warm/cold period thus corresponds to a weaker/stronger than average subpolar gyre and higher/lower heat content [cf. Häkkinen *et al.*, 2013, Figure 5]. In the Gulf Stream region, however, the cold and warm anomalies have been associated with southward and northward shifts of the Gulf Stream position induced by variations in the meridional overturning circulation [Joyce and Zhang, 2010], leakage of slope waters [Rossby and Benway, 2000], and temporal variability of the NAO [Frankignoul *et al.*, 2001]. The preceding studies elucidate changes in the Gulf Stream controlled by both atmospheric forcing, mainly associated with the NAO, and changes in the meridional overturning circulation in a region where the circulation of the subpolar and subtropical gyres interacts. The impact from these two sources of variability is difficult to separate as they might be induced by the same climatic forcing.

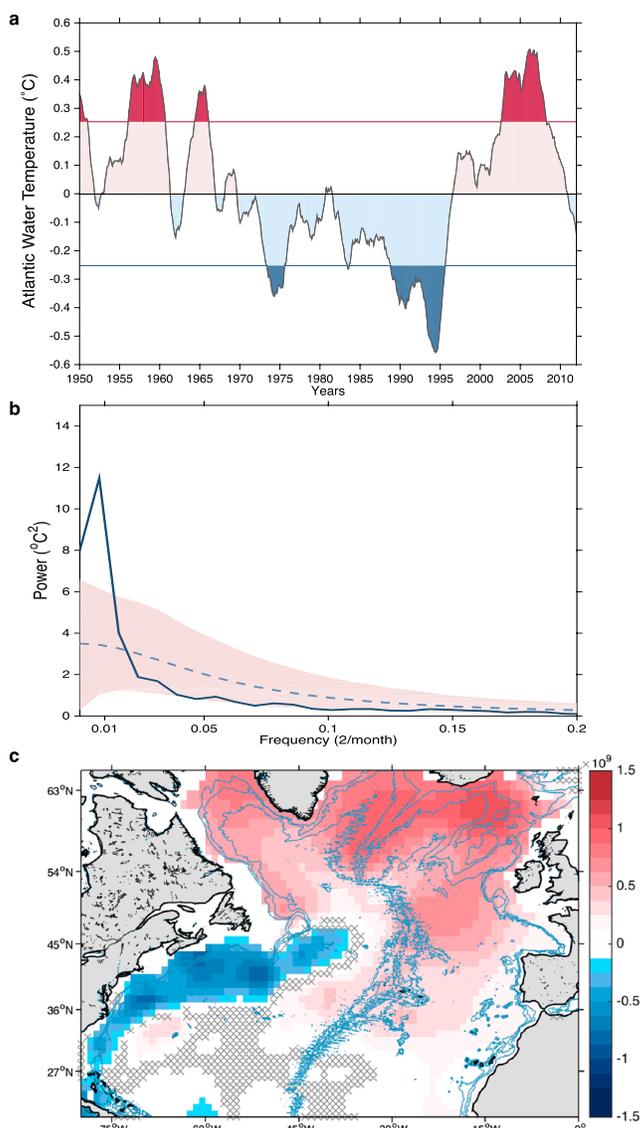
Based on the progression of ocean heat content in the top 700 m (Figure 3), we shed some light on how the warm-to-cold (Figures 3a–3c) and cold-to-warm (Figures 3d–3f) AWT phase transitions may occur. Propagating anomalies from the subtropics, with an amplification in the SPNA gyre, are observed. It is noteworthy that during a cold-to-warm (warm-to-cold) regime transition, a cold (warm) anomaly from the subpolar gyre moves southward along the western boundary, while concurrently, a warm (cold) anomaly from the Gulf Stream region advects along the mean path of the North Atlantic Current toward the eastern SPNA and subsequently around the subpolar gyre following the mean circulation. Figure S4 further suggests that this ocean heat content dipole is strengthened, outside these transition periods, under persistent NAO forcing.

Using an ensemble of initialized decadal prediction experiments, Yeager *et al.* [2012] pointed out that SPNA temperature regime shifts can be tied to the low-frequency advection of heat anomalies associated with the meridional overturning circulation and NAO-related buoyancy forcing [Robson *et al.*, 2012, 2016]. Recently, McCarthy *et al.* [2015] reported that the decadal evolution of North Atlantic heat content is affected by changes in the ocean circulation [e.g., Grist *et al.*, 2010], which responds to the NAO, through excursions in the subtropical-subpolar gyre boundary and anomalous circulation in the intergyre-gyre region [Marshall *et al.*, 2001; Eden and Willebrand, 2001; Herbaut and Houssais, 2009]. Through a similar mechanism, Wouters *et al.* [2012] found that temperature anomalies from the subtropics to the subpolar region, similar to that in Figure 3, are advected cyclonically toward the Labrador Sea where they influence the deep water formation and hence the overturning circulation. The advection of Gulf Stream waters into the subpolar gyre via the eastern boundary has also been proposed to be induced by changes in the strength and horizontal shape of the subpolar and subtropical gyres due to low-frequency variations in the wind-stress curl [Häkkinen and Rhines, 2009; Häkkinen *et al.*, 2011a] (Figure S4). It is thus expected that these decadal heat anomalies flowing into the SPNA are associated with spin-up or slowdown of the overturning and/or the wind-driven gyre circulation, and they coincide with changing phase of the AMO/AWT.

### 3.3. AWT Synchronizes Atlantic and Pacific Climate Variability

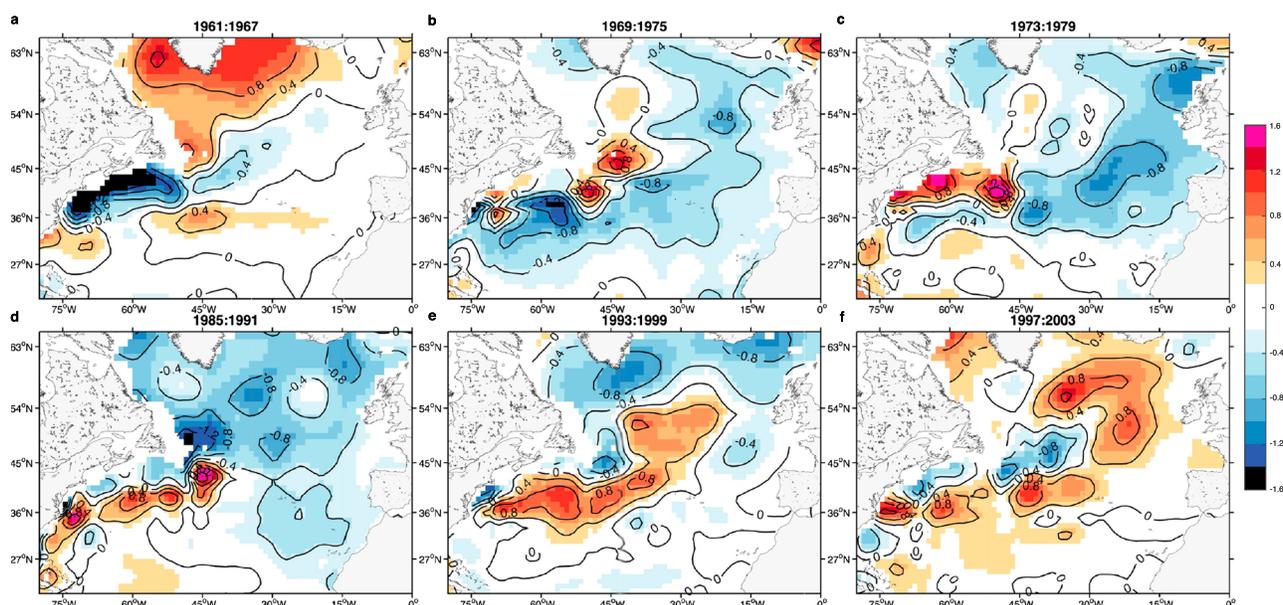
To demonstrate large-scale features and to better understand the global linkages associated with AWT, composite analyses using anomalies of SSTs and nonzonal geopotential heights at 200 hPa are constructed (Figure 4) (Figures S5 and S6). The latter is informative in terms of highlighting tropical-extratropical linkages associated with the flux of atmospheric Rossby waves connecting the Pacific to the Atlantic [Ding *et al.*, 2014]. The SST patterns (Figure 4a), both in the North Atlantic and Pacific, reflect horseshoe characteristics, which generally mirror the leading modes of SST variability in the North Atlantic and Pacific widely known as the AMO [Enfield *et al.*, 2001] and PDO [Mantua, 1997], respectively. In the SPNA, SST anomalies show a basin-wide warming/cooling associated with anomalous positive/negative phases of AWT (Figure S7). These anomalies tend, particularly in the western subpolar gyre, to be strongly enhanced by air-sea fluxes under specific atmospheric regimes [see, e.g., Barrier *et al.*, 2015; Häkkinen *et al.*, 2011b].

From a global perspective, AWT is seen to be associated with a teleconnection pattern originating from the tropical Pacific (Figure 4b), which expresses itself well in the upper troposphere at 200 hPa (anomalies at this



**Figure 2.** Characteristics of AWT variability. (a) AWT index (°C) during the 1950–2012 period (shading). The raw AWT (Figure S2) has been deseasoned, detrended, and smoothed with a 25 month running mean. Dark blue and red indicate anomalous periods (larger and smaller than 1 standard deviation) of AWT. (b) Power spectrum of the raw AWT using the Welch estimation method (solid line). The dashed line shows the power spectrum of the first-order autoregressive model, AR(1), having the same lag-1 autocorrelation as the AWT time series. The shading represents the 99% confidence limits obtained by generating 1000 random AR(1) models of the AWT series. Note the significant power in the low-frequency band of the spectrum with decadal and longer time scales. There is a particular peak at 17 year period. (c) Regression of ocean heat content anomalies ( $J m^{-2}$ ) onto AWT, where a dipole between the Gulf Stream and subpolar gyre is highlighted. Gray crosses indicate the nonsignificant regions below the 99% confidence level assessed using a two-sided *t*-test.

level represent the thickness of the troposphere, and hence, colder/warmer than average SST anomalies in the tropical Pacific are characterized by anomalously lower/higher pressure throughout the tropics and troposphere depth) in the form of a quasi-stationary Rossby wave pattern bridging the tropical Pacific and the Atlantic through the sub-Arctic. The tropical Pacific forces and sets up a coherent wave train structure (it is noteworthy that the first negative geopotential height anomaly center is typically located off the equator at subtropical latitudes away from the thermal source [Horel and Wallace, 1981; Trenberth et al., 1998]) leading, in part, to an eastward shift and a deepening of the Aleutian Low as well as an intensified high-pressure ridge in the North Atlantic reminiscent of a negative NAO-like mode. For example, Ding et al. [2014] linked the



**Figure 3.** Spatial progression of ocean heat content anomalies ( $\text{J m}^{-2} \times 10^9$ ) associated with the temperature transitions reflected in AWT. The 7 year time windows for the warm-to-cold transition are averaged for (a) 1961–1967, (b) 1969–1975, and (c) 1973–1979 periods. For the cold-to-warm transition the averaging is done for the periods (d) 1985–1991, (e) 1993–1999, and (f) 1997–2003 (see the entire 1949–2013 evolution in Figure S3). Figures 3a and 3d show averaging during a strictly warm/cold phase, while Figures 3b and 3e represent an intermediate phase before the transition to a strictly cold/warm state as shown in Figures 3c and 3f. These time windows have been chosen in a symmetric fashion (see Figure 2a) to visualize the transition from warm-to-cold and cold-to-warm periods. We, therefore, had to overlap the intermediate period in Figures 3c and 3d.

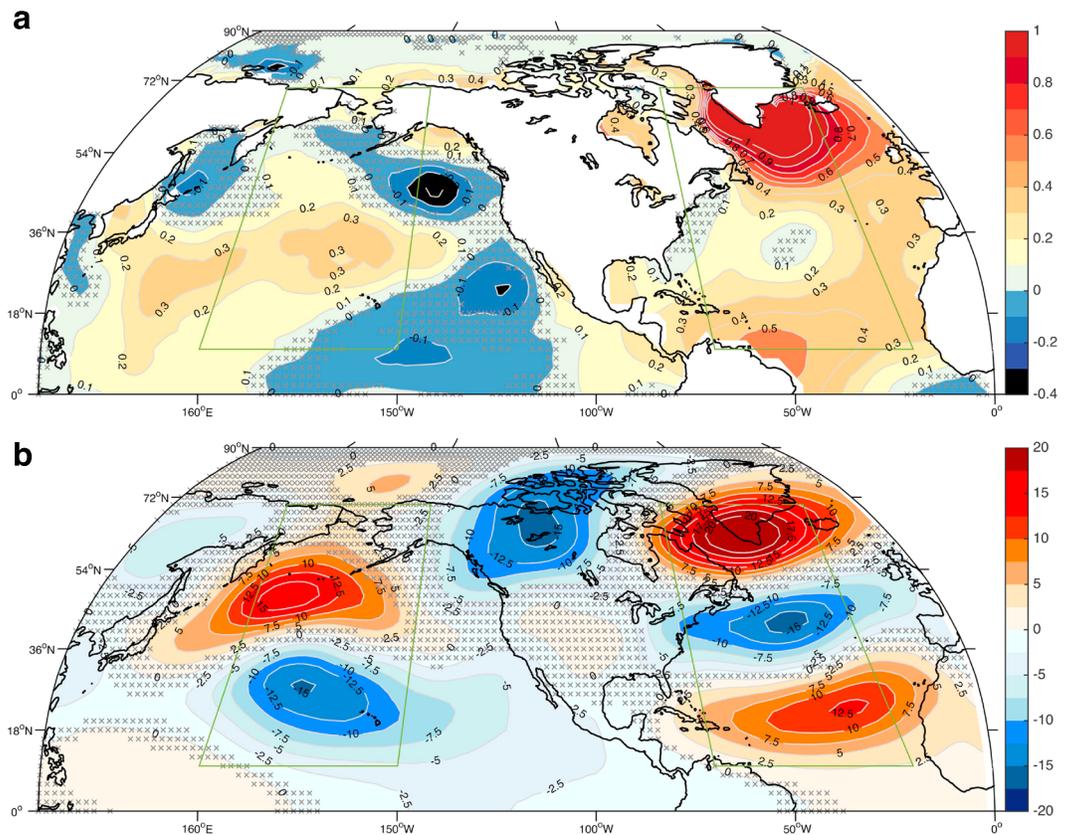
pronounced surface warming in northeastern Canada and Greenland to the negative NAO trend, which was found to be a response to the above mentioned anomalous Rossby wave train activity originating in the tropical Pacific. Moreover, *Trenberth et al.* [2014] pointed out that most atmospheric anomalies during the recent hiatus are of tropical Pacific origin and resemble the PDO.

### 3.4. Is the Atlantic Leading the Pacific?

We observe that an SST signal first originates within the Gulf Stream region outside Cape Hatteras almost a decade (maximum correlation at  $\sim 4$ – $6$  years) before it reaches the SPNA (Figure 5a). The propagation pattern is compatible with that of ocean heat content (Figure S3). Note, however, that the signal also shows a propagation toward the tropical Atlantic. This is consistent with a horseshoe pattern where the temperature signal communicates with both the SPNA and the subtropics following the subpolar and subtropical gyres, respectively, an impression reinforced by regressing SSTs onto the AWT at different lags (Figures S8 and S9). A discussion on similarities and differences between AWT and AMO is offered in the supporting information.

The atmospheric variability in the North Atlantic is notably leading the AWT (Figure 5b). This is manifested in the upper troposphere by a tripole pattern which resembles that induced by the NAO (Figure 5b). Whether this is a lagged response to the basin-wide spread of SST anomalies originally initiated in the subtropics along the Gulf Stream path is beyond the scope of the present study. Several studies have, however, pointed out that AMO-like SST anomalies are able to modify the strength of the large-scale atmospheric circulation through shifts in the position of the baroclinic zone [*Czaja and Frankignoul, 1999, 2002; Gastineau and Frankignoul, 2012; Peings and Magnusdottir, 2014; Gastineau and Frankignoul, 2015*].

In the Pacific, however, oceanic and atmospheric variability are evidently lagging changes in the Atlantic (Figure 5b). Subtropical Pacific SSTs lag AWT with a maximum correlation of 1–3 years (Figure 5b), and the associated atmospheric thickness (850–200 hPa) shows a dipole pattern between the subtropics and extratropics (as a response to the large-scale SST pattern or PDO) extending from the Pacific into the Atlantic, thereby completing a full interbasin Rossby wave train picture (Figure 5d). In the tropics and subtropics, an interbasin dipole pattern in the pressure field between the Atlantic and Pacific [see, e.g., *McGregor et al., 2014;*

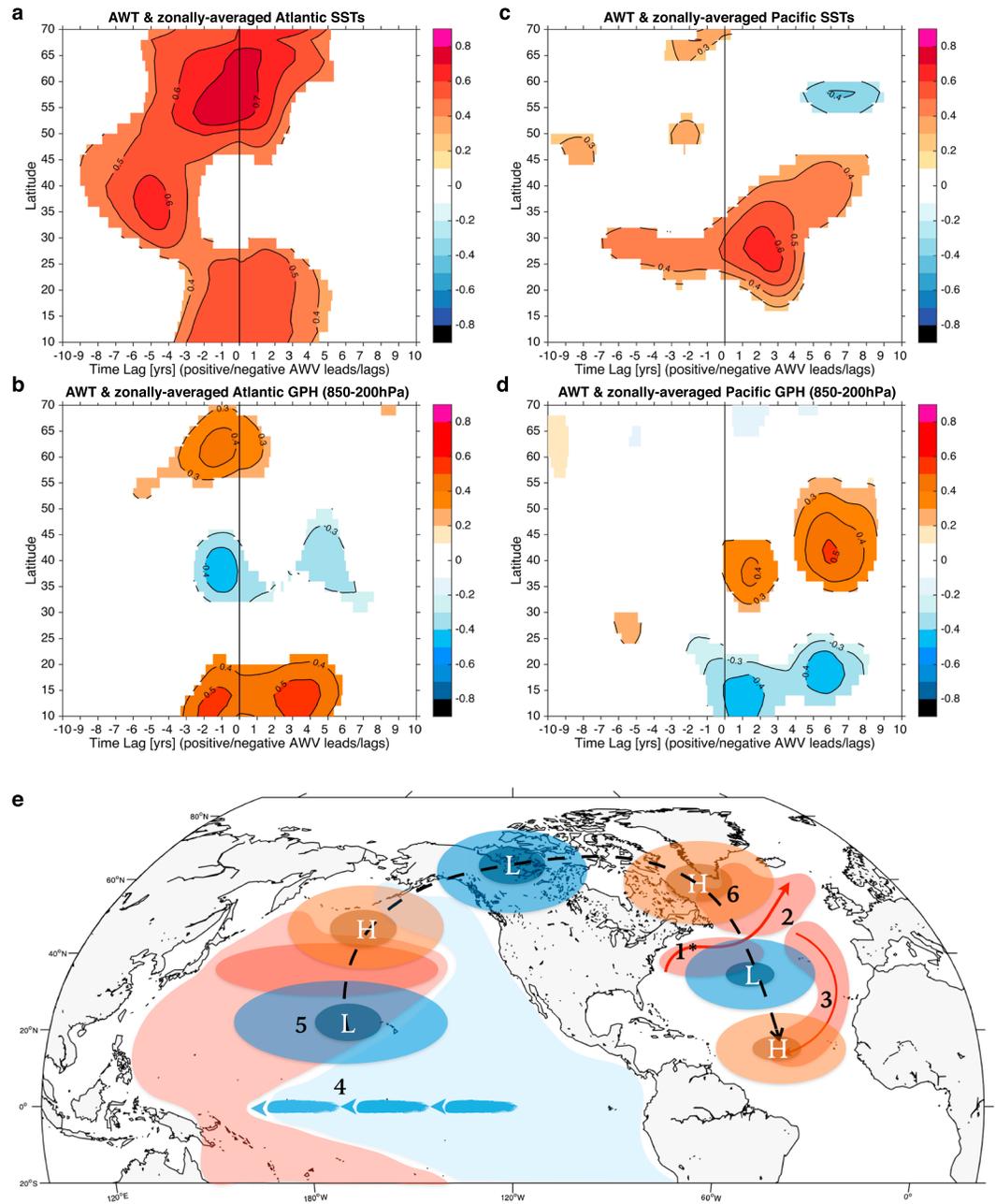


**Figure 4.** AWT variability and its global linkages. AWT-based composite analysis of (a) SST anomalies ( $^{\circ}\text{C}$ ), and (b) nonzonal 200 hPa geopotential height anomalies (gpm). The composite is based on the difference between events larger and less than 1 standard deviation for the anomalously warm and cold AWT periods (dark red/blue in Figure 2a), respectively. Nino3.4 has been removed prior to the analysis. Gray crosses indicate the nonsignificant regions below the 99% confidence level assessed using a two-sided *t* test.

*Chikamoto et al., 2015*] is observed and persists there for an extended number of years. Our results thus suggest that the Atlantic amplifies the negative and positive anomalies of the internally generated variability of the PDO [see, e.g., *Chikamoto et al., 2012*].

In conclusion, we show evidence that SPNA and tropical Atlantic SST anomalies are consistent with an advective origin due to changes in the ocean circulation [*Zhang et al., 2016; Drews and Greatbatch, 2016*]. However, the Pacific decadal variability is not amplified until temperature anomalies have connected with the tropical Atlantic and the basin-scale pattern linked to AWT is fully developed. This results in an interbasin gradient or seesaw between the Atlantic and Pacific and a shift in the Walker circulation (Figure 5e). This transbasin variability (Atlantic warming/cooling-Pacific cooling/warming) has been recently suggested to have amplified the recent Pacific cooling and hence a slowdown in global mean surface air temperature [*McGregor et al., 2014*].

To further understand the physical link between the Atlantic and Pacific, we construct an interbasin SST gradient or transbasin variability following *McGregor et al. [2014]*. This index does not only combine information on how the basin-average Atlantic and Pacific SSTs vary but also mirrors the strength of the trade winds and hence shifts of the Walker circulation (Figure S10). We note that the negative and positive phases of this index covary with the cold and warm periods of AWT with a significant lag of 21 months. The warming (cooling) of the North Atlantic Basin reflected by positive AWT phase leads to a positive (negative) SST transbasin variability, i.e., difference between the Atlantic and Pacific. As a result, sinking/rising motion and upper level convergence/divergence occurs in the central Pacific/Atlantic and easterly winds are strengthened in the central western Pacific region, which amplifies the cooling in the tropical Pacific [*England et al., 2014; McGregor et al., 2014; Kucharski et al., 2015; Li et al., 2015*], and vice versa. Thus, Atlantic climate variability plays an important role for the position of the Walker circulation and contributes to the generation of Pacific decadal variability.



**Figure 5.** AWT and Atlantic-Pacific connectivity. Lag-lead correlation in years based on AWT and zonally averaged (a) Atlantic SST, (b) Pacific SST, (c) Atlantic, and (d) Pacific geopotential height (GPH) averaged between 850 and 200 hPa. The zonal averaging is performed within the green boxes (cf. Figure 4). The shaded regions (Figures 5a–5d) are statistically significant at the 99% confidence level based on the random-phase test using 5000 Monte Carlo simulations. Niño3.4 has been removed prior to the analysis. (e) Schematics of the global linkages for a typical warm phase, where (1) the Gulf Stream region appears to be the main source of the warm anomaly, which (2) progresses toward the SPNA and also (3) reaches the tropical Atlantic (Figures S8 and S9). (4) This creates a large-scale SST gradient between the Atlantic and Pacific that modifies the Walker circulation and strengthens the trade winds. (5) The negative PDO phase is hence amplified, which excites a flux of Rossby waves into the Atlantic. (6) This organization reinforces the high-pressure anomaly over the subpolar gyre region.

#### 4. Summary and Conclusions

The purpose of this study has been to gain a better understanding of the interbasin linkages between the Atlantic and Pacific in relation to the decadal variability that characterizes AWT in the SPNA (Figure 2). This is found to be associated with a decadal-scale progression of heat content anomalies from the subtropics into the subpolar gyre and coincide with basin-wide, AMO-like, climatic changes. Ocean circulation is evidently playing a role in inducing the observed North Atlantic changes [Zhang *et al.*, 2016; Drews and Greatbatch, 2016]. The strength of the meridional overturning [Robson *et al.*, 2016] and wind-driven circulation [Häkkinen *et al.*, 2011a; McCarthy *et al.*, 2015] are expected to dominate the evolution of ocean heat content anomalies; however, their relative roles are not yet fully understood.

Here we have shown that AWT in the SPNA synchronizes with the dominant modes of climate variability in the Atlantic and Pacific and appears to contribute to the low-frequency Pacific decadal variability with a maximum lag of  $\sim 2$ – $3$  years (Figure S7). While our analyses were based entirely on observations, and are restricted to a limited period of reliable observations, evidence can also be found in forced atmosphere and coupled climate model experiments, wherein imposed SST anomalies are applied. For example, Chikamoto *et al.* [2012] found that Pacific stepwise climate shifts are found to lag changes in Atlantic SSTs by around 2 years. It is, however, important to recognize that this interbasin connection occurs via the tropics after extratropical SSTs have communicated with the tropical Atlantic [Guan and Nigam, 2009; Ruiz-Barradas *et al.*, 2013]. This, in turn, induces the Atlantic-Pacific SST gradient necessary to modify to the Walker circulation and can translate into a multiyear persistence predictive skill [McGregor *et al.*, 2014; Chikamoto *et al.*, 2015]. Our findings are further supported by Dunstone *et al.* [2011], where tropical Atlantic SSTs are shown to be forced from the subpolar gyre region and concluded to generate predictable low-frequency variability of the atmosphere in the tropical Atlantic [see, e.g., Hawkins *et al.*, 2011; Msadek *et al.*, 2014].

The Atlantic-Pacific lag-lead relationship with the AWT suggests that the synchronized atmospheric anomalies connecting the tropical Pacific to the Atlantic through the sub-Arctic are in the first place initiated by the NAO, which manifests itself as a tripole pattern (Figure 5). The Rossby wave flux from the tropical Pacific and toward the Atlantic is, however, not excited until the AWT changes phase and the transbasin variability is “activated” and is likely to feedback (e.g., through turbulent heat fluxes) on the subpolar region. It is thus important to consider this tropical-extratropical teleconnection of Pacific origin to better understand the anomalously warm and cold multiyears in the SPNA, where the AMO has its largest signal [Ruiz-Barradas *et al.*, 2013; Buckley and Marshall, 2016].

The decadal variability of AWT in the SPNA and its associated global linkages are shown here to be an essential aspect of the tropical interactions between the Atlantic and Pacific Oceans, with potential for improved decadal predictability [Dunstone *et al.*, 2011; Chikamoto *et al.*, 2015; Keenlyside *et al.*, 2015]. However, the mechanisms at play during the early 21st century decadal slowdown were rather pronounced as compared to those of the 1950s to the 1970s. This could be symptomatic of the sparse data record preceding the wide advent of expendable bathythermograph measurements in the mid-1970s. It could also suggest that global warming is amplifying the Atlantic and Pacific climate modes that enhance the appearance of transbasin linkages and feedbacks, particularly due to the relatively strong basin-wide warming of the tropical North Atlantic over the past two decades.

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