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Key Points:

- Sea surface temperature warming over the tropical Atlantic can induce a cold spring over mid-latitude North America
- Tropical Atlantic warming can trigger a cyclonic circulation anomaly over the mid-latitude North Atlantic through Rossby wave dynamics
- Atmospheric circulation adjustment further drives North American cooling through cold advection and cloud radiative feedback

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

X. Li,
lixichen@mail.iap.ac.cn

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Cold Springs Over Mid-Latitude North America Induced by Tropical Atlantic Warming

Yurong Hou[1,2], Nathaniel C. Johnson[3], Chueh-Hsin Chang[4,5], Weijun Sun[6], Kai Man[1,2], Yujie Miao[1,2], and Xichen Li[1]

[1]International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, [2]University of Chinese Academy of Sciences, Beijing, China, [3]Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, USA, [4]Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan, [5]Center for Climate Change Prediction Research, Ewha Womans University, Seoul, South Korea, [6]College of Geography and Environment, Shandong Normal University, Jinan, China

Abstract In recent decades, severe cold winters and springs have frequently occurred over mid-latitude North America, despite the anthropogenic global warming trend. In this study, we reveal a possible mechanism by investigating the teleconnection between tropical oceans and North America. Through observational analysis and numerical experiments, we reveal that an anomalous tropical Atlantic warming can trigger a cold spring over central-western mid-latitude North America. The tropical Atlantic warming intensifies regional deep atmospheric convection and generates a stationary Rossby wave train propagating poleward, forming an anomalous low pressure center over the mid-latitude North Atlantic. This low-level circulation adjustment further intensifies the cold advection and increases the cloud cover over central-western North America, cooling the surface through cloud radiative feedback. The mechanisms revealed in this study may contribute to the improvement of predictability of cold springs over North America, and have broad implications for agriculture production, power supply, and public health.

Plain Language Summary North America has experienced a series of cold springs in recent decades, even under the background of global warming. These cold springs have large impacts on transportation, agriculture, power supply, and public health. In this study, we find that anomalous cold springs over mid-latitude North America are tightly associated with the tropical Atlantic variability. In particular, an increase in the tropical Atlantic temperature of 1°C may induce up to 4°C decrease over central-western North America. Further investigation based on observational analysis and numerical model experiments reveals the pathway of this linkage. The tropical Atlantic warming triggers planetary waves, forming an anticlockwise circulation anomaly over the mid-latitude North Atlantic. This circulation adjustment transports cold air from the higher-latitudes to central North America. It meanwhile transports more moisture from the North Atlantic to central-western North America and increases cloud cover, which reflects the solar radiation and further cools the land surface. While previous studies focus on the impacts of Arctic amplification and tropical Pacific variabilities on cold winters/springs over North America, this work highlights the importance of the tropical Atlantic in triggering North American cold springs.

1. Introduction

Under the background of the anthropogenic global warming, the occurrence of extreme cold events over Northern Hemisphere mid-latitude land areas has recently opposed this trend (Diffenbaugh et al., 2017; Johnson et al., 2018), manifested in anomalous cold winters/springs on intraseasonal and interannual timescales. In particular, North America has experienced several anomalous cold winters and springs in recent decades (Doss-Gollin et al., 2021; Matthias & Kretschmer, 2020; Van Oldenborgh et al., 2015), accompanied by more frequent severe cold air outbreaks and snowfalls (Lee et al., 2015; Palmer, 2014). For example, record-breaking snowfalls swept across British Columbia's southwest coast and Washington State in April-May 2022, leading to a relatively cold spring in the mean state over the west coast of North America. These anomalously cold winters/springs have significant impacts across a broad range of industries and sectors, including transportation, power supply and public health. Moreover, cold springs often adversely affect the vegetation growth (Wang et al., 2011) and the agricultural production in North America.

A series of hypotheses (Guo et al., 2017; Kug et al., 2015; Liu et al., 2015; Sigmond & Fyfe, 2016; Sun et al., 2019; Wettstein & Mearns, 2002; Zheng et al., 2018) have been proposed to explain these cold winters over North America. For example, Arctic climate variabilities, including surface warming over the Chukchi-Bering Seas (Kug et al., 2015), as well as sudden stratospheric warmings (Zhang et al., 2020) and disruption of polar vortex (Cohen et al., 2021; Lee et al., 2019) may all drive cold winters over North America. On the other hand, a positive phase of North Atlantic Oscillation (NAO) can cause a warm anomaly over the northeastern U.S. and a cold anomaly over neighboring Canadian areas, further driving a regional snowpack anomaly and increasing the ice cover over the Great Lakes (Bai et al., 2012; Ghatak et al., 2010; Hurrell & Van Loon, 1997; Wettstein & Mearns, 2002).

In addition to the drivers from the mid- and high-latitudes, remote forcings from tropical oceans are likely to contribute to anomalous temperature over North America through atmospheric teleconnections. La Niña events are usually associated with an anomalous cold winter over northwestern North America (Guo et al., 2017; Nishihira & Sugimoto, 2022) and may enhance cold extreme events (Martineau et al., 2021; Sung et al., 2019), while the Madden-Julian Oscillation may impact the wintertime surface air temperature (SAT) variability over North America (Lin & Brunet, 2009; Seo et al., 2016; Zheng et al., 2018). However, most previous studies focus on the effects of the tropical Pacific and the tropical Indian Ocean (Ge & Luo, 2022; Lin & Brunet, 2009; Nishihira & Sugimoto, 2022; Seo et al., 2016; Sigmond & Fyfe, 2016; Zheng et al., 2018), while remote forcings associated with the tropical Atlantic are relatively less understood. Additionally, mechanisms for North American cold springs are less investigated than those for cold winters, although the weakening of Aleutian low driven by tropical sea surface temperature (SST) trends is suggested to drive a multi-decadal SAT trend over northwestern North America (Sun et al., 2019). This motivates us to investigate the effect of the tropical Atlantic SST variability on springtime SAT anomalies over North America on interannual time scales.

Even though the tropical Pacific SST variability is considered to have stronger global impacts than other ocean basins across a range of timescales, the tropical Atlantic SST variability can also exert substantial influences on global climate than otherwise recognized. Anomalous warming over the entire tropical Atlantic contributes to the increase of the precipitation over the Amazonian rain forest (Wang et al., 2018). It also drives a deepened Amundsen Sea Low through Rossby wave dynamics, leading to rapid warming over West Antarctica (Li et al., 2014). The north tropical Atlantic (NTA) SST variability usually induces rainfall anomalies in the northeast Brazil, the Sahel and most of the U.S. (Giannini et al., 2003; Kushnir et al., 2010; Marengo et al., 2017).

On the other hand, the tropical Atlantic variability also interacts with climate variability at the higher-latitudes and with other tropical ocean basins (Chen et al., 2015; Li et al., 2016; Xie & Carton, 2004; Zhang & Han, 2021). Both El Niño events and a negative phase of NAO can heat the NTA through modulating the northeast trade winds and thus the latent heat flux over the tropical Atlantic (Czaja et al., 2002; Enfield & Mayer, 1997; Huang, 2004; Saravanan & Chang, 2000). The NTA warming in turn feeds back to the ENSO system and the NAO by driving a central-eastern equatorial Pacific cooling (Ham et al., 2013) as well as a negative phase of NAO and a dipole SST response over the extratropical North Atlantic in spring (Wu et al., 2007).

In this study, we investigate the impacts of the tropical Atlantic SST variability on SAT anomalies over North America in boreal (the same below) spring on interannual time scales. With a combination of the observational-based statistical analysis and climate model experiments, we reveal that the tropical Atlantic SST variability generates a Rossby wave train that propagates to the extratropical Atlantic and induces SAT variations over North America. The tropical Atlantic warming can trigger an anomalous low pressure (cyclonic) center over mid-latitude North America and the North Atlantic. This chain of processes contributes to surface cooling over the west coast of North America through both thermal advection and cloud radiative feedback.

2. Data and Methods

2.1. Datasets and Statistical Methods

The UK Met Office Hadley Centre's SST data set (HadISST) (Rayner et al., 2003) is used in the data analysis and model simulation. We use the Global Precipitation Climatology Project (GPCP) observational data set to examine tropical Atlantic precipitation anomalies (Huffman et al., 2009). We use the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5) (Hersbach et al., 2020) to obtain monthly averaged atmospheric variables including SAT, sea level pressure (SLP), and geopotential height (GPH), etc.

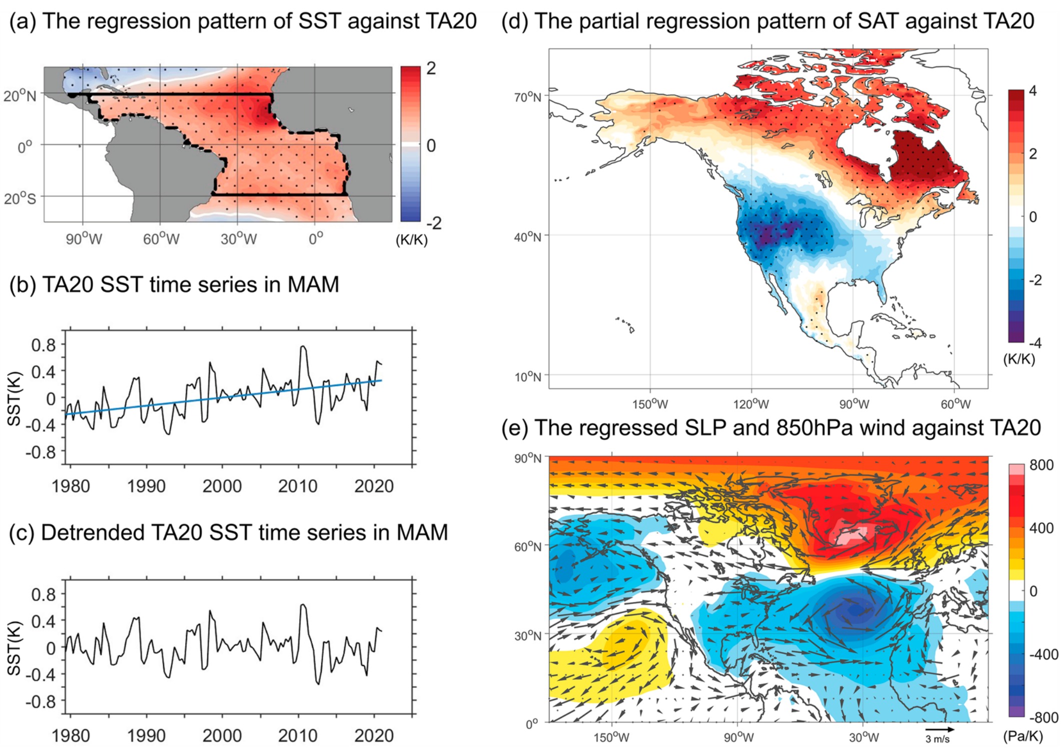

Figure 1. Observed atmospheric anomalies over North America associated with the tropical Atlantic variability in spring. (a) The spatial pattern of the anomalous tropical Atlantic SST, that is, the regression pattern of the SST against the detrended tropical Atlantic SST time series (as shown in c) in MAM from 1979 to 2020 (Units: K/K). The tropical Atlantic is defined as the area between 20°S and 20°N, within the Atlantic basin (black contour in a). (b) The area-weighted mean tropical Atlantic SST time series (Units: K) in MAM from 1979 to 2020, named as the TA20 SST index. The blue solid line indicates the linear trend of the TA20 time series. (c) The detrended TA20 time series (Units: K). (d), The partial regression pattern of North American SAT anomalies against the detrended TA20 SST time series (as shown in c) in MAM during the period of 1979–2020, with the Niño 3.4 index removed (Units: K/K). Panel (e) same as (d) but for the SLP (color shading, Units: Pa/K) and the 850 hPa wind (arrows, Units: $m \cdot s^{-1}$/K). Stippling indicates that the regression coefficients are statistically significant at the 5% level based on a Student's *t*-test.

In this study, linear regression/partial regression analysis is used to investigate the relationship between tropical Atlantic SST variabilities and SAT anomalies over North America in spring. Given the complexity of tropical climate variabilities, we used four SST indices to represent tropical Atlantic SST variabilities, including the tropical Atlantic (TA20, 20°S–20°N, Figures 1a and 1b), the tropical north Atlantic (TNA, 57.5°W–15°W, 5.5°N–23.5°N, Figures S1a and S1b in Supporting Information S1) (Enfield et al., 1999), the tropical south Atlantic (TSA, 30°W–10°E, 20°S–0°, Figure S1c and S1d in Supporting Information S1) (Enfield et al., 1999) and the Atlantic Niño (ATL3, 20°W–0°W, 3°S–3°N, Figure S1e and S1f in Supporting Information S1) (Zebiak, 1993) SST time series. Because ENSO can in part drive the tropical Atlantic SST variability (Xie & Carton, 2004), we linearly remove the Niño 3.4 signal (SST anomalies averaged from 170°W to 120°W, 5°S to 5°N) in all partial regression analyses. We apply Student's *t*-tests to evaluate statistical significance.

2.2. Model Simulation

We use the National Center for Atmospheric Research climate model, the Community Atmosphere Model version 5 (CAM5), to simulate the teleconnection between the tropical Atlantic SST forcing and the SAT response over North America. We employ the finite-volume dynamical core of CAM5 with a global horizontal resolution of about 2° (F19_F19). The SST over the tropical Atlantic is the only external surface boundary forcing in our experiment.

In this study, we perform a transient experiment with CAM5 forced by the observed monthly averaged SST during the 1979–2020 period. The experiment includes 12 ensemble members, starting from different initial conditions. Each ensemble member is driven by the observed SST variability over the TA20 region (20°S–20°N, Figures 1a and 1b) with 10° buffer zones on its north and south boundary. The SSTs outside this region are set to the seasonally varying, climatological mean state over the period 1981–2010. We calculate the ensemble mean of the simulation results, representing the model response to the tropical Atlantic SST forcing.

3. Results

3.1. Teleconnection Between Tropical Atlantic and North American SAT

To investigate the relationship between the tropical Atlantic SST variability and springtime North American SAT anomalies, we first perform a linear regression analysis of the SAT against the monthly-mean TA20 (Figure 1c) SST time series in spring (March-April-May, MAM) during the 1979–2020 period. The springtime TA20 time series exhibited a positive trend of 0.12 K/decade (Figure 1b). Before the regression, we first remove the linear trend and exclude the Niño 3.4 index from these time series. The regression result (Figure 1d) shows a significant continental-wide cold anomaly over mid-latitude North America in spring, especially over the central part of the U.S. and its west coast, associated with a positive SST anomaly over the tropical Atlantic.

Given the complexity of tropical Atlantic SST variabilities, we further regress the North American SAT against other three tropical Atlantic SST indices, including TNA, TSA and ATL3 time series (Figures S1a, S1c, and S1e in Supporting Information S1), to evaluate the robustness of the teleconnection between tropical Atlantic SST variabilities and North American SAT anomalies. All three indices exhibit warming trends during the 1979–2020 period. These linear trends and the Niño 3.4 index are removed before the regression. The regressed SAT patterns against the three SST indices all show significant cooling anomalies over mid-latitude North America (Figure S2 in Supporting Information S1), similar to that in Figure 1d, but with slightly weaker magnitudes. This similarity validates the robustness of the teleconnection between the tropical Atlantic warming and the surface cooling over mid-latitude North America on interannual time scales. Because the TA20-regressed SAT pattern exhibits largest amplitude (Figure 1d), we focus on the influence of TA20 on North American SAT anomalies in the rest of this study.

The tropical SST variability usually impacts the mid-/high-latitude climate system through triggering tropical deep atmospheric convection that excites atmospheric Rossby waves that modulate the large-scale atmospheric circulation over the mid- and high-latitudes. We next examine the tropical precipitation and the large-scale atmospheric circulation anomalies associated with the tropical Atlantic SST variability through linear regression. The TA20 SST warming coincides with an increase in tropical precipitation (Figure S3 in Supporting Information S1), which indicates the intensification of deep atmospheric convection, over the equatorial Atlantic. These changes in tropical Atlantic convective precipitation are further associated with a Rossby wave pattern (Figure 1e), characterized by an anomalous low pressure center over the mid-latitude North Atlantic and a high pressure center over Greenland at the 850 hPa-level. This regression pattern shares a similarity with the negative phase of NAO with a westward shift in the high pressure center.

3.2. CAM5 Experiments Reproduce the Teleconnection

The linear regression results indicate that warm anomalies over the tropical Atlantic may be associated with cold springs over mid-latitude North America. However, statistical analysis cannot identify the causality of the teleconnection. We therefore perform an atmospheric model experiment (CAM5) to clarify the causal relationship between the tropical Atlantic SST and North American SAT anomalies (See Method Section).

The simulation results confirm that the tropical Atlantic warming can generate a stationary Rossby wave pattern over the mid- and high-latitude Atlantic (Figure 2a), further driving a cooling pattern over central-western North America (Figure 2b). The simulated Rossby wave train resembles the observation (Figure 1e). However, the low pressure center over the mid-latitude North Atlantic at the low-level suffers from a westward shift in comparison to that of the observation, whereas the anomalous high pressure center over Greenland is shifted eastward. Given the complexity of the jet system and the strong wave-mean flow interaction over the North Atlantic, the simulation results reasonably reproduce the circulation response to the tropical Atlantic forcing inferred from the observation, especially the low pressure center over the North Atlantic.

The simulated SAT response to the tropical Atlantic SST forcing exhibits similar but broader cooling anomalies over North America (Figure 2b) compared to the observation (Figure 1d). Remarkably, the strongest cooling

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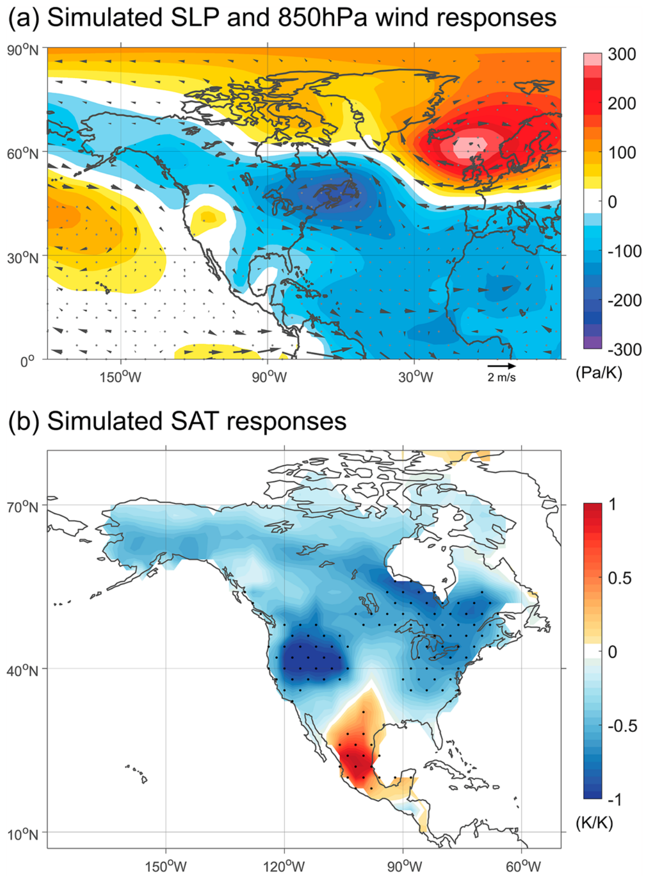

Figure 2. Simulated atmospheric responses to the tropical Atlantic SST warming in spring. (a) The SLP (color shading) and the 850 hPa wind (arrows) responses in CAM5 experiment, driven by the warm SST over the tropical Atlantic (See Method). Panel (b) same as (a), but for the SAT response over North America. Stippling indicates the ensemble mean regression coefficients are statistically significant at the 5% level based on a Student's *t*-test.

anomaly appears over the central-western part of mid-latitude North America, agreeing well with the observations. The model experiment result (Figure 2b) does not, however, reproduce the warming pattern well over northeastern North America (Figure 1d), partly due to the eastward shift of the anomalous high pressure center in the simulation (Figure 2a).

The similarity of SAT and atmospheric circulation anomalies between the statistical analysis and numerical model experiments not only verifies the robustness of the tropical Atlantic - North America teleconnection, but also clarifies the physical pathway. That is, the tropical Atlantic SST anomalies trigger a regional deep atmospheric convection that generates a stationary Rossby wave train over the North Atlantic and further drive North American surface temperature anomalies. In the next section, we will clarify the mechanisms how the tropical Atlantic warming-induced atmospheric circulation anomalies contribute to cold springs over mid-latitude North America.

3.3. Physical Processes Driving North American Cold Springs

A potential pathway for the large-scale atmospheric circulation adjustment to influence the regional SAT is through thermal advection. In order to investigate the effect of the tropical Atlantic SST on the anomalous thermal advection over North America, we regress the springtime temperature advection (at the 850 hPa-level) against the TA20 SST time series using ERA5 reanalysis data set. These results show that the tropical Atlantic warming-induced thermal advection leads to cooling over entire mid-latitude North America (Figure 3a). The tropical Atlantic warming-induced anomalous low pressure center (Figure 1e) over eastern North America and the mid-latitude North Atlantic advects cold air from the higher-latitudes to central-western areas of North America. While this advection process clearly contributes to cold springs over North America, its cooling pattern does not capture the strongest cooling signal over the central-western part of mid-latitude North America (Figure 1d), implying that other mechanisms may also play important roles in driving cold springs over North America.

Other than thermal advection, recent studies (Sedlar et al., 2011; Yu & Zhong, 2018) suggest that cloud feedback associated with anomalous atmospheric circulation can also contribute to surface temperature anomalies through its radiative effects. Therefore, we examine the regressed changes of the total cloud cover in spring in response to the TA20 SST variability. Cloud cover significantly increases over central-western North America between 40°N and 60°N in response to the tropical Atlantic warming. Similar to that of the thermal advection, the tropical Atlantic warming-induced circulation adjustment may drive anomalous moisture convergence over mid-latitude North America (Figure 3c) and contribute to the increase in cloud cover over central-western North America (Figure 3b).

The changes in cloud cover may contribute to SAT anomalies through short-wave and long-wave radiative forcings. We regress surface short-wave and long-wave radiative fluxes (downward) over the North American continent against the TA20 SST time series. In response to the cloud changes induced by the tropical Atlantic warming, the downward short-wave radiation over central-western North America decreases significantly (Figure 3d), with a maximum amplitude of up to 10 W m^{-2}/K. On the other hand, the tropical Atlantic warming-induced cloud cover increase can also drive a positive long-wave radiative forcing to the surface (Figure 3e), contrary to the effect of short-wave radiation. However, the magnitude of the long-wave radiative forcing (Figure 3e) is overwhelmed by that of the short-wave radiation (Figure 3d), leading to a net cooling effect over central-western North America (Figure 3f). This spatial pattern agrees well with the anomalous SAT pattern in Figure 1d, especially the maximum cooling over the central-western part of mid-latitude North America, indicating that the cloud feedback triggered by the circulation adjustment contributes substantially to the teleconnection between the tropical Atlantic warming and the mid-latitude North American cooling.

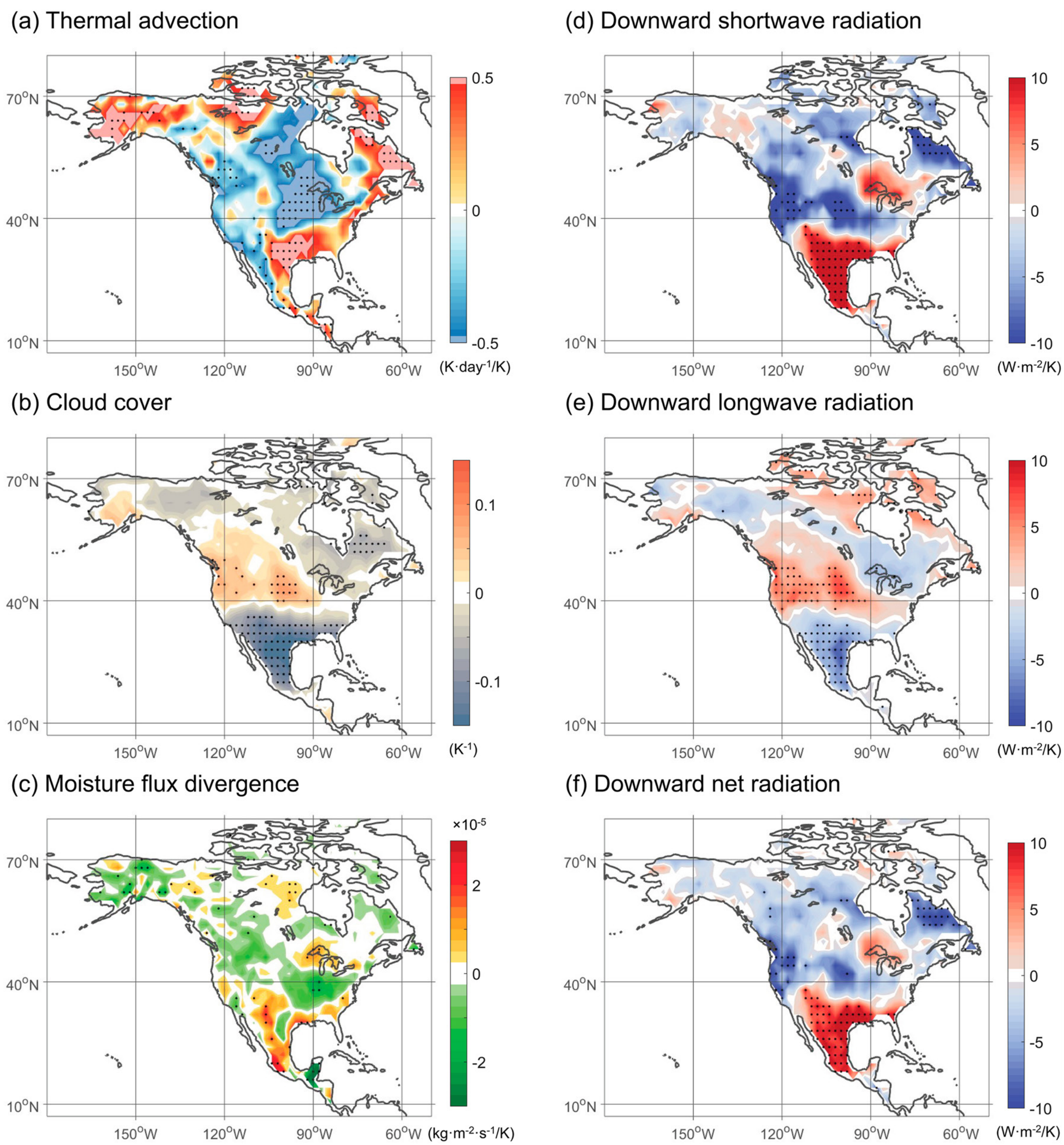

Figure 3. Thermal advection and cloud radiative forcing over North America associated with the tropical Atlantic warming in spring. (a) The partial regression pattern of the thermal advection at 850 hPa against the detrended TA20 SST time series (Figure 1c), with the Niño 3.4 index removed (Units: $K \cdot day^{-1}/K$). Panel (b) same as (a), but with the total cloud cover (Units: K^{-1}). Panel (c) same as (a), but with the moisture flux divergence from the surface to 500 hPa (Units: $kg \cdot m^{-2}\ s^{-1}/K$), with positive values (red) indicating the divergent anomalies and negative values (green) indicating the convergent anomalies. Panels (d, e) same as (a), but for the downward shortwave (d) and long-wave (e) radiation flux (Units: $W \cdot m^{-2}/K$), respectively. Panel (f) denotes the downward net radiation flux associated with the TA20 SST time series. Stippling indicates that the regression coefficients are statistically significant at the 5% level based on a Student's *t*-test.

4. Conclusions and Discussion

In this study, we investigate the relationship between the tropical Atlantic SST variability and SAT anomalies over North America in spring. Based on the statistical analysis and the numerical model experiments, we reveal that the tropical Atlantic warming intensifies the deep atmospheric convection which generates a stationary Rossby wave pattern over the North Atlantic (contours in Figure 4) with an anomalous cyclonic circulation center over the mid-latitude North Atlantic. This low-level large-scale atmospheric circulation adjustment advects cold air (blue arrow in Figure 4) from the high-latitudes to central-western North America while increases the cloud cover over central-western North America, which further induces the surface cooling through its radiative effects (Figure 4). This chain of mechanisms links the tropical Atlantic SST variability to North American SAT, allowing

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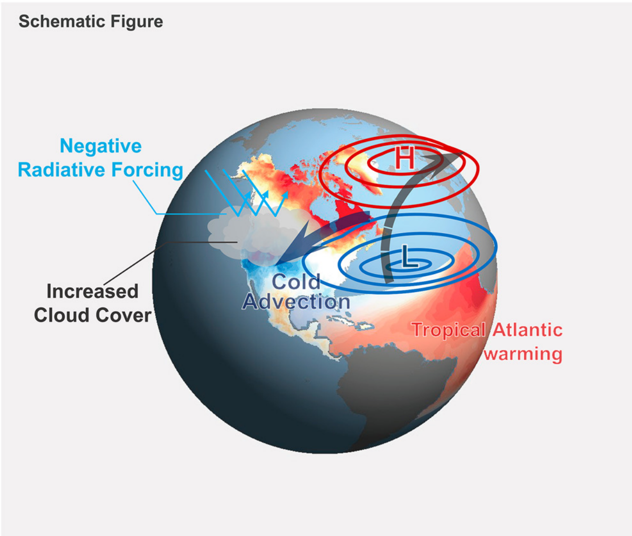

Figure 4. Schematic diagram of physical mechanisms of the teleconnection between the tropical Atlantic warming and the surface cooling over mid-latitude North America in spring. Anomalous tropical Atlantic SST warming leads to an enhanced atmospheric deep convection that excites a poleward propagating Rossby wave train into the North Atlantic. The resulting negative NAO-like circulation pattern drives springtime North American temperature anomalies primarily through cold advection and cloud shading with increased cloud cover.

the tropical Atlantic warming to trigger a cold spring over mid-latitude North America. Based on the linear methods used in this study, we anticipate that anomalous cooling in the tropical Atlantic would induce anomalies of opposite sign.

Here, we focus on the effect of the tropical Atlantic on the occurrence of cold springs over North America on interannual time scales, given that anomalous cold springs have been prevalent over parts of North America in recent decades (Sun et al., 2019). Besides this newly established teleconnection, climate variabilities over the tropical Pacific, the North Atlantic, as well as the Arctic sea ice and polar vortex are all likely to contribute to the SAT variability over North America, as revealed by previous studies (Cohen et al., 2021; Infanti & Kirtman, 2016; Lee et al., 2019; Liu et al., 2015; Sigmond & Fyfe, 2016; Sun et al., 2019; Sung et al., 2019; Wettstein & Mearns, 2002; Zhang et al., 2020; Zheng et al., 2018). However, the spatial patterns of SAT anomalies triggered by different teleconnections are distinct (Guo et al., 2017; Hurrell & Van Loon, 1997; Kug et al., 2015; Liu et al., 2015; Seo et al., 2016).

It is important to indicate that the inter-basin interactions (Figure S6 in Supporting Information S1) may contribute to the impacts of tropical oceans on the mid-latitudes. In particular, an El Niño event can heat the Indian Ocean and the NTA through atmospheric bridges (Alexander & Scott, 2002; Chambers et al., 1999), while the tropical Atlantic warming in return heats the Indian Ocean and drive a La Niña-like pattern in the tropical Pacific (Kucharski et al., 2011, 2015; Li et al., 2016). These effects may facilitate the tropical Atlantic SST variability and further impact the North American temperature. Moreover, the Matsuno-Gill model (Gill, 1980; Matsuno, 1966) also largely contributes to the teleconnection pattern. The SST variability over one ocean basin may drive that over other basins through Gill-effect, subsequent Walker circulation adjustment and Ekman pumping (Hamouda & Kucharski, 2019).

A good example is the interaction between the tropical Pacific and the tropical Atlantic (Alexander & Scott, 2002; Ham et al., 2013) and their combined effects on the higher-latitudes (Li et al., 2015; Simpkins et al., 2016). To better clarify this interactive relationship, we perform an additional analysis by linearly regressing the springtime North American SAT against the standardized Niño 3.4 index with (Figure S4b in Supporting Information S1) and without (Figure S4a in Supporting Information S1) the TA20 time series removed, and then linearly regressing the SAT against the standardized TA20 time series with (Figure S5b in Supporting Information S1) and without (Figure S5a in Supporting Information S1) the Niño 3.4 index removed, respectively. Results suggest that the relationship between the tropical Atlantic SST and the North American SAT is of similar amplitude as that between ENSO and the North American SAT. The tropical Atlantic SST is, nevertheless, explaining the most North American SAT variability in the mid-latitude central-western region (Figure S5 in Supporting Information S1), where ENSO has little influence (Figure S4 in Supporting Information S1). Given the complexity of the tropical inter-basin interactions and the tropical-mid-latitudes teleconnections, the combined and interactive effects of these climate variabilities on North American cold springs remain unclear, which we will further investigate in our future study.

In recent decades, along with the anthropogenic global warming, mid-latitude North America frequently suffered from cold winters and springs, which seriously affected agricultural production, power supply, and transportation systems. By building a relationship between the tropical Atlantic SST and North American SAT variabilities, this study helps us to achieve a better understanding of the mechanisms of North American cold springs, which may contribute to improving the seasonal predictability of these cold events and have broad public health and economic implications.

Data Availability Statement

The HadISST data is available at https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html. The GPCP data is available at https://psl.noaa.gov/data/gridded/data.gpcp.html. The ERA5 reanalysis data is available at https://www.ecmwf.int/en/forecasts/datasets.

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