Hot Summers in the Northern Hemisphere

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Abstract The past two summers of 2017 and 2018 are very hot in the Northern Hemisphere, but the causes are not clear. Here we identify natural internal variabilities of seven atmospheric circulation patterns that can cause the increase of summer surface air temperature: North Atlantic pattern, Europe pattern, East Atlantic pattern, West Atlantic pattern, Chukchee Sea-North America pattern, Arctic Ocean-North America pattern, and Beaufort Sea-Siberia pattern. The magnitude of increased air temperature induced by internal variabilities associated with these atmospheric circulation patterns is comparable to or even larger than that caused by global warming. A combination of natural internal variabilities and global warming explains summer surface air temperature variations in the Northern Hemisphere. The results show that accurate forecast of these atmospheric circulation patterns can help to predict summer surface air temperature in the Northern Hemisphere.

Plain Language Summary Previous studies suggest that surface air temperature variations in the Northern Hemisphere are affected by greenhouse effect, El Niño–Southern Oscillation, the North Atlantic Oscillation, and so on. However, the past two summers of 2017 and 2018 in the Northern Hemisphere are still very hot even without the variations such as El Niño–Southern Oscillation and the North Atlantic Oscillation. Here we identify seven atmospheric circulation patterns by using atmospheric teleconnection method, and find that a combination of these identified atmospheric circulation patterns and global warming explains summer surface air temperature variations in the Northern Hemisphere. Our results also suggest that accurate forecast of the atmospheric circulation patterns can help to predict the summer surface air temperature in the Northern Hemisphere.

1. Introduction

The summer is becoming hotter in recent decades. Due to the increased occurrence of heatwaves which often lead to more heat-related injuries and deaths (Barriopedro et al., 2011; Mora et al., 2017), the research on surface air temperature (SAT) variation becomes of crucial importance. For the SAT in the Northern Hemisphere (NH), previous studies suggest that the SAT variations are influenced by greenhouse effect (Kaufmann & Stern, 1997), El Niño–Southern Oscillation (ENSO; Klein et al., 1999), and the North Atlantic Oscillation (NAO; Li et al., 2013). However, the summer in the NH is still hot even without the variations such as ENSO and the NAO, implying that the summer SAT and its causes need to be investigated.

In the past two years, the NH experiences two hot summers (Figure S1). For example, the National Oceanic and Atmospheric Administration reported that 2017 was the third warmest year on record for the globe, which is not caused by warming effect of an El Niño event; the Washington Post reported that the NH has recorded the hottest temperature around the beginning of July 2018, with a record-breaking high temperature in Southern California and an incredible heat event in Siberia; the World Meteorological Organization reported that Scandinavia was strongly hit by heatwaves in the middle of July 2018, with a record temperature of 33.5 °C in Badufoss, Norway and 33.4 °C in Kevo, Finland. Figure 1a shows the SAT anomalies in the NH during the summer of 2017 relative to the climatological mean of 1971–2000. Large and warm SAT anomalies appear in many places of the NH, including the west of North America, southern Europe, and the region around Lake Baikal. Besides, cool SAT anomalies are observed in the east of North America. Figure 1b presents the SAT anomalies in the NH during the summer of 2018. Compared to Figure 1a, the SAT anomalies during the summer of 2018 exhibit a different distribution, with warm SAT anomalies in the west of North America, northern Europe (especially in Scandinavia), and Siberia. The
different distributions of summer SAT anomalies suggest that we cannot automatically and simply attribute hot summers in the NH to global warming.

Here we focus on atmospheric circulations in association with the hot summers. Figures 1c and 1d illustrate the geopotential height (GHT) and wind anomalies at 500 hPa in the NH during the summers of 2017 and 2018. It can be seen that the warm (cool) SAT anomalies are basically coincided with the positive (negative) GHT anomalies and anticyclonic (cyclonic) circulation anomalies. Furthermore, there is a meridional dipole pattern of GHT anomalies located over the East Atlantic and Europe during the summer of 2017, whereas a zonal dipole pattern of GHT anomalies appears over the Beaufort Sea and Siberia during the summer of 2018. It seems that atmospheric circulation patterns may contribute to the SAT anomalies in the NH during the summers of 2017 and 2018. However, how to describe atmospheric circulation patterns in a simple and quantitative way and to what extent atmospheric circulation patterns affect the SAT variations are unclear.

Figure 1. SAT and atmospheric circulation anomalies during the summers of 2017 and 2018. (a and b) SAT anomalies (shading, units: °C) in the NH during the summers of 2017 and 2018. (c and d) The 500-hPa GHT anomalies (shading, units: gpm) and wind anomalies (vectors, units: m/s) in the NH during the summers of 2017 and 2018.
2. Data Sets and Methods

2.1. Data Sets

The analysis is based on boreal summer (June to August) mean data for the period of 1950–2018. The atmospheric data set of the National Centers for the Environmental Prediction/National Center for Atmospheric Research reanalysis I (NCEP/NCAR-I) is used, which includes SAT, GHT, and horizontal winds on a 2.5° × 2.5° grid (Kalnay et al., 1996). The European Centre for Medium-Range Weather Forecasts 40-year reanalysis (ERA40; Uppala et al., 2005) is also used to verify the seesaw relationship between the two poles of atmospheric circulation patterns. The climatological mean is defined as the mean over the period of 1971–2000.

2.2. Teleconnection Method

The method used to define atmospheric circulation patterns in this study is based on the teleconnection method promoted by Wallace and Gutzler (1981), but for the boreal summer. First, the teleconnectivity matrix is defined as the maximum negative correlation ($T_i$) between each grid point (denoted by the subscript i) and any other grid point (denoted by the subscript j) in detrended 500-hPa GHT over the region (180°W–180°E, 25°–90°N):

$$T_i = \min \left( r_{ij} \right)$$

(1)

Second, the teleconnection lines, which connect two grid points having the strongest negative correlation with each other, are plotted on the teleconnectivity map to reveal atmospheric circulation patterns (Figure 2). To obtain the dominant atmospheric circulation patterns in the NH, only the teleconnection lines significant at the 99.99% confidence level are plotted (see supporting information for details). If there are more than one teleconnection lines in same direction in the region nearby, we treat them as one atmospheric circulation pattern and only the teleconnection line having the strongest negative correlation is shown. Specially, although there are two teleconnection lines with different directions in the western Atlantic, the southern poles of the two teleconnection lines are close to each other and we thus still treat them as one atmospheric circulation pattern. The atmospheric circulation patterns we find are North Atlantic pattern, Europe pattern, East Atlantic pattern, West Atlantic pattern, Chukchee Sea-North America pattern, Arctic Ocean-North America pattern, and Beaufort Sea-Siberia pattern.

To describe the variations of the atmospheric circulation patterns, we define simple indices by detrended 500-hPa GHT over the poles of the atmospheric circulation patterns (Table S1 in supporting information):

$$TI = \frac{H_A - H_B}{2},$$

(2)

where $H_A$ ($H_B$) is the standardized detrended 500-hPa GHT anomalies over Pole A (B) of the atmospheric circulation patterns. West Atlantic pattern consists of four poles; thus, $H_A$ ($H_B$) is the mean of the standardized detrended 500-hPa GHT anomalies over the two poles in the Western Atlantic (South of Greenland).

2.3. The Stepwise Fitting Method for Reconstructing SAT Anomalies

The stepwise fitting method is a method for adding and removing terms from a multilinear regression model based on their statistical significance, and is usually used to build statistical models when variables are not independent each other (Taylor et al., 1998). In this study, the stepwise fitting method is employed to check whether the SAT anomalies during the summers of 2017 and 2018 can be explained by global warming and natural internal variabilities associated with the atmospheric circulation patterns we defined. First, the natural SAT anomalies in the NH are obtained by removing global warming (for simplicity, we use the linear trend in this paper although global warming is not linear) from the raw SAT variations (Henley et al., 2015). Second, to avoid overfitting and interference from weak atmospheric circulation patterns, the atmospheric circulation patterns with the indices between 0.8 and −0.8 are filtered out before the stepwise fitting procedure for a specified year. Third, the reconstructed natural SATs are obtained by using principal atmospheric circulation patterns determined by the stepwise fitting procedure (see supporting information for...
Fourth, the reconstructed SATs are finally obtained by adding the global warming component to the reconstructed natural SATs.

2.4. Attribution Analysis

Based on the reconstructed SATs, attribution analysis is conducted to examine the role of global warming and internal variabilities associated with atmospheric circulation patterns. First, the SAT variations explained by global warming (SAT\textsubscript{gw}) are estimated as difference between the raw SATs and detrended SATs. Then, the SAT variations explained by one atmospheric circulation pattern are derived as the product of its index and its regression coefficient of the detrended SATs in the stepwise fitting models, and the SAT variations explained by atmospheric circulation patterns (SAT\textsubscript{acp}) are derived as the sum of them. The residual (SAT\textsubscript{res}) represents the SAT variations that cannot be linearly explained by global warming and internal variabilities. The contributions of global warming and internal variabilities associated with atmospheric circulation patterns are derived as

$$C = \frac{|\text{SAT}_{gw}| + |\text{SAT}_{acp}|}{|\text{SAT}_{gw}| + |\text{SAT}_{acp}| + |\text{SAT}_{res}|}$$

where |SAT| represents the absolute value of SAT.
2.5. The Stepwise Fitting Method for Predicting SAT Anomalies

The stepwise fitting method is also employed to predict the SAT anomalies during the summers of 2017 and 2018 based on the known atmospheric circulation pattern indices and historical data. For the predicted SAT anomalies during the summer of 2017, we use the atmospheric circulation pattern indices in 2017 and the historical data from 1950 to 2016. First, the atmospheric circulation patterns in 2017 with their indices between 0.8 and −0.8 are filtered out before establishing statistical models. Then, the predicted natural SATs are obtained by using the atmospheric circulation pattern indices in 2017 and statistical models based on the historical data from 1950 to 2016. Finally, the predicted SATs in 2017 are acquired by adding the global warming component for 2017 to the predicted natural SATs. Similarly, predicting the 2018 summer SAT anomalies uses the atmospheric circulation pattern indices in 2018 and the historical data from 1950 to 2017.

3. Results

Atmospheric circulation patterns can be identified by using teleconnection method (Wallace & Gutzler, 1981) and rotated principle component analysis method (Barnston & Livezey, 1987) or empirical orthogonal function method (Ding & Wang, 2005; Wulff et al., 2017). To get a better representation of atmospheric circulation patterns in this study, we objectively obtain atmospheric circulation patterns in the NH by using teleconnection method based on Wallace and Gutzler (1981), but for the boreal summer. The atmospheric circulation patterns we find and define are North Atlantic pattern, Europe pattern, East Atlantic pattern, West Atlantic pattern, Chukchee Sea-North America pattern, Arctic Ocean-North America pattern, and Beaufort Sea-Siberia pattern (Figure 2). North Atlantic pattern (Europe pattern, East Atlantic pattern, West Atlantic pattern, Chukchee Sea-North America pattern, Arctic Ocean-North America pattern, Beaufort Sea-Siberia pattern) is characterized by the seesaw relationship in detrended 500-hPa GHT between Greenland (southern Europe, Eastern Atlantic, Western Atlantic, North America, North America, Siberia) and the British Isles (East of the British Isles, West of the British Isles, South of Greenland, Chukchee Sea, Arctic Ocean, Beaufort Sea) (Table S1 and Figure S2). The seesaw relationship between the two poles of the atmospheric circulation patterns is still evident in the ERA40 data set for the period of 1958–2002 (Figure S3), although there are some discrepancies in comparison with the NCEP/NCAR-I data set (Greatbatch & Rong, 2006). To describe the variations of atmospheric circulation patterns, we define simple indices by detrended 500-hPa GHT over the poles of the atmospheric circulation patterns as shown in equation (2) of section 2.2. For brevity, NAI (EUI, EAI, WAI, CNAI, ANAI, and BSI) is abbreviation for North Atlantic pattern index (Europe pattern index, East Atlantic pattern index, West Atlantic pattern index, Chukchee Sea-North America pattern index, Arctic Ocean-North America pattern index, and Beaufort Sea-Siberia pattern index). These indices can express well the structures of the natural atmospheric circulation patterns in a simple and quantitative way (Figure S4).

The linear trend of summer SAT in the NH is presented in Figure 3a. Summer SAT in most regions of the NH exhibits a warming trend for the period of 1950–2018, with strong trends located in southern Europe, the Sahara desert, and the region around Lake Baikal. Although global warming is not linear and uniform over time, these observed SAT trends can be approximately attributed to human-caused SAT increase. For simplicity, natural SAT variations are obtained by removing the linear trend from the raw SAT variations (Henley et al., 2015). Figures 3b–3h show the regressed natural SAT anomalies onto the atmospheric circulation pattern indices we defined. The atmospheric circulation patterns, which represent atmospheric internal variables, have remarkable influences on the SAT in the NH. For example, East Atlantic pattern significantly affects the detrended SATs in the west of North America, east of North America, and the region around Lake Baikal, whereas Beaufort Sea-Siberia pattern significantly influences the SATs in Siberia, Beaufort Sea, and northern Europe. It should be noted that the atmospheric circulation patterns not only affect the SATs in the poles of the atmospheric circulation patterns but also may have a remote impact on the SATs in other regions. Furthermore, different atmospheric circulation patterns have different effects on the SAT variations in the NH, and the SAT anomalies in the NH are always caused by one or more atmospheric circulation patterns. As shown in Figures 3i–3o, the dominant atmospheric circulation patterns during the summer of 2017 are Europe pattern, East Atlantic pattern, West Atlantic pattern, and Arctic Ocean-North America pattern, whereas the significant atmospheric circulation patterns during the
Figure 3. Summer SAT variations in association with global warming and atmospheric internal variabilities. (a) Linear trend of summer SAT (units: °C per decade) in the NH for period of 1950–2018. The areas significant at the 95% confidence level are dotted. (b–h) Regressed summer SAT anomalies (units: °C) onto NAI, EUI, EAI, WAI, CNAI, ANAI, and BSI for the period of 1950–2018. In (b)–(h), the data are detrended before analysis, and the areas significant at the 95% confidence level are dotted. (i–o) Standardized time series of NAI, EUI, EAI, WAI, CNAI, ANAI, and BSI (bar) and seven-year running mean of the atmospheric circulation pattern indices (black line) for the period of 1950–2018. The dashed lines denote the reference line of ±0.8.
summer of 2018 are North Atlantic pattern, Europe pattern, West Atlantic pattern, and Beaufort Sea-Siberia pattern. Moreover, the BSI reached its maximum value since 1950 in the summer of 2018, and the EAI had its second maximum value in the summer of 2017.

**Figure 4.** Combined effect of global warming and atmospheric internal variabilities on summer SAT. (a and b) Reconstructed summer SAT anomalies (shading, units: °C) in the NH during the summers of 2017 and 2018. The black rectangles in (a) and (b) denote the regions used for attribution analysis. (c) Attribution analyses of the SAT variations (units: °C) in the west of North America (125°–112.5°W, 37.5°–57.5°N), southern Europe (15°–35°E, 37.5°–47.5°N), and Lake Baikal (92.5°–127.5°W, 47.5°–60°N) during the summer of 2017. GW is abbreviation for global warming. (d) Same as in (c) but for the SAT variations in the west of the United States (125°–112.5°W, 37.5°–50°N), northern Europe (5°–30°E, 52.5°–62.5°N), and Siberia (95°–132.5°W, 60°–72.5°N) during the summer of 2018.
The question is whether internal variabilities associated with the atmospheric circulation patterns and global warming can explain the SAT anomalies during the summers of 2017 and 2018. In this study, the stepwise fitting method (Taylor et al., 1998) is used to reconstruct SAT variations in the NH based on the atmospheric circulation pattern indices and global warming as described in section 2. As presented in Figure 4a, the reconstructed SAT anomalies well resemble the observed SAT anomalies, with warm SAT anomalies in the west of North America, southern Europe, and the region around Lake Baikal during the summer of 2017. The reconstructed SAT anomalies in the summer of 2018 are also similar to the observation, with warm SAT anomalies in the west of the United States, northern Europe, and Siberia (Figure 4b). These suggest that global warming and internal variabilities associated with atmospheric circulation patterns jointly account for the hot summers of 2017 and 2018. For a quantitative assessment, we choose the regions of the warm SAT anomalies shown in the boxes of Figures 4a and 4b. The calculation shows that global warming and internal variabilities collectively explain 70.4%, 78.9%, and 83.1% of the total SAT variations in the west of North America, southern Europe, and Lake Baikal, respectively, during the summer of 2017. During the summer of 2018, global warming and internal variabilities explain 77.4%, 87.9%, and 86.9% of the total SAT variations in the west of the United States, northern Europe, and Siberia, respectively.

As shown in Figures 4c and 4d, the natural SAT variations in these regions are largely controlled by one or more atmospheric circulation patterns. During the summer of 2017, the SATs in southern Europe and in the region around Lake Baikal are controlled by Europe pattern and East Atlantic pattern, respectively, whereas the SAT in the west of North America is affected by both East Atlantic pattern and West Atlantic pattern. During the summer of 2018, the SAT in the west of the United States (Siberia) is controlled by West Atlantic pattern (Beaufort Sea-Siberia pattern), whereas the SAT in northern Europe is jointly influenced by Europe pattern and Beaufort Sea-Siberia pattern. The influence of natural internal variabilities on the SAT variations is comparable to that of global warming, and even has a larger magnitude in the west of North America during the summer of 2017 and in all three selected regions during the summer of 2018. In short, a hot summer in the NH is a combined result of global warming and internal variabilities associated with atmospheric circulation patterns.

Another question is how the atmospheric circulation patterns have a remote influence on the SAT, such as the influence of East Atlantic pattern on the SATs in Lake Baikal and in the west of North America, the effect
of West Atlantic pattern on the SATs in the west of United States, and the impact of Beaufort Sea-Siberia pattern on the SAT in northern Europe. Our study suggests that the atmospheric circulation patterns affect the SAT in the remote regions possibly via circumglobal wave train (see supporting information for details).

Next question is whether the summer SAT anomalies in the NH can be predicted if we know the atmospheric circulation pattern indices. Figure 5 shows the predicted SAT anomalies during the summers of 2017 and 2018 based on the known atmospheric circulation pattern indices and historical data. For the predicted SAT anomalies during the summer of 2017, we use the atmospheric circulation pattern indices in 2017 and the historical data from 1950 to 2016. The stepwise fitting method is also used here to select principal atmospheric circulation patterns affecting SAT anomalies and establish statistical models. Similarly, predicting the 2018 summer SAT anomalies uses the atmospheric circulation pattern indices in 2018 and the historical data from 1950 to 2017. The predicted SAT anomalies during the summers of 2017 and 2018 all resemble the observed SAT anomalies. These indicate that accurate forecast of the summer atmospheric circulation patterns can help to predict the summer SAT in the NH.

4. Conclusion and Discussion

In summary, seven atmospheric circulation patterns are identified in the NH summer: North Atlantic pattern, Europe pattern, East Atlantic pattern, West Atlantic pattern, Chukchee Sea-North America pattern, Arctic Ocean-North America pattern, and Beaufort Sea-Siberia pattern. A combination of natural internal variabilities associated with these atmospheric circulation patterns and global warming explains the summer SAT variations in the NH. Two recent hot summers of 2017 and 2018 in the NH can be reconstructed and predicted if these atmospheric circulation pattern indices are known or given. Our results suggest that accurate forecast of the atmospheric circulation patterns can help to predict the summer SAT in the NH.

In previous studies, some similar atmospheric circulation patterns have been described by using different data sources and methods. For example, the summer NAO, which corresponds to North Atlantic pattern, is obtained as the first empirical orthogonal function mode of summer mean SLP (Greatbatch & Rong, 2006) or daily SLP (Folland et al., 2009) over the Euro-Atlantic sector. To compare the atmospheric circulation patterns with some of previous studies, we regress summer SLP anomalies onto NAI, EUI, EAI, WAI, CNAI, ANAI, and BSI defined in the present paper (Figure S6). The summer NAO in Greatbatch and Rong (2006) exhibits a similar spatial pattern to North Atlantic pattern, whereas the SLP anomalies around the southern pole of the summer NAO in Folland et al. (2009) are much stronger than that around the northern pole. The East Atlantic pattern proposed by Wulff et al. (2017) is shifted to the west compared to that in our study, and it seems more like West Atlantic pattern we identified. Moreover, the spatial pattern of circumglobal teleconnection in Ding and Wang (2005) agrees well with that of West Atlantic pattern in the Eastern Hemisphere. Nevertheless, it should be noted that the atmospheric circulation patterns we identified have more clear spatial structures, and the calculation of indices in our study is relatively simpler than those by other methods.

This study emphasizes the influence of the atmospheric circulation patterns on the SAT variations in the NH, but do not necessarily downplay other climate phenomena that may also play roles in the SAT variations, such as ENSO, and sea ice in the Arctic. Ding et al. (2011) revealed two leading modes of tropical-extratropical teleconnection by using maximum covariance analysis, and discussed their relationship with tropical monsoon-related rainfall and ENSO. Li and Ruan (2018) found a North Atlantic-Eurasian teleconnection, and investigated its effect on precipitation and SAT in the Eurasian region (Li et al., 2019). The North Atlantic-Eurasian teleconnection, which consists of five poles, seems like a combination of East Atlantic pattern and Europe pattern in our study. The relative importance of these variations in the summer SAT in the NH and possible interplay among them should be further investigated.

Acknowledgments

We thank the editor and reviewers whose comments and suggestions help improve the paper. This study is supported by the National Natural Science Foundation of China under grant 41731173, the Pioneer Hundred Talents Program of the Chinese Academy of Sciences, the Leading Talents of Guangdong Province Program, the Strategic Priority Research Program of the Chinese Academy of Sciences under grant XDA20060502, the National Program on Global Change and Air-Sea Interaction under grant GASI-IPOVAI-03 and GASI-IPOVAI-04, and Independent Research Project Program of State Key Laboratory of Tropical Oceanography (LTOZZ1802). Data related to this paper can be downloaded from the following: NCEP/NCAR-I (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html) and ERA40 (https://apps.ecmwf.int/datasets/data/era40-moda/levtype=pl/).

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