Amplified summer warming in Europe–West Asia and Northeast Asia after the mid-1990s

Xiaowei Hong1,5, Riyu Lu2,3 and Shuanglin Li1,4

1 Climate Change Research Center and Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People’s Republic of China
2 State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People’s Republic of China
3 University of the Chinese Academy of Sciences, Beijing, People’s Republic of China
4 Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, People’s Republic of China
5 Author to whom any correspondence should be addressed.

Abstract
Regional temperature changes are a crucial factor in affecting agriculture, ecosystems and societies, which depend greatly on local temperatures. We identify a nonuniform warming pattern in summer around the mid-1990s over the Eurasian continent, with a predominant amplified warming over Europe–West Asia and Northeast Asia but much weaker warming over Central Asia. It is found that the nonuniform warming concurs with both the phase shift of the Atlantic Multi-decadal Oscillation (AMO) and the decadal change in the Silk Road Pattern (SRP), which is an upper-tropospheric teleconnection pattern over the Eurasian continent during summer. We suggest that the AMO may modulate the decadal change in SRP and then induce the zonal asymmetry in temperature changes. Our results have important implications for decadal prediction of regional warming pattern in Eurasia based on the predictable AMO.

1. Introduction
Climate change has become an undoubted fact, with global mean temperature showing an increasing tendency. However, the amplitudes of temperature increase are spatially nonuniform. Typically, temperature increases more quickly in high latitudes of the Northern Hemisphere, so called the polar amplification (Screen and Simmonds 2010, Pithan and Mauritsen 2014, Xie et al 2015). Another well-known spatial pattern of temperature increase is in the ratio of land warming to ocean warming which is greater than unity (Sutton et al 2007, Dong et al 2009, Boer 2011, Joshi et al 2013). Understanding the underlying mechanisms for regional temperature changes is crucial for recognizing the impacts on societies and ecosystems, which vary on the regional scale.

As such, the Eurasian continent experienced a significant warming trend, potentially causing people to suffer more from hot extremes in summer. Actually, the summer temperature tended to be much higher after the mid-1990s in many regions of Eurasia, and this decadal summer warming has been well documented by previous studies which focused on Europe (Sutton and Dong 2012, Stainforth et al 2013, Dong et al 2017) and Northeast Asia (Chen and Lu 2014, Dong et al 2016, Chen et al 2017). The warming over Central Asia, however, attracted much less attention. This may be partially due to the relatively lower population, but more likely because this region has not experienced a temperature increase as strong as Europe and Northeast Asia, as shown in figure 1(a). Such a regional feature of summer temperature increase over the Eurasian continent can also be found in previous studies (Zhu et al 2012, Han et al 2016). This regional pattern of warming is peculiar, since a stronger warming rate more usually appears over the drier regions such as Central Asia relative to the wetter regions such as Europe and Northeast Asia (Zhou et al 2015, Zhou et al 2016).

Some previous studies attempted to explain the decadal change in the Eurasian summer temperature.
For instance, the sea surface temperature (SST) changes in the North Atlantic, such as the Atlantic Multidecadal Oscillation (AMO), have been suggested to play a substantial role in resulting in this decadal warming (Sutton and Dong 2012, Kamae et al. 2014, Dong et al. 2016, Dong et al. 2017). On the other hand, direct anthropogenic forcings, including anthropogenic greenhouse gases and aerosol emissions, are also important in inducing the warming (Stott et al. 2000, Kamae et al. 2014, Dong et al. 2017). However, the mechanisms suggested by these studies, which focus on the warming over individual regions, cannot adequately explain the regional asymmetry in decadal temperature changes. For instance, one cannot expect the positive phases of AMO to warm up Europe and Northeast Asia but not to affect Central Asia. The main purpose of this study is to illustrate the possible mechanisms for the regional pattern, i.e. stronger warming over Europe and Northeast Asia but weaker warming over Central Asia.

2. Datasets

The monthly atmospheric circulation variables (including the winds and geopotential height) datasets used in the present study are from the National Centers for Environmental Prediction/National Center for Atmospheric Research (Kalnay et al. 1996), over the period of 1958–2016. Also employed is the 1958–2015 high-resolution (0.5° x 0.5°) land surface temperature dataset based on the weather station records (version 3.24) (Harris et al. 2014) from the Climatic Research Unit. All of the datasets are conducted with a
Figure 2. (a) Time series of the original (bar) and decadal (black line) components of the SRPI (both have been standardized), the zonal temperature difference ($T_{diff}$, defined by surface temperature differences between the west/east and central boxes in figure 1(a)). Units: °C. Red lines, dashed one for the original series and solid one for the decadal series), and the 121 month smoothed AMO index (blue line, obtained from www.esrl.noaa.gov/psd/data/timeseries/AMO/). Thick vertical lines indicate the phase turning points of AMO. (b) As for figure 1(a), but for 200 h Pa horizontal winds (units: m s$^{-1}$, vectors). Only the zonal wind or meridional wind differences significant at the 0.05 level are plotted. Red (blue) shading indicates positive (negative) correlation coefficients between the original SRPI and 200 h Pa meridional wind anomalies. Thick black lines are copied from figure 1(a).

June–July–August (JJA) average calculation before analysis. The decadal components are obtained through a nine-year Gaussian low-pass filter.

3. Results

Figure 1(a) shows the differences of JJA surface temperature anomalies between two periods: 1997–2016 (P2) and 1964–1996 (P1). These two periods are used to show the regional feature of decadal changes in temperatures, and further reasons will be given later in the discussion on figure 2(a). From figure 1(a), almost the entire Eurasian continent has experienced a significant warming, but the most prominent warming occurs over a large scope of two mid-latitude domains: one in Europe, West Asia and Northeast Africa (hereafter as Europe–West Asia) and the other in Northeast Asia. The area-weighted temperature increases within these two domains, specified as (20°–60°N, 10°–60°E) and (35°–55°N, 90°–120°E), are 1.22 and 1.10 °C, respectively. The warming over the two domains is much stronger than that over Central Asia, specified as (35°–55°N, 60°–90°E), which has a value of 0.70 °C.

The regional feature of warming rate appears in the entire troposphere, which is seen from the much stronger upward gradient of geopotential heights over Europe–West Asia and Northeast Asia relative to Central Asia (figure 1(b)). The difference in vertical gradient of geopotential heights implies a linkage of regional warming to the upper-tropospheric circulation changes.

The thick black lines in figure 1(a) indicate the regions of temperature anomalies significantly related to the Silk Road Pattern (SRP, or the circum-global teleconnection (CGT) in some studies), which is a well-known teleconnection pattern over the Eurasian continent in summer (Lu et al. 2002, Enomoto et al. 2003, Ding and Wang 2005, Yasui and Watanabe 2010, Du et al. 2016, Hong and Lu 2016). The SRP index (SRPI) is defined as the principle component of the leading mode (PC1) for 200 hPa meridional wind anomalies within the domain (20°–60°N, 0°–150°E), and is displayed as grey bars in figure 2(a). The substantial consistency of the amplified warming regions with the positive centers of the SRP-related
temperature anomalies implies that the SRP might play a role in inducing the nonuniform warming.

It is worth mentioning that the original SRPI is used to obtain the related temperature anomalies (thick black lines in figure 1(a)). Therefore, it is required that the SRP exhibits a decadal change so that the SRP can affect decadal temperature changes. The SRPI does show an evident decadal variability which explains 29.6% of its total variance (figure 2(a)). The decadal SRPI is in a positive phase from the mid-1960s to the mid-1990s and this is followed by a negative phase afterwards. These two periods correspond well to those used to show the decadal differences in temperature in figure 1.

We define a zonal temperature difference index ($T_{\text{diff}}$) by subtracting the mean over Central Asia from the mean over Europe–West Asia and Northeast Asia to quantify the zonally inhomogeneous warming. $T_{\text{diff}}$ exhibits an obvious decadal change: it has been intensifying significantly from the mid-1990s (figure 2(a)). The decadal SRPI in a positive phase from the mid-1960s to the mid-1990s and this is followed by a negative phase afterwards. These two periods correspond well to those used to show the decadal differences in temperature in figure 1.

The decadal warming over Europe–West Asia and Northeast Asia is dynamically consistent with each other. Figure 2(b) shows the 200 h Pa horizontal wind differences between 1997–2016 and 1964–1996. There are two significant anticyclonic anomalies over the west and east of Eurasia, respectively, which are consistent with the amplified warming therein. In addition, the wind differences between the two periods strongly resemble the SRPI-related wind anomalies (shadings in figure 2(b)), coherent with the strong decadal component of SRPI. This is seen from a high pattern correlation coefficient (−0.92) between the decadal differences and SRPI-related anomalies of meridional winds within the domain (20°–60°N, 0°–150°E). Furthermore, the SRPI has a close relationship with $T_{\text{diff}}$ not only on the decadal timescale, but also on the interannual. The correlation coefficient between their decadal components is −0.87, significant at the 0.01 level with the effective degrees of freedom in consideration, and the value is −0.63 between their interannual components. All these results suggest that the SRP can play a crucial role in inducing the amplified warming in Europe–West Asia and Northeast Asia.

To validate the role of SRP on the zonally heterogeneous warming, we examine the surface temperature differences between the two periods after removing the SRP-related components. Here we define the SRP-related temperatures as the product of SRPI and the linear regression coefficients of temperatures at each grid point onto the SRPI for individual years. After removing the SRP-related components, the warmth difference between the two periods becomes much weaker over the west and east of Eurasia (comparing figure 3(a) with figure 1(a)). The domain-averaged values are 0.82 and 0.75 °C over Europe–West Asia and Northeast Asia, respectively, both weakened by about one-third as much as the original values (i.e. 1.22 and 1.10 °C). In comparison, the warming rate over central Eurasia is almost unaffected by the removal of the SRP-related component. The temperature increase is 0.71 °C, close to the original increase between the two periods (0.70 °C). On the other hand, after removing the SRP, the temperature increase over Central Asia (0.71 °C) is comparable to that over Europe–West Asia (0.82 °C) and Northeast Asia (0.75 °C). The effect of the SRP can be more intuitively seen from figure 3(b), which shows the temperature differences averaged over 35°–55°N. The warmth over both the west and east of Eurasia is weakened by over 0.3 °C after the SRP-related components are removed.

4. Discussion

The above results indicate that the decadal variation of the SRP induces the amplified warming over Europe–West Asia and Northeast Asia. A question arises naturally: what causes the decadal variation of SRP? Previous studies proposed various sources of the SRP, including the forcings along the SRP and over Africa and South Asia (Lu et al 2002, Ding and Wang 2005, Yasui and Watanabe 2010, Wei et al 2015). However, the SRP is viewed as a teleconnection pattern on the interannual timescale, and no discussion on decadal change is found in any of these studies.

The decadal change in the SRP tends to be out of phase with the AMO phases (figure 2(a)). The two periods used for the composite analyses are determined by the AMO phases, i.e. a negative phase in 1964–1996 and a positive phase in 1997–2016. The SRPI tends to be positive during most years of the former period but negative during the latter period, resulting in the opposite signs of the meridional wind differences and SRP-related anomalies (figure 2(b)). These results suggest that the AMO may have an important role in modulating the decadal variability of the SRP.

Previous studies suggest that the AMO can modulate interannual teleconnection patterns. For instance, the AMO can modulate the summer North Atlantic Oscillation (SNAO) (Goswami et al 2006), which is basically measured by sea level pressures (e.g. Folland et al 2009). Our analysis shows a relationship between the SRP and SNAO, with the correlation coefficient between the SRPI and SNAO index (following Folland et al (2009)) being 0.32. This moderate relationship between the SRP and SNAO may be due to decadal shifts in the zonal location of the SNAO’s southern center (Sun et al 2008, 2009). We hypothesize that the AMO might modulate the SRP through its upper-tropospheric fingerprints, while modulating the SNAO through its lower-tropospheric fingerprints. Further investigations are needed but beyond the scope of this study.

The decadal change in the SRP found here is distinguished from the decadal CGT pattern obtained by
previous studies (Lin et al 2016, Wu et al 2016). This difference results primarily from the distinction between the analysis methods: we perform the empirical orthogonal function (EOF) analysis on the original data, while the EOF analysis is performed by using the decadal filtered data in these previous studies. Therefore, the difference between the decadal change in SRP and the decadal CGT pattern is analogous to the difference between decadal change in the El Niño Southern Oscillation and the dominant pattern of decadal SST change in the equatorial central and eastern Pacific. One of the different features between the decadal CGT pattern and the SRP is that the former shifts westward relative to the latter by about 1/4 wavelength, as mentioned by Wu et al (2016).

5. Conclusions

In this study we identified a zonally nonuniform decadal summer warming after the mid-1990s over the Eurasian continent. This decadal warming is featured by amplified warming over Europe–West Asia and Northeast Asia, with the domain averaged temperature being 1.22 and 1.10 °C, respectively. However, the warming over Central Asia is weaker, indicated by the domain averaged temperature being 0.70 °C. This heterogeneous decadal warming occurs throughout the troposphere.

Further analyses indicate that the decadal variability of the Silk Road Pattern (SRP) is responsible for the nonuniform warming over the continent. The SRP exhibits an evident decadal component that explains 29.6% of the total variance. The decadal variation of SRP is in phase with that of the regional warming pattern, also consistent with the AMO phase. This suggests that the AMO may have played an important role in the amplified warming over Europe–West Asia and Northeast Asia through modulating the decadal variation in SRP. Considering that the AMO has a cycle of about 65–80 years (e.g. Enfield et al 2001) and has entered into a positive phase since the mid-1990s, it implies that there will be strong warming over Europe–West Asia and Northeast Asia in the coming decade.
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ORCID iDS

Xiaowei Hong https://orcid.org/0000-0001-7548-8141

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