Differences in the Silk Road Pattern and Its Relationship to the North Atlantic Oscillation between Early and Late Summers

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ABSTRACT

The Silk Road Pattern (SRP) is an upper-tropospheric teleconnection pattern along the Asian westerly jet in summer on the interannual time scale, and it exerts great influences on the climate of the Eurasian continent. Results in the present study indicate that the SRP exhibits considerable distinctions between early and late summers (i.e., 1 June–9 July and 10 July–31 August, respectively). The SRP is stronger and more geographically fixed in late summer in comparison with its counterpart in early summer. Furthermore, the SRP is closely connected with the summer North Atlantic Oscillation (SNAO) in late summer, but not in early summer. This closer connection in late summer is manifested clearly in the leading mode of upper-tropospheric meridional wind anomalies over the North Atlantic–Eurasian continent domain. The intensified SNAO–SRP relationship in late summer can be explained by the subseasonal change of the SNAO: albeit being a seesaw pattern common in both early and late summers, there is a shift of this pattern toward the northwest–southeast one in late summer from a north–south one in early summer. The southeastern pole of SNAO in late summer extends into the Eurasian continent, and efficiently triggers the SRP to propagate along the Asian jet. By contrast, the south pole of SNAO in early summer is confined over the North Atlantic and is thus less effective to trigger the SRP propagation.

1. Introduction

The Silk Road Pattern (SRP), also viewed as the circumglobal teleconnection pattern (CGT) in some studies (Ding and Wang 2005; Yasui and Watanabe 2010), is a well-known zonally propagating teleconnection pattern in summer on the interannual time scale (Lu et al. 2002; Enomoto et al. 2003). It appears as alternate southerly and northerly anomalies along the midlatitude Asian westerly jet from the western Eurasian continent to East Asia, and is demonstrated to be the dominant mode of the meridional wind anomalies over the mid-latitude Eurasian continent (Sato and Takahashi 2006; Kosaka et al. 2009; Yasui and Watanabe 2010; Chen and Huang 2012; Hong and Lu 2016; and many others). The SRP has been well documented to exert great influences on the summer climate anomalies over a broad area of midlatitude Northern Hemisphere (e.g., Lu et al. 2002; Enomoto 2004; Wakabayashi and Kawamura 2004; Chen and Huang 2012; Saeed et al. 2014; Wang and He 2015; Hong et al. 2017, 2018; Jin and Guan 2017; Wang et al. 2017).

The SRP has some unique features. The most striking one is that it is confined within the upper-tropospheric...
Asian westerly jet, which can be explained by the waveguide effect of the jet according to the wave ray theory (Hoskins and Ambrizzi 1993). On the other hand, anomalous cells of the SRP tend to be geographically fixed to preferred longitudes (Lu et al. 2002; Sato and Takahashi 2003; Ding and Wang 2005), because the geographically fixed pattern can extract the kinetic energy more efficiently from the basic flow (Sato and Takahashi 2003; Kosaka et al. 2009). Finally, the disturbances, such as the upper-tropospheric meridional wind anomalies around the Caspian Sea, are crucial in guaranteeing the appearance of the SRP, which has been well documented by various previous studies (e.g., Enomoto et al. 2003; Sato and Takahashi 2006; Yasui and Watanabe 2010; Kosaka et al. 2009; Hong and Lu 2016).

Earlier research has demonstrated well that the midlatitude wave patterns are strongly constrained by the basic flow. For instance, the midlatitude waves are usually trapped by the jet stream, and their wave paths and wavelength are determined by the basic flow (Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993). The strong dependence of the midlatitude wave patterns on the basic flow has also been documented by some recent studies (Manola et al. 2013; Holman et al. 2014; Lin et al. 2017a,b), with both observational and model results.

It is well known that the basic state changes remarkably in different periods during summer. For instance, the upper-tropospheric jet stream advances northward dramatically in July, over both the eastern and western part of the Eurasian continent (Kuang and Zhang 2005; Lin and Lu 2008; Lin et al. 2017a). Considering the close connection between the SRP and the basic states, we may expect that the SRP would behave differently under changes of the basic flow during different periods of summer. However, most previous studies explored the summer-mean SRP as a whole directly, assuming that the SRP changes little throughout the whole summer. Ding and Wang (2005) noticed some differences in CGT patterns from month to month in summer, but they just listed these differences, not paying much attention to them, let alone the related underlying mechanisms.

The present study will give an illustration on distinctive features of the SRP in different periods of summer (i.e., early and late summers as divided in the study), which will be shown in section 3. Then section 4 will illustrate the relationship between the North Atlantic Oscillation and the SRP in early and late summers, respectively. Finally in section 5, the conclusions and a discussion will be given. The remnant of this paper will start with an introduction for the dataset and method, as in section 2.

2. Dataset and method

The data used in this study include the daily and monthly circulation variables from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis products (Kalnay et al. 1996), on a horizontal resolution of 2.5° × 2.5°, with a time span of 1958–2016.

Following Yasui and Watanabe (2010), the SRP is obtained through the empirical orthogonal function (EOF) analysis on the 200-hPa meridional wind (V200) anomalies within the domain 20°–60°N, 0°–150°E and is defined as the leading mode. Therefore, the SRP index (SRPI) is taken as the standardized time series of the first principal component (PC). In this study, we use the original V200 anomalies (i.e., no detrending or filtering analysis is applied before the EOF analysis).

3. Distinguished features of the SRP between early and late summers

The patterns of the first mode of V200 anomalies in June and August are shown in Fig. 1 to intuitively illustrate the subseasonal change in the SRP. Both months show a clear SRP, but the patterns exhibit some appreciable differences. First, the SRP tends to be more confined along the Asian jet and stronger in August than in June. The variances explained by the SRP in these 2 months also confirm the difference in the SRP intensity:
the leading mode explains 19.1% and 25.4% of total variance in June and August, respectively. Second, the SRP in June shifts eastward over the Eurasian continent in comparison with that in August. Finally, the SRP in both months are generally along the Asian jet, and thus the August one is relatively northward shifted, which is consistent with the subseasonal northward march of the Asian jet. The SRP in July (not shown) exhibits a spatial distribution similar to that in August, and the SRP in these 2 months are more similar to that in summer mean [June–August (JJA)] (e.g., Yasui and Watanabe 2010; Hong and Lu 2016). This is different from Ding and Wang (2005), who mentioned that the June and August wave patterns are similar with each other but differ from the July pattern because of different domains for comparison: the entire Northern Hemisphere in Ding and Wang (2005), but only the Eurasian continent in this study. These monthly differences suggest the necessity of investigating the subseasonal change of SRP during summer.

A sliding pattern correlation method is applied in this study to objectively determine a cutoff point of subseasonal change in SRP. The SRPs before and after this point least resemble each other and thus subseasonal change can be highlighted. Details of this method are as follows. First, we specify a particular date (e.g., 1 July), and this date separates the whole summer into two periods (i.e., 1 June–1 July and 2 July–31 August). Then we obtain the leading modes in the period-mean V200 anomalies (i.e., the SRP patterns) for these two periods, respectively, through the EOF analysis within the domain 20°–60°N, 0°–150°E. Finally, the pattern correlation coefficient between the spatial distributions of these two patterns is calculated, and its absolute value is set as the value on 1 July. Here, the absolute value is used because of the arbitrariness of signs of EOF patterns. Repeat the above procedure, with the specified date sliding from 1 July to 31 July, and obtain one value for each calendar date. The date with the minimum value is taken as the division, suggesting a minimum resemblance between the SRP patterns before and after this date.

With this method, the division is determined as 9 July (Fig. 2), and thus the two periods are 1 June–9 July (P1 or early summer) and 10 July–31 August (P2 or late summer), respectively. As shown in Fig. 2, the pattern correlation coefficient between the SRPs in these two periods is only 0.47, indicating the necessity of investigating the SRP for the two periods separately. The pattern correlation coefficient in late July is much higher than that in early July, in agreement with the uniqueness of June SRP and similarity between the July and August SRP. We have extended the sliding period from 1 July–31 July to 15 June–15 August, and obtained similar results, verifying that 9 July is the cutoff point for the robust distinctions between the SRPs in early and late summers.

It is interesting that this division based on the SRP for early and late summers, that is, 9 July, coincides with the withdraw time of the mei-yu season (e.g., Tao and Chen 1987; Ding 2005). In addition, Li and Lu (2018) investigated the circulation anomalies affecting rainfall of the Yangtze River basin during summer, and found that the SRP plays a crucial role in middle summer but not in early summer. The separating date between early and middle summers in their study is also 9 July.

Figure 3 shows the SRP-related V200 anomalies in P1 and P2, respectively. The distinctions between early and late summer SRP resemble each other but are more marked than those between June and August (Fig. 1). There are significant V200 anomalies centered over the Caspian Sea in P2, which have been demonstrated to play a crucial role in triggering the downstream SRP for the summer-mean situation (e.g., Hong and Lu 2016), while in P1 the V200 anomalies deviate eastward. The leading mode explains more variance in P2 (30.6%) than in P1 (21.2%), suggesting a stronger SRP in P2 than in P1. This stronger pattern is particularly evident in the upstream domains of the SRP (i.e., over Europe and West Asia) (Figs. 3a and 3b). There are also significant anomalies over the North Atlantic in P2, but not in P1. The wave activity flux associated with the SRP, which is calculated according to the formula of Takaya and Nakamura (2001), also implies that the wave train originates over the North Atlantic in P2 but around the entrance of the Asian westerly jet in P1. These results suggest that there would be connections between the SRP and the anomalies over the North Atlantic in late summer, which will be discussed in the following section. In addition, the SRP tends to exhibit a clearer decadal
variation in P2 than in P1, indicated by the variances explained by the decadal component (represented by 9-yr Gaussian filtering of PC1) being 28.0% for P2 and 9.7% for P1.

Comparison between the SRPs in P1 and P2 can be further interpreted by Fig. 4, which shows the horizontal distribution of one-point correlation coefficients between the base point and V200 anomalies at each grid, following previous studies (e.g., Lu et al. 2002). The base point is set originally as the center with greatest SRP-related V200 anomaly around the Caspian Sea. In P1 this point is 40°N, 60°E and in P2 it is 45°N, 47.5°E, based on the results in Figs. 3a and 3b. We also moved the base point to the west or to the east with 2.5° in longitudes each time and remain the latitude location unchanged (40°N for P1 and 45°N for P2), to test whether the SRP is geographically fixed, which is another important feature of the SRP (Lu et al. 2002; Sato and Takahashi 2003; Ding and Wang 2005). For brevity, Fig. 4 only shows the original patterns (Figs. 4b and 4e), the 15° westward-shifted (Figs. 4a and 4d), and eastward-shifted (Figs. 4c and 4f) patterns.

The teleconnection pattern in P2 (Fig. 4e) is indeed stronger than in P1 (Fig. 4b), in agreement with the results in Figs. 3a and 3b. On the other hand, when the base point shifts to the west or to the east, the teleconnection patterns changes little in intensity in P1 (Figs. 4a and 4c) but weakens dramatically in P2 (Figs. 4d and 4f), indicating that the SRP is well geographically fixed in P2 but not in P1.

These differences of the SRP between P1 and P2 can be quantitatively illustrated by the teleconnectivity shown in Fig. 5. Here, the teleconnectivity is defined by the area-weighted squared values of correlation coefficients within the domain 20°–60°N, 0°–150°E, denoted by the box in Fig. 4, which includes the major body of SRP both in P1 and P2, and consistent with the EOF analysis domain for SRP definition. The correlation coefficient at each grid in the domain is calculated by using V200 anomalies at this grid and at the base point, as in Fig. 4. The result indicates that the teleconnectivity in P2 is evidently greater than in P1 for the original teleconnection pattern (values at 0°), verifying that the SRP in P2 is stronger than in P1. On the other hand, when the base point shifts to the west or to the east, the teleconnectivity decreases rapidly in P2 but changes gently in P1. This contrasting comparison confirms that the SRP in P2 is more geographically fixed than in P1.

4. Connection with the summer North Atlantic Oscillation between early and late summers

Results in the preceding section indicate that the SRP is closely related to the anomalies over the North Atlantic in P2, consistent with the summer-mean results in previous studies (e.g., Sun et al. 2008; Yasui and
However, this relationship tends to be weak in P1. This suggests a subseasonal change in the relationship from early summer to late summer. In this section, we examine this subseasonal change and discuss its role in distinguishing the features of SRP between early and late summers.

Figure 6 shows the sea level pressure (SLP) anomalies over the North Atlantic regressed onto the SRP1. The anomalies in P2 are characterized by a significant northwest–southeast-orientated seesaw pattern, with a significant positive anomalous center over the British Isles and a negative one over Greenland (Fig. 6b). This pattern resembles well the distribution of SLP anomalies associated with the summer North Atlantic Oscillation (SNAO) revealed in previous studies (e.g., Sun et al. 2008, 2009; Folland et al. 2009; Bladé et al. 2012). This resemblance suggests a close connection between the SRP and SNAO in P2. By contrast, the anomalies in P1 are very weak (Fig. 6a), suggesting an absence of the SNAO–SRP relationship.

It is interesting that the SRP has a quite different relationship with the North Atlantic anomalies between early and late summers. Is this difference related to subseasonal change in the North Atlantic circulations? To answer this question, we perform an EOF analysis on SLP anomalies within the domain 30°–85°N, 70°W–30°E.
for early and late summers, respectively (Figs. 7a and 7b). We use the standardized PC1 time series as the SNAO index (SNAOI). For both periods, the SNAO is featured as a dipole pattern. However, there are appreciable differences in the south poles between the two periods: the south pole extends from the North Atlantic northeastward to northern Europe in early summer (Fig. 7a) but is located over northern Europe in late summer (Fig. 7b). Therefore, the dipole pattern tends to be in a north–south distribution in early summer but exhibits a northwest–southeast distribution in late summer. Furthermore, the distribution of the SNAO-related anomalies in late summer (Fig. 7b) has a great similarity to that in Fig. 6b, with the pattern correlation coefficient being as high as 0.97 within the domain used for the SNAOI definition. In addition, the temporal correlation coefficient between the SRPI and SNAOI is 0.44 in P2, which is significant at the 0.01 level. These all confirm the significance of the SNAO–SRP relationship in late summer. By comparison, the SNAO-related anomalies in early summer (Fig. 7a) differ much from the SRP-related (Fig. 6a), with a very small pattern correlation coefficient of 0.09. The weak SNAO–SRP relationship in early summer can also be confirmed by the small temporal correlation coefficient (0.03) between the SRPI and SNAOI.

Figures 7c and 7d show the V200 anomalies regressed onto the SNAOI in P1 and P2, respectively. The V200 anomalies behave substantially differently between P1 and P2, consistent with the results shown in Figs. 7a and 7b. In P1, the V200 anomalies are mainly scattered over the North Atlantic and Europe, while the anomalies along the Asian jet are weak (Fig. 7c). There are significant positive anomalies at the entrance of the Asian jet, but they are centered over the eastern Mediterranean Sea and not efficient in triggering the anomalies downstream along the Asian jet. In P2 (Fig. 7d), by contrast, the V200 anomalies show up as a clear wave-like pattern from the North Atlantic to East Asia. There are significant positive anomalies over the Caspian Sea, which have been demonstrated to be crucial to trigger the downstream SRP (e.g., Enomoto et al. 2003; Sato and Takahashi 2006; Kosaka et al. 2009; Yasui and Watanabe 2010; Hong and Lu 2016). Accordingly, the anomalies over the Eurasian continent are approximately along the Asian jet axis, consistent with those related to the SRP in P2 (Fig. 3b). The pattern correlation coefficient in the V200 anomalies within the domain 20°–60°N, 0°–150°E between Figs. 3b and 7d is as high as 0.80, verifying the close connection between the SRP and SNAO in P2.

Figures 7a and 7b indicate that the SNAO exhibits distinct features between P1 and P2. To obtain the date for strong subseasonal change in the SNAO, we apply the aforementioned sliding pattern correlation method, a procedure similar to that for SRP in Fig. 2, to objectively determine a cutoff point of subseasonal change in SNAO. The result (Fig. 8) shows that the leading modes in the SLP anomalies within the domain 30°–85°N, 70°W–30°E (i.e., the SNAO patterns) share the least similarities on 10 July, close to the cutoff point (9 July) of subseasonal change in SRP (Fig. 2).

Furthermore, we calculate the 31-day sliding correlation coefficients between the SRPI and SNAOI (Fig. 9) to identify the exact date for the obvious subseasonal change in the SNAO–SRP relationship. Here the SNAOI and SRPI are defined by the PC1 of EOF analysis on the SLP and V200 anomalies averaged over the 31-day sliding windows, respectively, within their specific domains mentioned before. For instance, the value on 1 August delineates the absolute value of the correlation coefficient within 17 July–16 August. Here again, we use the absolute values of the correlation coefficients to deal with the arbitrary signs of EOF.
patterns. The SNAO–SRP relationship exhibits a dramatic enhancement in late summer, seen from the remarkable rise in correlation coefficients, with high and significant correlation from late July to mid-August. Considering the 31-day sliding window used here, this result indicates that the SNAO–SRP relationship is closest from mid-July to the end of August, coherent with the period covered by P2. We also used the 21-, 41-, and 51-day sliding windows and obtained similar results (not shown). This suggests the robustness of subseasonal change in the SNAO–SRP relationship during summer.

The close SNAO–SRP relationship in P2 is manifested as the leading mode of V200 anomalies over the North Atlantic and Eurasian continent, more specifically, the domain 20°–80°N, 60°W–150°E (Fig. 10c). It features a distinct wavelike pattern from the North Atlantic to East Asia. The wave activity from the North Atlantic penetrates into the entrance of the Asian jet (i.e., around the Caspian Sea) and propagates eastward along the jet, triggering the downstream SRP. Both the circulation anomalies and wave activity flux associated with this mode are very similar to those connected with

![Figure 7](image-url)

**Fig. 7.** The (a),(b) SLP anomalies (contours; Pa) and (c),(d) V200 anomalies (contours; m s\(^{-1}\)) regressed onto the standardized SNAOI in (a),(c) P1 and (b),(d) P2. Vectors are the SNAOI-related wave activity flux (m\(^2\) s\(^{-2}\)) at 200 hPa. Bold lines in (c) and (d) delineate the climatological jet axes. Shading indicates anomalies significant at the 0.05 level based on the Student’s t test. The boxes in (a) and (b) denote the domain used to define the SNAO.

![Figure 8](image-url)

**Fig. 8.** As in Fig. 2, but for the SLP anomalies within the domain 30°–85°N, 70°W–30°E. The dashed line indicates the date with the lowest pattern correlation coefficient.

![Figure 9](image-url)

**Fig. 9.** The 31-day sliding correlation coefficients between the SNAO1 and SRPI (see the text for details). We have shown the absolute values of all the correlation coefficients here for convenience of analyses.
the SRP in P2 (Fig. 3b). Actually, the correlation coefficient between PC1 of this mode with the SRPI in P2 is as high as 0.99, and that with the SNAOI is 0.52, both significant at the 0.01 level. This mode explains 20.5% of the total variance on the V200 anomalies, and can be separated well from the second mode (Fig. 10d). In contrast, the wave path splits into two directions in P1 after going through the northwestern Europe (Fig. 10a): one is along the Asian jet and the other, and more remarkable one, is along the northern edge of the Eurasian continent. This pattern is similar to that in Iwao and Takahashi (2006, 2008) but with a more eastward phase. The second mode in P1 exhibits a clear teleconnection pattern along the Asian jet (Fig. 10b), but it cannot be separated from the first mode. In addition, the wavelength of the teleconnection in P1 tends to be smaller than that in P2.

The results in this section demonstrate a close relationship between the SRP, which is the leading mode of V200 anomalies over the Eurasian continent, and the SNAO, which is the leading mode of SLP anomalies over the North Atlantic, in P2 but not in P1. This subseasonal change in the SNAO–SRP relationship can explain at least partially the differences in SRP between P1 and P2. The SNAO is characterized by a northwest–southeast seesaw pattern in P2, with its southeast pole extending into the Eurasian continent and triggering the SRP along the Asian jet. While in P1, the SNAO is characterized by a north–south seesaw pattern, with its south pole confined over the North Atlantic, and thus not efficient to trigger the SRP over the Eurasian continent.

The subseasonal change in basic flows during summer may be responsible for the intraseasonal change in the SNAO–SRP relationship. In comparison with early summer, the Asian jet is located poleward during late summer (as shown in Figs. 3a and 3b), and its entrance part shifts northward (Lin et al. 2017a, their Fig. 14). This northward shift of the jet can create a preferable condition for the disturbances from the North Atlantic to enter the jet and trigger the downstream wave pattern, resulting in the significant SNAO–SRP relationship. However, it remains unknown what mechanisms cause the difference in SNAO between early and late summers, which is interesting but beyond the scope of the present study.

5. Conclusions and discussion

Using the daily reanalysis data with a time span of 1958–2016, the present study identified that the Silk Road Pattern (SRP) differs considerably between early and late summers (i.e., 1 June–9 July and 10 July–31 August). Specifically, the SRP in late summer is stronger and more geographically fixed, in comparison with that in early summer.

Further results indicate that the SRP is closely connected with the summer North Atlantic Oscillation (SNAO), which is the dominant mode on the SLP

Fig. 10. V200 anomalies (contours; m s$^{-1}$) regressed onto the standardized (a),(c) PC1 and (b),(d) PC2 time series obtained through EOF analysis on the V200 anomalies within the domain 20°–80°N, 60°W–150°E for (a),(b) P1 and (c),(d) P2. Shading indicates anomalies significant at the 0.05 level based on the Student’s $t$ test. Vectors are the related wave activity flux (m$^2$ s$^{-2}$). Bold lines delineate the mean jet axes.
anomalies over the North Atlantic, in late summer but not in early summer. The significant SNAO–SRP relationship in late summer even manifests as the dominant mode of the upper-tropospheric meridional wind anomalies over the North Atlantic–Eurasia domain. It is interesting that the SNAOs are also identified to exhibit an evident subseasonal change between early and late summers (a north–south seesaw pattern versus a northwest–southeast seesaw pattern). The subseasonal change in the SNAO patterns concurs with that in the SRP, both occurring around 9–10 July. The southern pole of the SNAO seesaw pattern is confined over the North Atlantic in early summer, but extends to the Eurasian continent in late summer. Such an SNAO in late summer can effectively trigger the SRP, but not in early summer.

The subseasonal change of the SNAO patterns can explain the differences in the SNAO–SRP relationship and the intensity/phase-lock feature of the SRP between early and late summers. Furthermore, in late summer the northward advancement of the Asian westerly jet, particularly its entrance part, which is near the southeast cell of SNAO pattern, may favor the establishment of SNAO–SRP linkage. It may be hypothesized that the subseasonal change in the SNAO is attributed to a change of the basic flows, and this hypothesis must be tested in the future. Finally, this study implies that the SRP, together with the SNAO, might play a crucial role in affecting the weather and climate of the Eurasian continent in late summer, which also requires further researches.

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