1. Introduction

The summertime circumglobal teleconnection (CGT) is characterized by a wave train along the upper-tropospheric westerly jet in the mid-latitudes of the Northern Hemisphere (Ding and Wang, 2005). It significantly affects mid-latitude climate on interannual timescales (Lu et al., 2002; Ding and Wang, 2005; Huang et al., 2011; Saeed et al., 2011; Schubert et al., 2011; Kosaka et al., 2012; Wang et al., 2013; Lin, 2014; Zhang and Zhou, 2015). Many studies, therefore, have been devoted to understanding mechanisms for the formation and maintenance of the CGT (Ding and Wang, 2005; Yasui and Watanabe, 2010; Ding et al., 2011; Chen and Huang, 2012; Chen et al., 2013; Hall et al., 2013; Lee et al., 2014). In particular, it would greatly enhance the understanding of and help predict the CGT if the heating sources responsible for triggering the CGT could be identified (Yasui and Watanabe, 2010).

The CGT could be induced by heat forcing related to tropical summer monsoon rainfall (Ding and Wang, 2005; Yasui and Watanabe, 2010; Yim et al., 2014). Several studies have highlighted the role of the Indian summer monsoon rainfall (Ding and Wang, 2005; Lin, 2009; Ding et al., 2011). They have proposed that Indian heat forcing could trigger a westward-propagating Gill-type Rossby wave response and form an anticyclonic anomaly at the entrance of the Asian westerly jet in the upper troposphere (Rodwell and Hoskins, 1996), initiating an eastward-propagating CGT-like wave train trapped within the strong westerly jet (Enomoto et al., 2003). Similarly, this anticyclonic disturbance could also be excited by divergent flow-induced vorticity advection, because of heat forcing over the tropical western Indian Ocean (Chen and Huang, 2012). Yasui and Watanabe (2010) investigated dynamical forcings of the CGT in a dry atmospheric general circulation model. They proposed that the mid-latitude diabatic heat forcing around the Mediterranean Sea (MS) region, rather than those over tropical monsoon regions, can form the CGT pattern most efficiently.

However, rainfall exhibits a strong annual cycle over the MS region, with a wet winter season and a dry summer season. The absence of summer rainfall, because of the effect of the monsoon-desert mechanism (Rodwell and Hoskins, 1996), may hinder the development of a downstream-extended wave train similar to that proposed in winter by Watanabe (2004). Instead, intense summer rainfall occurs to the north over continental southern-central Europe (SCE) (Figure 2). This gives rise to the following question: Can the diabatic heating related to the SCE rainfall modulate the CGT? This question is investigated in this study.

2. Data and methods

The monthly atmospheric data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Re-Analysis (ERA-40) from 1958 to 2002 (Uppala et al., 2005). The monthly precipitation data are obtained from the Climatic Research Unit (CRU), University of East Anglia, UK, with a horizontal resolution of 0.5° × 0.5° (Mitchell and Jones, 2005). Summer is defined as June, July, and August.

A barotropic model is used to investigate the effect of SCE rainfall on the CGT. The linearized barotropic vorticity equation is

\[
\frac{\partial \zeta'}{\partial t} = -\nabla \cdot \nabla' - V' \cdot \nabla \left( f + \zeta' \right) - V' \cdot \nabla \left( f + \zeta' \right) \nabla \cdot V' - \kappa \zeta' e \nabla \cdot \zeta',
\]

where

- \( \zeta' \) is the linearized vorticity,
- \( f \) is the Coriolis parameter,
- \( \kappa \) is the vertical viscosity.

This study provides an alternative mechanism for the formation and maintenance of the CGT.

Keywords: circumglobal teleconnection; southern-central European summer rainfall; Mediterranean Sea heating; rainfall feedback
where the over bar represents the zonal-mean variables and the prime is the deviation from the zonal-mean state. \( \mathbf{V}_u \) and \( \mathbf{V}_v \) are the rotational and divergent wind components, respectively, \( f \) is the Coriolis parameter, and \( \zeta \) is the relative vorticity. The zonal-mean flow is set to the summertime climatological values at 200 hPa calculated from the ERA-40 data averaged over 1958–2002. The biharmonic diffusion coefficient, \( \varepsilon \), is set to \( 2.34 \times 10^{-6} \) m\(^4\) s\(^{-1}\) and the damping coefficient, \( \kappa = 10 \) day\(^{-1}\), is used in this model. The vorticity equation is solved using the spectrum transform technique with a triangular truncation at wavenumber 21. The steady response is calculated as the 30-day mean averaged for 31–60 days.

3. Results

Figure 1(a) shows the spatial pattern of the negative phase of the summertime CGT, which is depicted by the anomalies of geopotential height at 200 hPa (H200) in the mid-latitudes of the Northern Hemisphere regressed against the minus CGT index (CGTI) for the period 1958–2002. The CGTI is defined as the normalized H200 anomalies averaged over west-central Asia (35°–40°N, 60°–70°E), in the same manner as Ding and Wang (2005), and its time series is shown in Figure 1(b). The CGT pattern is characterized by a mid-latitude wave train along the strong subtropical westerly jet in the upper troposphere with a zonal wavenumber of five. The negative H200 centers are significant over southwest Asia, east Asia, central North Pacific, and northeast North America, but weak over western Europe, consistent with the result of one-point correlation between the CGTI and the H200 anomalies identified by Ding and Wang (2005) in their Figure 1(b).

Related to the negative phase of the CGT, rainfall is significantly enhanced over SCE (Figure 2(a)). To better reveal their relationship, a rainfall index is calculated from the normalized summer-mean rainfall averaged over the SCE region (45°–50°N, 0°–30°E), whose time series is presented in Figure 1(b). The correlation coefficient between the CGTI and the SCE rainfall index (SCERI) is \( -0.43 \) for the period of 1958–2002 and is significant at the 99% confidence level based on Student’s t-test, indicating a strong link between the summer rainfall over SCE and the CGT. In addition, no significant rainfall anomalies were found in the MS land region.

Previous studies have highlighted the role of diabatic heat forcing around the MS region in the CGT (Enomoto et al., 2003; Yasui and Watanabe, 2010). As shown in Figure 2(b), intense summer rainfall occurs over the SCE region. The climatology and standard deviation of summer-mean rainfall are approximately 3 and 0.7 mm per day, respectively, over the SCE region, compared with 0.7 and 0.3 mm per day, respectively, in the MS land region (30°–45°N, 0°–40°E) from 1958 to 2002. A similar result is obtained using the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) global precipitation data (Xie and Arkin, 1997) from 1979 to 2002, with the climatology and standard deviation of 2.6 and 0.6 mm per day, respectively, over the SCE region versus 0.6 and 0.3 mm per day, respectively, over the MS region. Rainfall is much stronger over the SCE region than the MS region in both climatology and interannual variability.

To investigate the possible feedbacks of the SCE rainfall, we calculated H200 anomalies related to the SCERI (Figure 3(a)). The SCE rainfall is linked to a mid-latitude wave train along the westerly jet around the entire Northern Hemisphere, similar to the CGT pattern (Figure 1(a)). To reveal characteristics of the associated Rossby wave propagation, the zonal and meridional components of wave-activity flux for stationary Rossby waves (W) were employed following Takaya and Nakamura (2001):

\[
W = \frac{1}{2|V|} \left( \overline{u} \left( \psi_x^2 - \psi_y \psi_{x,y} \right) + \overline{v} \left( \psi_y^2 - \psi_x \psi_{x,y} \right) \right)
\]

where |V| is the magnitude of the horizontal wind vector \((u, v)\), and \( \psi \) is the stream function; the over bar indicates the climatological summer mean averaged over 1958–2002, and the subscript and prime notations signify the partial derivatives and anomalies related to the SCERI, respectively.

Associated with the mid-latitude wave train, wave-activity flux propagates southeastward from eastern Europe into the Asian westerly jet at its entrance over west-central Asia, and then extends downstream along the westerly jet (Figure 3(b)). In theory, Rossby waves propagate eastward along strong westerlies (Hoskins and Ambrizzi, 1993). The propagation of the wave-activity flux downstream of the SCE rainfall suggests a possible role of the SCE rainfall in triggering the mid-latitude wave train or the CGT pattern.

The role of the SCE rainfall in the CGT is confirmed by the response to a divergence forced over the SCE region in the barotropic model (Figure 3(c)). The two-dimensional sinusoidal forcing of the divergence in the region (45°–50°N, 0°–30°E) was prescribed in the model. We took the maximum upper-tropospheric divergence to be \( 3.0 \times 10^{-7} \) s\(^{-1}\), which corresponds to an outflow associated with approximately one standard deviation of the SCE rainfall of 0.7 mm per day according to Hoskins and Karoly (1981). Details of the barotropic model are described in Section 2. The steady responses of the geopotential height (Figure 3(c)) resemble the H200 anomalies related to SCERI (Figure 3(a)). The geopotential height responses at mid-latitudes were calculated from stream function responses to the SCE divergence forcing based on the geostrophic balance. The resemblance includes positive anomalies over eastern Europe and a mid-latitude wave train along the Asian westerly jet. The negative geopotential height response over west-central Asia corresponds to a negative value of the CGTI, which agrees with a significant negative correlation of the
Figure 1. (a) Anomalies of the geopotential height at 200 hPa (H200, contour) regressed against the minus CGTI. The CGTI is defined as the 200-hPa geopotential height averaged over west-central Asia (35°–40°N, 60°–70°E), the region depicted by the black box, following Ding and Wang (2005). Shading indicates significance at the 95% confidence level, and the contour interval is 5 gpm. The red contour depicts the climatological westerly jet at 200 hPa with zonal winds exceeding 20 m s⁻¹. (b) The normalized time series of the CGTI (black bar) and the SCERI (blue solid line). The SCERI is calculated as the summer-mean rainfall averaged over the region (45°–50°N, 0°–30°E) surrounded by the blue box in Figure 2.

Figure 2. (a) Anomalies of the CRU precipitation (contour) regressed against the minus CGTI over Europe. Shading indicates significance at the 95% confidence level, and the contour interval is 0.2 mm day⁻¹. (b) Climatology (contour) and standard deviation (shading) of summer CRU precipitation. The contour interval is 1 mm day⁻¹ and the shading interval is 0.2 mm day⁻¹.

CGTI with the SCE rainfall (Figure 1(b)). The result implies that SCE summer rainfall can trigger the CGT.

In addition to the weaker model response, a different H200 pattern over Europe exists between the SCERI-related anomalies (Figure 3(a)) and the barotropic model response to the SCE divergence forcing (Figure 3(c)). These differences suggest other factors or feedbacks may still be quite important. For example, Zuo et al. (2013) found that synoptic eddy-vorticity forcing over the North Atlantic plays an important role in triggering a downstream-extended wave train that links the North Atlantic sea surface temperature (SST) anomalies to East Asian summer monsoon. In addition, nonlinear effects are excluded in the current barotropic vorticity equation model. All these factors and feedbacks need to be considered comprehensively to understand the CGT–SCE rainfall connection.

4. Conclusion and discussion

Strong rainfall occurs over SCE in boreal summer. SCE rainfall can trigger the CGT pattern. Related to the SCE rainfall, the upper-tropospheric divergence forcing induces a southeastward-propagating wave flux into the Asian westerly jet at its entrance, corresponding to an anticyclonic anomaly over eastern Europe and a cyclonic anomaly over west-central Asia. Subsequently, the wave flux further extends eastward along the westerly jet because of the waveguide effect, forming a CGT-like wave train.

This study highlights the role of SCE rainfall in the CGT. However, the CGT may also exert some influence on the SCE rainfall. The stationary Rossby wave related to the CGT propagates southeastward from the exit of the North Atlantic upper-tropospheric westerly jet via western and eastern Europe toward southwest
Asia along a great-circle route (Figure 1(a)). The eastward and northward moisture transport associated with the cyclonic anomaly over western Europe may contribute to enhanced rainfall over SCE (Figure 2(a)). The interaction between the SCE rainfall and the CGT leads to their significant linkage.

This study proposes that the SCE summer rainfall induces a CGT-like wave train (Figure 3), which is different from previous studies that highlighted the important role of summer diabatic heating over the eastern MS region (Enomoto et al., 2003; Yasui and Watanabe, 2010). The fact that rainfall is much stronger over SCE than over the MS in the interannual variability suggests a more important contribution of the summer rainfall over SCE than over the MS to the interannual variation of the CGT. Their relative contribution is indicated by the CGTI-related summer rainfall anomalies (Figure 2(a)), with a significant relationship of the CGT with the summer rainfall in SCE but not with that in the MS land region. The correlation coefficient of -0.43 between the CGTI and the SCERI suggests that approximately 20% of the variance of the CGT is associated with the SCE summer rainfall.

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