Assessment of the Teleconnection Patterns Affecting July Precipitation in China and Their Forcing Mechanisms in the Met Office Unified Model

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ABSTRACT

In this study, we evaluate the ability of the MetUM to reproduce the Silk Road (SR) and Europe–China (EC) teleconnection patterns and their relationship with precipitation over China. The SR and EC patterns are the main modes of interannual variability of July upper-tropospheric meridional wind. The three main factors to the formation of these patterns are analyzed: 1) the tropical precipitation anomalies, which act as a forcing mechanism; 2) the emission of Rossby waves in the Mediterranean–Caspian Sea region; and 3) the basic state of the tropospheric jet over Eurasia. It was found that the model has some difficulty reproducing the main modes of variability in atmosphere-only mode (SR and EC pattern correlation of 0.31 and 0.54, respectively) with some improvement in coupled mode (pattern correlations of 0.56 and 0.44, respectively). Relaxation experiments were used to assess the impact that improving circulation in key regions has on the teleconnections. It was found that nudging wind and temperatures in the forcing regions within the tropics improved the Silk Road pattern whereas nudging in the region where the jet transitions between the North Atlantic Ocean and Eurasian continent—correcting the basic state—had the most impact on the EC teleconnection pattern. This suggests that while the Silk Road pattern is more sensitive to changes in the forcing, the Europe–China pattern is more sensitive to the basic state.

1. Introduction

The interannual variability of summer climate in East Asia is dominated by meridional teleconnections (Lau et al. 2000; Wang et al. 2001; Lu 2004) in the form of zonally elongated anomalies that appear in the meridional direction in both the lower and upper troposphere (Lu and Lin 2009). Chen and Huang (2012) state that the monthly atmospheric circulation in the extratropics is characterized by these stationary teleconnection patterns and that the climate is largely influenced by these patterns. One of the most prominent features of the Northern Hemisphere midlatitude circulation is the upper-level westerly tropospheric jet due to its strength

(Hoskins and Ambrizzi 1993; Lu et al. 2002). Kosaka et al. (2009) propose that the interannual variability of the meridional 200-hPa wind is strongest along the Asian jet, which suggests the presence of Rossby wave trains propagating through the jet. Many studies have investigated the teleconnection patterns and stationary Rossby waves propagating eastward within the Asian jet in June–August (Ambrizzi et al. 1995; Rodwell and Hoskins 1996; Krishnan and Sugi 2001; Lu et al. 2002; Wu and Wang 2002; Enomoto et al. 2003; Enomoto 2004; Ding and Wang 2005; Sato and Takahashi 2006). The characteristics of these teleconnections are highly dependent on time scales (e.g., Blackmon et al. 1984; Hsu and Lin 1992; Kiladis and Weickmann 1992). Further, to the dependence on time scale, these midlatitude wave patterns are constrained by the basic flow as they are usually trapped within the jet stream and have their wavelength and path determined by it (Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993). Due to this, many have found that the wave-like teleconnection patterns that can be found in summer in the Northern Hemisphere also have subseasonal variations (Kuang and Zhang 2005; Lin and Lu 2008; Lin et al. 2017; Schubert et al. 2011).

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One such subseasonal teleconnection pattern that has been thoroughly studied and described is the Silk Road pattern (SR) and its interannual counterpart, the circumglobal teleconnection (CGT) (Enomoto et al. 2003; Ding and Wang 2005), which is the dominant mode of variability in upper-tropospheric meridional wind. The SR tends to present as anomalous centers in preferred longitudes (Lu et al. 2002; Sato and Takahashi 2003; Ding and Wang 2005). The geographically fixed nature of the anomalous centers can be explained by the enhanced efficiency by geographically fixed features in extracting kinetic energy from the basic flow (Sato and Takahashi 2003; Kosaka et al. 2009). This makes it one of the most dominant modes of climate variability over the Eurasian continent during the summer months (Kosaka et al. 2009). There are a number of aspects that contribute to the appearance of the SR. This pattern is closely associated with 1) the basic flow, 2) the summer North Atlantic Oscillation (sNAO; Hong et al. 2018), and 3) disturbances in the meridional wind anomalies. This latter point has been highlighted as crucial for guaranteeing the appearance of the Silk Road pattern, highlighting the importance of the Caspian Sea region (Enomoto et al. 2003; Sato and Takahashi 2006; Yasui and Watanabe 2010; Kosaka et al. 2009; Hong and Lu 2016).

The second mode of interannual variability of the upper-level meridional wind over Eurasia is not as well documented in literature as the SR. The first mention of this mode of variability appears in Huang et al. (2011) as a pattern appearing over Eurasia, with centers that spanned from northern Europe to East Asia, named by Chen and Huang (2012) as the Europe–China teleconnection pattern (EC). This pattern is not confined to the jet, presenting an arc-like pattern across Eurasia. Chen and Huang (2012) have shown that the EC is also the result of the propagation of stationary Rossby waves but these are not along the jet waveguide.

The excitation mechanisms of these teleconnection patterns have been discussed by authors with some conflicting views. While Yasui and Watanabe (2010) suggest that the interannual component of the SR is triggered by heating anomalies around the Mediterranean, other authors have proposed that Indian monsoon heating may be responsible for the excitation of the SR (Enomoto et al. 2003; Ding and Wang 2005). In fact, Rodwell and Hoskins (1996) used an idealized model study to demonstrate that the diabatic heating from the Indian monsoon resulted in diabatic cooling and the downward motion over the Eurasian continent and Mediterranean Sea and excited a quasi-stationary disturbance on the jet, triggering a barotropic structure propagating within the westerly jet (Enomoto et al. 2003). Hall et al. (2013)

and Joseph and Srinivasan (1999) argue that Rossby waves generated by the response to tropical convective heating are the mechanism for tropical influence on the midlatitudes and found that the three monsoon regions together (Africa, Asia, and West America) explain most of the extratropical response for a year that is neither El Niño or La Niña. On a comprehensive study of the excitation mechanisms of the two main modes of upper-level tropospheric jet variability, Chen and Huang (2012) have found the 1) north Indian Ocean and equatorial Pacific precipitation and 2) equatorial central Pacific, Indonesian, and equatorial Atlantic precipitation anomalies to be linked to the first two modes—the SR and EC—of extratropical meridional wind interannual variability, respectively. This is indicative of the SR playing a role in linking the Indian summer monsoon and the East Asian summer monsoon (Lu et al. 2002).

Literature has shown extensive links between these upper-level wind teleconnection patterns and the climate variability in East Asia (Hoskins and Ambrizzi 1993; Schubert et al. 2011; Wakabayashi and Kawamura 2004; Hsu and Lin 2007), in particular the effect on rainfall anomalies in Asian monsoon regions (Lau and Weng 2002; Lau et al. 2005). Huang et al. (2008) have proposed a model of the factors influencing persistent drought in northern China, which included the mid-latitude wave activity, which is complemented by the findings of Yang and Zhang (2008) and Chen and Dai (2009), who found a correlation between anomalous rainfall in Xinjiang (Northeast China) and the position of the Asian subtropical westerly jet stream and the quasi-stationary wave activity. This relationship between the upper-level tropospheric westerly jet and precipitation is not only true for northern China. Zhou and Huang (2008) also have found a strong relationship between the SR and EC patterns and precipitation along the Yangtze River.

Due to its impact on the East Asian climate variability and the influence it has on anomalous rainfall in the East Asian monsoon, the representation of teleconnection patterns in the modes of variability of the upper-tropospheric meridional wind in climate models is of high importance for the accurate representation of subseasonal and interannual variability of precipitation in East Asia. Work focusing on model performance around these patterns is limited but Kosaka et al. (2009) found that some CMIP3 climate models are able to reproduce the Silk Road pattern but the resolution is one of the aspects that could limit their performance.

This paper focuses on the following questions: 1) Is the Met Office's Unified Model (MetUM) able to produce the two main modes of interannual variability

FIG. 1. Regional domains used in the nudging sensitivity experiments.

of the upper-tropospheric westerly jet in an atmosphere-only configuration or is ocean coupling necessary? 2) Are the processes by which these teleconnection patterns influence precipitation in East Asia present in the model. According to Lu et al. (2002), the SR has a clearer structure during late summer (July–August) and the July and August patterns are similar and more representative of the entire summer (Hong et al. 2018). To remove subseasonal variations, this work will focus on July.

2. Data and methods

In this work, we used the MetUM climate model in both atmosphere-only and coupled configurations. The atmosphere-only configurations correspond to MetUM Global Atmosphere 7.0 (GA7) (Walters et al. 2019). These climate integrations were produced with the same surface temperature, sea ice fractions, and other external forcings as in the Atmospheric Model Intercomparison Project (AMIP) framework of phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). The period considered for analysis of the AMIP integrations, as well as the reanalysis, was between 1982 and 2008. The coupled model configurations used correspond to MetUM Global Coupled Model 3.0 (GC3) (Williams et al. 2018). They are 100-yr free-running simulations in which the greenhouse gas and aerosol forcings are set to values from the year 2000, which is the same as experiment 2 in the Coupled Model Intercomparison Project 3 (CMIP3). The climate model simulations were conducted at an N96 horizontal resolution in the atmosphere (approximately 1.25° at 45° latitude) and the coupled simulation with the same atmosphere at a 0.25° ocean resolution.

As a control, and considered to be the truth for the purposes of assessing model fidelity, ERA-Interim (Dee et al. 2011) was used. Since reanalysis precipitation is a product of parameterizations, any analysis performed using ERA-Interim precipitation was also

compared against GPCP Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, from their website at <https://www.esrl.noaa.gov/psd/> (Adler et al. 2003).

a. Nudging experiments

To explore possible mechanisms linking model errors from remote regions and improvements in the simulated teleconnection patterns over Eurasia, we conducted a series of N96 AMIP sensitivity experiments using the nudging/relaxation methodology first outlined in Klinker (1990) and since by others including Douville et al. (2011), Hall et al. (2013), Rodríguez et al. (2017), and Rodríguez and Milton (2019). The nudging methodology involves relaxing the free-running model simulation back to reanalyses over a chosen domain. The AMIP simulation is nudged back to ERA-Interim temperatures and winds with a 6-hourly relaxation time scale at all model levels. These relaxation experiments were done for several different regions (Fig. 1). In addition to the domains in Fig. 1, a further nudging experiment was performed for a whole tropical band between 10°S and 10°N . For all regions, a buffer zone of 10° where the nudging increments are exponentially damped to zero to ensure a smooth transition between the nudged and free-running parts. The motivation for the regions chosen will be discussed in the following sections.

b. Modes of variability and teleconnection patterns

The July upper-level tropospheric jet teleconnection patterns are a representation of the main modes of variability of the monthly mean 200-hPa meridional wind. These patterns were calculated by applying an empirical orthogonal function (EOF) algorithm to calculate the principal components (PCs) in the domain of $30^\circ\text{--}60^\circ\text{N}$, $30^\circ\text{--}130^\circ\text{E}$ (henceforth referred to as Eurasia). The gridpoint correlation between each of the two PCs and the geopotential height at 200-hPa monthly time series (for the same period considered for the EOFs)

TABLE 1. Variance explained by the SR and EC patterns and pattern correlation between model simulations and reanalysis. These correlations are all significant at the 90% confidence level. Asterisks show which modes of variability are statistically significant based on North's rule.

Configuration	SR		EC	
	Explained variance (%)	Correlation	Explained variance (%)	Correlation
ERA-Interim	31.84	—	18.03	—
GA7 N96	25.58	0.31	31.87	0.54
GC3 N96 O25	25.05	0.56	21.47	0.44
South Asian monsoon	34.47*	0.52	25.14*	0.10
Tropical band	33.22	0.50	16.49	0.25
Africa	38.17*	0.49	18.71*	0.48
N. Atlantic–W. Europe	17.58	0.41	27.62*	0.56
Maritime Continent	39.94*	0.40	16.91*	0.12
Tropical west Pacific	37.19*	0.28	20.86*	0.21
Tropical Atlantic	39.14*	0.26	17.36	0.27

represents the teleconnection pattern. The statistical significance of the EOFs is assessed using the method proposed by North et al. (1982), henceforth referred to simply as North's rule.

To assess the existence of these modes in the model, the same procedure was followed using both atmosphere-only and ocean–atmosphere coupled configurations of the MetUM. To ensure that the patterns are assigned the correct type, the pattern correlation of the model and reanalysis (Table 1) was used to assign the SR or EC modes, along with a subjective assessment of the orientation (zonal for the SR and arc-like for the EC pattern).

Following Chen and Huang (2012) the relationship between the meridional wind modes of variability and precipitation is explored using the correlation coefficient calculated between the meridional wind PCs and the precipitation anomaly time series for both ERA-Interim and MetUM focusing on China. For “truth” we are using ERA-Interim precipitation in this study, but similar results are obtained using GPCP monthly precipitation anomalies.

To investigate the excitation mechanism put forward as being responsible for these patterns, the correlation between the 200-hPa PCs and the precipitation time series at each grid point over the tropics and Northern Hemisphere subtropics (global band between 15°S and 30°N) was also calculated and is discussed in section 4.

The remainder of this paper is as follows: section 3 describes the observed interannual upper-tropospheric wind teleconnection patterns and their relationship with precipitation over China. Sections 4 and 5 explore the impact of model errors on the representation of the teleconnection patterns and precipitation variability over China, analyzing the dynamical mechanisms underpinning the process. This is followed by a short discussion.

3. Upper-level jet teleconnection patterns and precipitation over China

The midlatitude teleconnection patterns, calculated as the correlation between the monthly time series of each of the two leading PCs of 200-hPa meridional wind and the 200-hPa geopotential, are shown for ERA-Interim along with the correlation of meridional wind PC's with the precipitation anomaly time series over China (first rows in Figs. 2 and 3). The teleconnection patterns are characterized by wavelike patterns of positive–negative centers with higher correlation coefficients over Eurasia (statistically significant regions in white contours) that are consistent with the SR and EC patterns described by Chen and Huang (2012).

a. The SR teleconnection pattern and precipitation

The leading mode for ERA-Interim (Fig. 2) starts from the Mediterranean and Caspian Sea (at the entrance of the Asian subtropical jet) and is oriented zonally along the core of the jet stream with three consecutive significant anomalous centers over central Europe, western Asia, and middle Asia, decaying at the exit of the Asian jet. This pattern is consistent with the SR pattern first named by Enomoto et al. (2003) and further described by Chen and Huang (2012). The precipitation pattern associated with the SR shows a significant positive correlation region in the north of China, stronger to the west and negative over Tibet and Guangxi province in the southeast (Fig. 2). This is consistent with results presented by Chen and Huang (2012), who showed that the first mode of variability of precipitation in Northwest China is related to the SR (as the pattern of precipitation EOF is similar to that of the correlation between meridional wind PC and precipitation). Chen and Huang (2012) also argue that at the larger synoptic to planetary scales the correlation between the

FIG. 2. (left) Silk Road (SR) teleconnection pattern obtained by calculating the correlation between the monthly mean July 200-hPa geopotential height and the PC of July monthly mean 200-hPa meridional wind for (top) ERA-Interim and (middle), (bottom) different model simulations. This teleconnection pattern is the first mode in the reanalysis but these have been matched by calculating the pattern correlation for the model and visually analyzing the orientation of the pattern. Dark gray contours are the July climatological zonal wind speed. Percentages are the variability explained by the mode. Where asterisks are present, the mode is statistically significant and not contaminated by subsequent modes as defined by North's rule. (right) The correlation between July 200-hPa meridional wind PCs associated with the Silk Road patterns from the left panels and the July precipitation over China. White contours in teleconnection and precipitation patterns represent where the correlation is statistically significant at the 90% level.

teleconnection patterns and precipitation response can be explained by the omega equation (Holton 2004), applied for a short wave system where relative vorticity is larger than the planetary vorticity advection and therefore ascending (descending) motion can be found ahead of the trough (ridge). For the SR pattern shown here the trough (low geopotential height anomalies) centered at 90°E provides the necessary ascent over Northwest China to give enhanced rainfall anomalies in that region (Fig. 2).

The SR teleconnection pattern for the MetUM GA7N96 AMIP simulation shows a generally weaker pattern dominated by one large positive center east of the Caspian Sea, but less coherence in pattern centers upstream and downstream. This is reflected in the relatively low correlation of 0.31 between the reanalysis and GA7 patterns (Table 1). Unlike the reanalysis, the model SR is the second mode rather than the first mode of interannual variability. It should be highlighted that

the model modes do not pass North's criteria (North et al. 1982) and therefore are not statistically significant. This does not mean the model does not produce the observed modes, but they are contaminated. The time-mean Asian subtropical jet also shows significant biases, being too weak over southern Europe and over northern China and the Korean peninsula. More discussion of these basic state jet biases is given in the next section. The model precipitation patterns associated with this teleconnection pattern are dominated by suppressed precipitation in northern and northwestern China, which is the opposite of the pattern for the ERA-Interim SR patterns. In contrast, the coupled version of the model, GC3, shows a better representation of the SR teleconnection pattern (correlation of 0.56 with ERA-Interim pattern; Table 1) and reduced jet biases over Asia. However, this does not translate into an improved precipitation correlation pattern associated with this SR mode. There is a signal of

FIG. 3. As Fig. 2, but for the Europe–China (EC) teleconnection pattern.

enhanced precipitation over northern China but the large positive anomaly in Northwest China seen in ERA-Interim is not captured, despite the GC3 and ERA-Interim teleconnection pattern being very similar in this region (Fig. 2).

b. The EC teleconnection pattern and precipitation

The second mode of meridional wind interannual variability also exhibits a wave-like pattern extending from the North Atlantic to China through an arc-like path over Eurasia. This pattern shows five significant anomalous centers located over the North Atlantic, central Europe, eastern Europe, central Asia, and China (Fig. 3). This pattern is consistent with the description of the EC teleconnection pattern presented by Chen and Huang (2012). By examining the wave activity fluxes [as in Plumb (1985) and Takaya and Nakamura (1997, 2001)] Chen and Huang (2012) concluded that, similarly to the SR, this pattern is the result of the propagation of stationary Rossby waves. The difference in propagation structure is suggested to be due to the fact that while the Silk Road pattern is trapped within the Asian jet stream waveguide the Europe–China pattern propagates through an arc-like path (Hoskins and Karoly 1981). The pattern associated with the EC is positive in the northeast of China and Guangxi and Guangdong provinces and negative throughout the middle [note this is opposite in

sign to the EC mode in Chen and Huang (2012)]. Although the SR is found to be associated with the first mode precipitation interannual variability, the EC is not found to be associated with a main mode of precipitation variability. The ERA-Interim precipitation pattern associated with this teleconnection shows a tripole pattern with reduced precipitation in a zonal strip across central China (including the Yangtze River valley region) and enhanced precipitation over Northeast and Southeast China [see an equivalent pattern in Fig. 9b in Chen and Huang (2012)]. Both the GA7 AMIP and GC3 coupled models produce patterns similar to reanalysis EC teleconnection pattern (although for GA7, the mode associated with the EC pattern is favored over the SR) with pattern correlations of 0.54 and 0.44 respectively (Table 1). The GA7 and GC3 modeled precipitation correlation associated with the EC teleconnection capture the enhanced precipitation in central China, although it is more truncated in the east and the drier regions north and south are less distinct in the model simulations.

In the following section we investigate potential forcing mechanisms for the SR and EC patterns guided by the analysis of Chen and Huang (2012) and use the nudging experiments with the GA7 AMIP version of MetUM to investigate possible local and remotely forced model systematic errors in these

teleconnection patterns and associated precipitation variability over China.

4. Mechanisms and model error sources

A useful starting point for thinking about the dynamical mechanisms underpinning the SR/EC teleconnection patterns is the time-mean vorticity equation [Eq. (1)] for a single pressure level following Sardeshmukh and Hoskins (1988). The equation shows the rotational components of the flow on the left-hand side, where ζ is the absolute vorticity and $\mathbf{V}_\psi$ is the rotational vector wind. An overbar represents a time mean and a primed quantity is a deviation from the time mean (transient eddy). The right-hand side shows a number of forcing terms for the rotational flow; the Rossby wave source (RWS; S is hereafter referred to as RWS in the text), the transient eddy vorticity flux convergence, and the frictional damping term. This equation neglects twisting and tilting terms in the vorticity equation. The RWS [Eq. (2)] consists of two terms; the first is the vortex stretching term where vorticity is generated locally through the divergence and the second is the advection of the absolute vorticity gradient by the divergent wind. Sardeshmukh and Hoskins (1988) identified that this latter term has the potential to generate a vorticity source and Rossby wave response at more remote locations (e.g., subtropics) rather than directly over areas of divergence:

$$\frac{\partial \bar{\zeta}}{\partial t} + \bar{\mathbf{V}}_\psi \cdot \nabla \bar{\zeta} = S - \nabla \cdot \overline{\mathbf{V}'\zeta'} + F, \quad (1)$$

$$S = -\nabla \bar{\mathbf{V}}_x \cdot \bar{\zeta} = -\bar{\mathbf{V}}_x \cdot \nabla \bar{\zeta} - \bar{\zeta} \nabla \cdot \bar{\mathbf{V}}_x. \quad (2)$$

In the following sections we discuss the potential roles of the time-mean basic state, tropical heating anomalies/errors, and their link to divergent circulation through the generation of the RWS.

a. The time-mean basic state

Given the tropical forcing mechanisms discussed in section 1, a plausible mechanism is that coupling may improve the model's tropical forcing/variability and this may feed into modes of upper-level tropospheric wind—as seen for example in the SR mode (Fig. 2). The main precipitation error structures remain unchanged between when coupling. There is a reduction in summer precipitation bias in the South Asian monsoon region and equatorial Indian Ocean (not shown), which may be influential in the improvement of the teleconnection patterns when coupling with the ocean. However, the zonal wind biases at 200 hPa in the Northern

Hemisphere (first row in Fig. 4) are larger in the coupled model than they are in the atmosphere only, particularly over and around Eurasia. The only region where the atmosphere-only model has a lower bias is over North America. The model, in both configurations, tends to have a weaker, broader jet over Eurasia and the Pacific exit region. Over the Atlantic, and the Iberian Peninsula (between 15° and 10°W), where the climatological jet has a sharp shift southward (Fig. 5), the model is unable to reproduce that, with the jet being more zonally oriented than in the reanalysis. Although this is true for both atmosphere-only and coupled configurations, this is a more marked issue in the coupled. In the context of the teleconnections in the upper-level tropospheric jet, the position and strength of the jet stream is an important factor (Hoskins and Ambrizzi 1993; Douville et al. 2011).

As mentioned previously (section 1), the strength and poleward displacement of the westerly jet stream can influence the propagation of planetary waves and the simulation of the tropical-extratropical interactions (Hoskins and Ambrizzi 1993). The strongest zonal wind speeds in July occur between 35° and 50°N, on average (Fig. 5). The atmosphere-only model configuration tends to be placed northward of the reanalysis jet whereas the coupled configuration tends to be displaced to the south. This is true over most of the Northern Hemisphere (with the exception of the west to mid-Eurasian continent, between approximately 10°W and 100°E). This is an issue that is known not to improve with increased resolution. As the jet stream transitions between the Atlantic Ocean and western Europe, it meanders south until reaching the Black Sea where it turns northward again. This is the area where biases in the position of the highest speeds are lower; east of 90°E the model starts diverging away from reanalysis. A question then arises: Is the position of the jet in the east Atlantic–western Europe sector a factor for the proper development of the teleconnection patterns? To answer that, a relaxation experiment was carried out where nudging of wind speeds and temperature was applied over that region (Fig. 1, section 2a). When nudging the area of 25°–65°N, 40°W–10°E (North Atlantic–western Europe) in an atmosphere-only setting, the position of the jet is effectively corrected in this area. This improves the position of the jet over Eurasia, only diverging from reanalysis at the exit of the jet (East Asia–west Pacific region). A similar experience with nudging over Africa also improves the position of the jet (to a lesser extent), although the downstream effect is weaker and results start to deteriorate east of 90°E. Both regions mentioned partly overlap over North Africa (Fig. 1) and some of the improved skill in both the position of the jet and the

FIG. 4. Bias (model minus ERA-Interim) of July monthly mean zonal wind (m s^{-1}) at 200 hPa (color) for different model configurations (atmosphere-only and coupled) and nudging experiments and mean July zonal wind (gray contours; drawn at 5 m s^{-1} intervals beginning at 15 m s^{-1}).

teleconnection pattern comes from this overlapping region in North Africa (not shown). The North Atlantic–western Europe nudging experiment also improves the bias of the zonal wind at 200 hPa (Fig. 4) by increasing the jet speed over Eurasia as well as making it narrower at the Pacific exit region, bringing it closer to reanalysis.

The improvement in the basic state from the nudging over the North Atlantic and western Europe is accompanied by an improvement in the SR and EC teleconnection patterns produced by the model (Fig. 8). The pattern correlation goes from 0.31 and 0.54 (standalone GA7N96) to 0.41 and 0.56 when nudging the North Atlantic–western Europe region for the SR and EC,

FIG. 5. Mean latitude at which the maximum westerly jet speed occurs for each of the model configurations and ERA-Interim in the Northern Hemisphere for July.

FIG. 6. Rossby wave source as defined by Sardeshmukh and Hoskins (1988) at 200 hPa in July for (top) ERA-Interim and (remaining rows) bias in relation to ERA-Interim. (left) Rotational component ($-\mathbf{V}_\chi \cdot \nabla \zeta$), (center) the divergent component ($-\zeta D$), and (right) the total RWS.

respectively. It should also be highlighted that the modes of interannual variability of meridional wind (EOFs) for the atmosphere-only configuration (GA7N96) are contaminated and therefore not significant (as defined by North's rule) while both the first and second modes of this experiment are significant. This shows the high impact the basic state has in these modes of variability. Of the nudging regions studied, this is the one that leads to the largest improvements to the Northern Hemisphere basic state as well as the teleconnection patterns.

b. Rossby wave source as response to tropical heating

On the large scale, tropical heating is balanced by the adiabatic cooling of ascent and the divergence of the

wind above the heating drives the rotational wind in the upper troposphere through the RWS term (Sardeshmukh and Hoskins 1988). In the boreal summer, the main areas of RWS in the Northern Hemisphere are located along the jet, with large positive centers over the Mediterranean and east of the Caspian Sea (first row in Fig. 6). The main contributions toward these centers are in the advection by the $\mathbf{V}_\chi$ term [Eq. (2)]. Between these two centers and over most of the Eurasian land region, extending into the Pacific along the jet stream are negative source regions. The atmosphere-only and coupled model configurations show similar error structure and similar contributions from the advection and stretching terms (Fig. 6). When nudging the North Atlantic–western Europe or Africa

regions, the bias in the advection component over the Caspian and Black Seas region is reduced, having an impact on the total bias. This may be due to the improvement in the position of the jet (Fig. 5) over Eurasia for the former and east of 30°E for the latter. There is also a reduction of the jet bias for these two relaxation experiments (Fig. 4), which is due to both improved position and strengthening of the jet in the region. Another region with high impact in improving the advection term of the RWS is the Maritime Continent. The impact on the stretching term is mainly seen when relaxing is applied in the South Asian monsoon and tropical band (and to a smaller extent the Maritime Continent) regions. The reduction in RWS bias is due to the forcing circulation being effectively corrected in the key areas where the heating anomalies are expected to cause the adiabatic cooling of ascent and divergence of the wind locally, which then drives the rotational wind. The bias reductions and improvement in RWS discussed for nudging regions such as the tropical band and South Asian monsoon are in line with improvement seen in the teleconnection patterns for these experiments (Fig. 8).

c. Forcing mechanism: Tropical heating anomalies

The forcing mechanisms of the modes of variability have been attributed to tropical heating anomalies (Rodwell and Hoskins 1996; Enomoto et al. 2003; Ding and Wang 2005; Hall et al. 2013). More specifically, Chen and Huang (2012) identified the Indian Ocean, equatorial Pacific, equatorial central Pacific, and equatorial Atlantic as key areas for the forcing of the SR and EC teleconnection patterns, respectively. To assess this relationship, the correlation between the PC associated with the teleconnection pattern and the monthly precipitation time series at each point in the tropics and Northern Hemisphere subtropics region defined between 15°S and 30°N was used (Fig. 7). This has been found to be robust across different reanalysis and precipitation datasets, with small variations in the statistical significance of the correlation but general agreement in the sign of the signal.

The correlation for ERA-Interim (first row of Fig. 7) is obtained using both wind PC and precipitation from ERA-Interim. For the SR (left column), the key areas are India, the Maritime Continent, the equatorial central/east Pacific, and the equatorial Atlantic whereas for the EC pattern they are the west to central Pacific and the equatorial Atlantic (significant with an 90% confidence level). This is consistent with the results of Chen and Huang (2012), with an additional contribution from the Maritime Continent not seen in Chen and Huang (2012). The model has a very weak correlation signal in both atmosphere-only and coupled configurations. In the atmosphere-only configuration there is a small area of positive correlation over the Maritime

Continent for the SR mode and little to no significant signal in the Pacific and equatorial Atlantic. The relationship between the EC mode and tropical rainfall in the model is opposite to the observed in the Pacific but does have a similar signal in the equatorial Atlantic. The coupled configuration has a very weak and mostly not statistically significant signal.

Considering the regions encountered to be correlated with the SR and EC modes, model relaxation experiments for specific areas were conducted (Fig. 1 in section 2a). Both the teleconnection patterns produced in such model experiments (Fig. 8) as well as the patterns associated with the forcing mechanisms (Fig. 7) were investigated. In the relaxation/nudging experiments the (zonal and meridional) winds and temperature are relaxed to ERA-Interim. The forcing signal in the nudging experiments is more significant than in the free-running simulations. The impacts of the nudging are at times remote (e.g., by nudging the tropical Atlantic, the SR forcing signal over the tropical Indian Ocean is improved and by nudging the tropical west Pacific, the EC forcing signal over the whole Pacific Ocean is improved). The nudging regions that produce the largest improvements in the SR pattern are the South Asian monsoon (0.52 correlation), the tropical band (0.50 correlation), and Africa (0.49 correlation). The South Asian monsoon region comprises the area that had some of the largest forcing signals for the SR and therefore the improvement in pattern can be attributed to improvements in the region. Even though the forcing diagnostic (Fig. 7) does not show a large improvement, this is due to the fact that the key forcing is the divergent flow due to heating and this is still being constrained through the wind and temperature even though moisture is not. This then corrects the forcing in the circulation while not necessarily producing the correct tropical precipitation (product of the model parameterization) and consequently having low impact on the forcing diagnostic. For the EC pattern, the nudging regions that show the most improvement are the North Atlantic–western Europe (0.56 correlation) and Africa (0.48 correlation). While improvements in the precipitation–teleconnection patterns are in line with improvements to the modes of upper-tropospheric wind interannual variability for some regions (i.e., North Atlantic–western Europe and South Asian monsoon), results from the nudging of the tropical band are more mixed.

5. Error sources and precipitation variability over China

The standard free-running model is not able to produce the observed relationship between the modes of

FIG. 7. Correlation between the first and second PC of 200-hPa July monthly mean meridional wind and tropical precipitation (band between 15°S and 30°N) where this is statistically significant at the 90% confidence level. Black contours represent the correlation between the first and second 200-hPa meridional wind PCs and the geopotential height at the same level (shaded contours in Figs. 2 and 3).

variability of upper-level tropospheric meridional wind and precipitation over China (Figs. 2 and 3). Given the improvement in the representation of the teleconnection patterns in some of the relaxation experiments (namely,

the South Asian monsoon and North Atlantic–western Europe ones), the impact of these improvements in the relationship of such teleconnection patterns and precipitation over China was also investigated (Figs. 9 and 10).

FIG. 8. Taylor diagram summarizing the ability of different model configurations to produce the (left) Silk Road and (right) Europe–China teleconnection spatial patterns. The x and y axes are the normalized standard deviation (so that the standard deviation of the control is always 1). The polar axis represents the correlation and the dotted blue circumferences represent the normalized error standard deviation.

The impact of the relaxation experiments on the precipitation relationship is lower than that seen on the teleconnection patterns. When nudging Africa and the South Asian monsoon regions, there is improvement in the signal associated with both teleconnection patterns for the former and the EC for the latter, capturing some of the features. These improvements are somewhat in line with the improvements seen for the teleconnection patterns. However, improvements in the meridional wind modes of variability do not always translate into improvements on the relationship with precipitation (e.g., the nudging to the North Atlantic–western Europe region). This may be due to a number of factors such as a disconnect between the teleconnection patterns and precipitation variability in the model as well. In addition, the nudging of the tropical band sees a large positive impact for the precipitation correlation associated with the EC pattern (Fig. 10), but the impact on the teleconnection patterns is arguably very low. That paradox may be due to local effects (i.e., moisture fluxes into the region), which may improve precipitation variability. These are a matter for further study and are not in the scope of the present work.

6. Discussion

The issue of East Asian climate variability and teleconnections is complex and models struggle to reproduce both the teleconnection patterns and their impacts (e.g., Kosaka et al. 2011; Kripalani et al. 2007). This may be due to a number of intertwined factors that result in a poor representation of East Asian climate variability, which has impacts on long-term (i.e., seasonal) forecasting and future climate projections. Many

studies reflect the sources of such errors from a local perspective but there is a lack of understanding of the reasons why models struggle with the teleconnections. This may partly be due to the complexity of the system and the models as well as nonlinear dynamic of teleconnections. Not only would the model have to reproduce every aspect discussed in previous sections (forcing in the tropics, Rossby wave source in the Caspian Sea region, and jet basic state) but it would also have to perfectly represent the interactions of these processes across regions and time scales along the teleconnection pathway.

The focus has been on understanding and improving the tropical heating anomalies in the expectation that it would improve the remote effects. Within the relaxation experiments, it has become clear that the tropical heating forcing is an important factor when looking at the teleconnection patterns. Some of the largest improvements in the SR pattern occur when circulation over the South Asian monsoon region is corrected (Fig. 8 and Table 1). This is consistent with the results found for the forcing diagnostics (Fig. 7) and early studies on the excitation mechanisms of the SR pattern. These results are valid despite the forcing diagnostic for this relaxation experiment not showing improvements when compared to the free-running model. This is because the diagnostic used is based on precipitation, which is still a product of the model physics and is not relaxed toward the reanalysis. However, the remote impact is still seen due to the excitation mechanism being the divergent flow due to heating, which is relaxed toward reanalysis.

On the other hand, other studies have found the basic state to be equally important in producing the correct teleconnections (e.g., Henderson et al. 2017). This is true

FIG. 9. Correlation between the wind PC of 200-hPa July monthly mean meridional wind associated with the Silk Road pattern and precipitation (band between 15°S and 30°N) where this is statistically significant at the 90% confidence level. White contours represent the correlation between the wind PC and the geopotential height at the same level (shaded contours in Fig. 2).

for both the SR and EC patterns, but within the model framework more so for the EC as this is the only relaxation experiment that improves this pattern. This is particularly interesting as it points to the EC pattern being more sensitive to basic state changes and

improvements whereas the SR tends to be more sensitive to the correction of the forcing divergence. It has been widely suggested that the formation of the SR is closely associated with the Asian upper-tropospheric westerly jet, as the pattern is trapped within the jet.

FIG. 10. As in Fig. 9, but for the Europe–China (EC) teleconnection pattern.

Within the model however, this does not appear to be the case.

One aspect that will merit further study is the impact of correcting the position of the strongest zonal velocities as well as the strength of the jet over Eurasia (effect of nudging of the North Atlantic and western Europe). This is particularly important as it leads to improved

model ability to produce the SR and EC patterns correctly. This result shows the importance of correcting the region where the jet transitions onto land on the overall behavior over Eurasia.

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