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Research Article

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Representation of Rossby wave propagation and its effect on the teleconnection between the Indian summer monsoon and extratropical rainfall in the Met Office Unified Model

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Abstract

Compared with Global Atmosphere 6 (GA6) of the UK Met Office Unified Model (UM), the dry bias over the Indian monsoon region in Global Atmosphere 7 (GA7) is significantly reduced. However, the physical processes controlling how this reduced dry bias in India influences rainfall teleconnections in the extratropics remain unclear. Thus, in this study, we use Rossby wave tracing in a horizontally nonuniform background flow to investigate how the improved simulation of monsoon rainfall in GA7 compared with GA6 affects extratropical rainfall teleconnections. We find that wave rays emanating from the upper troposphere in the Indian monsoon region first propagate westward, then divide into the Northern Hemisphere (NH) subtropical westerlies over Asia and the Southern Hemisphere (SH) subtropical westerlies. The wave ray trajectories in GA7 in years of strong Indian summer monsoon rainfall (ISMR) are closer to observations than those in GA6. We also find that the upper tropospheric meridional winds over the South Asian monsoon region and western Tibetan Plateau are much better simulated in GA7 than in GA6 owning to the improvement of ISMR and South Asian High (SAH), which leads to a more realistic simulation of the wave rays in GA7. The better simulated circulation teleconnections in GA7 then modulate the vertical motion and moisture transport, and hence affect extratropical rainfall anomalies in the NH and SH. This paper provides new insights for the assessment of tropical–extratropical teleconnections in models.
1. Introduction

The Unified Model (UM) is the atmospheric component of the numerical modelling system created by the UK Met Office (UKMO) for both weather and climate applications (https://www.metoffice.gov.uk/research/modelling-systems). It is widely used by many organizations and agencies around the world, particularly in the Australian–Asian region, including Australia, India, Korea, and the Philippines (https://www.metoffice.gov.uk/research/approach/collaboration/unified-model/partnership). Two versions of the UM, namely the UM Global Atmosphere 6 (GA6) and 7 (GA7) are being used by the UK and Australia to contribute to the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP6) (Hirst, 2015; Walters et al., 2019) and in their operational seasonal forecast systems (MacLachlan et al., 2015; Hudson et al., 2017). As a result, assessing the performance of the UM GA in the Australian–Asian monsoon region has been an important topic of past research.

As noted in previous UM assessments (Walters et al., 2014, 2017, 2019), the UM has a climatological rainfall deficit over the Indian subcontinent. However, the simulation of Indian summer monsoon rainfall (ISMR) within a given UM configuration was shown to improve when the model resolution was increased (Prakash et al., 2016; Jin et al., 2019). In a recent UM GA assessment study, Jin et al. (2019) showed that the area-averaged summer monsoon rainfall over the Indian subcontinent (70°–90°E, 5°–25°N) was significantly increased in GA7 compared with GA6. Furthermore, the increased ISMR in GA7 with N216 resolution improved monsoon–
desert rainfall teleconnections and generated more realistic remote rainfall correlation patterns in the Australian–Asian region. Part of the teleconnection patterns showed similarity with Rossby wave propagation from the tropics into the middle and high latitudes. However, as acknowledged by the authors, the underlying physical and dynamic processes supporting these improved rainfall teleconnection patterns and the increased ISMR in the simulations was not fully explored (Jin et al., 2019). The major goal of this study is therefore to further investigate how the simulation of Indian monsoon rainfall in GA6 and GA7 (Walters et al., 2017, 2019) affects the representation of tropical–extratropical rainfall teleconnections, and the nature of the underlying physical and dynamical processes. This analysis will also help to better understand the simulated current and future climate in these models in preparation for CMIP6.

The extratropical atmospheric response to tropical localized forcing is well established in both the Northern Hemisphere (NH) (Nitta, 1987; Hoskins and Rodwell, 1995; Rodwell and Hoskins, 1996; Kripalani et al., 1997; Wang et al., 2001; Ding and Wang, 2005, 2007; Lin, 2009) and the Southern Hemisphere (SH) (Wang et al., 2001; Lin, 2009; Lee et al., 2013; Liu and Wang, 2013; Zhao et al., 2019). Several summer teleconnection patterns in the NH associated with tropical monsoons have been investigated, including the Pacific–Japan pattern (Nitta, 1987, 1989), the East Asia–Pacific pattern (Huang and Lu, 1987, Huang and Sun, 1992), the circumpolar teleconnection pattern (Ding and Wang, 2005; Ding et al., 2011), the “silk road” pattern in the 200 hPa meridional velocity (Lu et al., 2002; Enomoto et al., 2003), the Indo–Asian–Pacific pattern (Li et al., 2011; Li et al., 2013), and the North Atlantic–
Eurasian teleconnection (Li et al., 2013; Li and Ruan, 2018; Li et al., 2019). In addition, the circulation variability in the SH induced by tropical heating was the topic of several studies, including the Pacific–South America pattern (Karoly, 1989), the South Africa–midlatitude pattern and the Maritime Continent–subtropical Australian pattern (Zhao et al., 2019). The mechanism proposed for these tropical–extratropical teleconnections is Rossby wave propagation and energy dispersion from localized tropical heating anomalies (Hoskins and Karoly, 1981; Branstator, 1983; Li and Nathan, 1994). As some theoretical studies have proved (e.g., Hoskins and Karoly, 1981; Simmons, 1982; Branstator, 1983; Lau and Lim, 1984; Branstator, 1985), these anomalies excite stable two-dimensional Rossby waves, thereby dispersing energy to remote regions of the globe.

These wave energy dispersion pathways can be well represented by the “great circle” ray trajectory (Hoskins and Karoly, 1981). However, in models with a zonally varying or zonally symmetric basic flow, stationary waves can only propagate in the westerlies and cannot cross the critical latitude (i.e., the zero zonal wind speed line; Hoskins and Karoly, 1981; Branstator, 1983). As there is a strong easterly wind prevailing at upper levels of the atmosphere in the Indian monsoon region during boreal summer, the Rossby waves are evanescent and cannot propagate into the SH in these kinds of models. In reality, however, the Asian monsoon system has a strong meridional circulation and its meridional wind cannot be neglected, compared with the zonal wind. Schneider and Watterson (1984) and Zhang et al. (1996) proved theoretically and numerically that the Hadley circulation allows Rossby waves to propagate from one
hemisphere to another via the easterly winds.

Li and Li (2012) further considered the barotropic, non-divergent vorticity equation in a horizontally nonuniform basic flow, and found that steady Rossby waves can propagate in the easterlies when supported by the meridional wind. On the basis of the theory of Li and Li (2012), further research has also demonstrated that stationary waves originating from the tropical easterlies can propagate across the equator (Li et al., 2015; Zhao et al., 2015, 2019).

Another physical mechanism behind cross-equatorial easterly teleconnections was proposed by Sardeshmukh and Hoskins (1988). They suggested that the equatorial forcing in the easterly winds induces a Rossby wave source in the subtropical westerlies caused by the advection of vorticity by the perturbed divergent flow. However, the divergent wind is much evident over upper tropospheric maritime continent during boreal summer and cannot simply explain the dynamical process of interhemispheric teleconnections associated with ISMR. In this study, therefore, stationary Rossby wave ray tracing is employed to investigate rainfall teleconnections simulated in the UM models.

The main focus of this study is to examine how the improved simulation of ISMR in GA7 compared with GA6 influences extratropical precipitation over the Australian–Asian monsoon region, and the nature of the underlying physical and dynamical mechanisms. We pay particular attention to exploring the signature of stationary Rossby wave energy dispersion in a horizontally nonuniform basic flow within the simulations.

The paper is organized as follows. In Section 2, the model, data, and methodology
used in this study are introduced. Section 3 is used to assess the rainfall simulations in
GA6 and GA7. Section 4 describes the circulation anomalies in the SH and NH
associated with ISMR and analyzes their influence on the extratropical rainfall.
Section 5 presents the trajectories obtained via Rossby wave ray tracing and discusses
the role of meridional wind ducts related to ISMR and South Asian High (SAH).
Section 6 contains a summary and discussion.

2. Model, data and methodology

2.1 Model

In this paper, we use monthly precipitation, winds, and geopotential height data
obtained from numerical experiments with the UM GA6 and GA7 (Walters et al., 2017,
2019) using a horizontal resolution of 60 km (N216 grid). We used atmosphere-only
UM GA simulations by forcing the model with daily observed sea surface temperature
(SST) and sea-ice conditions for the period 1982–2008, as in Walters et al. (2017, 2019)
and Jin et al. (2019).

Detailed descriptions of the UM GA6 and GA7 configurations have been provided
in several publications (Walters et al., 2017, 2019; Jin et al., 2019), and here we list
only some of the key features that are relevant to this study. The GA6 solves the non-
hydrostatic, fully compressible, deep-atmosphere equations of motion with a semi-
implicit semi-Lagrangian formulation and ENDGame dynamical core (Wood et al.,
2014). It uses extensively modified microphysics based on Wilson and Ballard (1999)
and a revised version of the convection scheme of Gregory and Rowntree (1990) that
includes downdrafts (Gregory and Allen, 1991) and convective momentum transport.
As pointed out by Walter et al. (2019) and Jin et al. (2019), GA7 includes further developments of the model’s microphysics scheme and incremental improvements to the implementation of the dynamical core. It includes improved treatment of gaseous absorption in the radiation scheme, improvements to the treatment of warm rain and ice clouds, and revisions to the model’s convection scheme to improve the fidelity of the simulation of rainfall. These developments lead to large reductions in four critical model errors: rainfall deficits over India during the South Asian monsoon, temperature and humidity biases in the tropical tropopause layer, deficiencies in the model’s numerical conservation, and surface flux biases over the Southern Ocean (Walters et al., 2019).

2.2 Observational data

In order to evaluate the simulated Indian Monsoon precipitation, we use monthly precipitation from the Global Precipitation Climatology Project (GPCP; Adler et al., 2003) for the period 1982–2008. Furthermore, the horizontal winds from ERA-Interim reanalysis (Dee et al., 2011) are used for the Rossby wave ray tracing, whilst the geopotential height from ERA-Interim reanalysis data with a resolution of 2.5° longitude by 2.5° latitude for the period 1982–2008 is used to evaluate the monsoon circulation.

The indices used in this study are as follows. The Niño-3.4 index obtained from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/), defined as the area-averaged SST anomalies over 5°S–5°N, 170°–120°W, is used to quantify the El Niño Southern Oscillation (ENSO). The Indian Ocean Dipole (IOD) Mode index
(DMI) obtained from National Oceanic and Atmospheric Administration (NOAA) 
(http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/DMI/) is defined as the difference in the SST anomaly between the tropical western Indian Ocean (10°S–10°N, 50°–70°E) and the southeastern Indian Ocean (10°S–0°N, 90°–110°E; Saji et al., 1999).

To quantify the Indian summer monsoon, many indices based on the precipitation, OLR or 850 hPa wind anomalies have been used in the literature (Wang et al., 2001; Li and Zeng, 2002, 2003, 2005; Ding and Wang, 2007). In this paper, in order to evaluate the ISMR-dependent teleconnections in GA6 and GA7, we define the ISMR Index (ISMRI) as the normalized area-averaged rainfall anomaly over the Indian subcontinent (5°–25°N, 70°–90°E), as in Jin et al. (2019). Furthermore, we define the ISMR as being strong (weak) when the ISMRI is above (below) 0.75 (–0.75) considering both the significance and the number of strong (weak) ISMR events. Furthermore, both the strong and weak ISMR years selected in observation and GA7 are six years, and the strong and weak ISMR years in GA6 are seven and six years, respectively. Note that by choosing a larger domain covering the whole of the south Asian monsoon region, Jin et al. (2019) showed that the agreement between GA7 simulations and observations was much improved. We define the south Asian monsoon region as the area over 5°–25°N, 30°–90°E.

2.3 Partial correlation

In our analysis, we use the first-order partial correlation coefficient (Anderson, 1984) to calculate the correlation between two time series, excluding the effect of one other control variable as follows:
where $r_{ij-k}$ denotes the partial correlation of variables $i$ and $j$, excluding the effect of $k$, $r_{ij}$ refers to the linear correlation between variables $i$ and $j$, $r_{ik}$ refers to the linear correlation between variables $i$ and $k$, and $r_{jk}$ refers to the linear correlation between variables $j$ and $k$.

The second-order partial correlation coefficient (Anderson, 1984), used to determine the correlation between two time series excluding the effect of two other control variables, is calculated as follows:

$$r_{ij-kh} = \frac{r_{ij-k} - r_{ih-k} \times r_{jh-k}}{\sqrt{(1-r_{ih-k}^2) \times (1-r_{jh-k}^2)}}$$

where $r_{ij-kh}$ denotes the partial correlation between variables $i$ and $j$, excluding the signals of $k$ and $h$, and $r_{ij-k}$, $r_{ih-k}$, and $r_{jh-k}$ can be obtained from Eq. (1).

2.4 Partial regression

The partial regression is adopted to estimate how much of the variation of the response variable can be attributed exclusively to one set of factors, once the effect of the other set has been taken into account and controlled for. Specifically, the influences of the considered factors on the studied variables are eliminated step by step. Let's take three independent variables $X$, $X1$, $X2$ as an example, and $Y$ be the dependent variable. Firstly, the effect of $X1$ on $y$ is removed by subtracting the regression of $Y$ on $X1$. The regressed values of $Y$ are assumed to follow certain distribution:
\[ \tilde{Y}'(t) = aX1'(t) + a1, \quad (3) \]

Primes represent departure from the mean state, \( a \) is the regression coefficient, and \( a1 \) is the intercept of linear regression. \( \tilde{Y}' \) indicates the linear contribution of \( X1' \) on \( Y' \). Then the effect of \( X1 \) on \( Y \) is eliminated by

\[ Y''(t) = Y'(t) - \tilde{Y}'(t). \quad (4) \]

\( Y'' \) is isolate from \( X1 \). Then the same way is used to remove the linear influence of \( X2 \) on \( y \). Linear contribution of \( X2 \) on \( Y'' \) is

\[ \tilde{Y}^{tr}(t) = bX2'(t) + b1, \quad (5) \]

where \( \tilde{Y}^{tr} \) indicates the regression of \( Y'' \) on \( X2' \). The linear influence of \( X2 \) can be excluded by

\[ Y^{tr*}(t) = Y''(t) - \tilde{Y}^{tr}(t). \quad (6) \]

In this case, the linear contributions of \( X1 \) and \( X2 \) on \( Y'(t) \) are removed. The \( \tilde{Y}^{tr*}(t) \) that is attributed exclusively to \( X \) takes the form of

\[ \tilde{Y}^{tr*}(t) = cX'(t) + c1, \quad (7) \]

in which \( c \) is the partial regression coefficient, and \( \tilde{Y}^{tr*} \) is the partial regressed value by \( X' \).

### 2.5 Rossby wave theory in a nonuniform horizontal basic flow

Rossby wave ray tracing theory describes the pathway of wave energy dispersion (Hoskins and Karoly, 1981; Li et al., 2015; Zhao et al., 2015, 2019) and has been widely used to explore atmospheric teleconnections. Thus, it is used in this study to reveal the dynamical link between ISMR and the extratropical climate. A linearized, spherical barotropic Rossby wave ray tracing model proposed by Li and Li (2012) and Li et al.
240 (2015) is employed to study steady, linear Rossby wave patterns in a nonuniform horizontal basic flow. According to Zhao et al. (2015, 2019), the dispersion relation of a barotropic Rossby wave is

\[ \omega = \bar{u}_M k + \bar{v}_M k + \frac{l \partial q / \partial x - k \partial q / \partial y}{K^2}, \]  

(8)

where \( \omega \) is the frequency, \((\bar{u}_M, \bar{v}_M) = (\bar{u}, \bar{v}) / \cos \phi \) is the Mercator projection of the basic-state zonal and meridional winds, \( \phi \) is the latitude, \( q = 2 \Omega \sin \phi + \nabla^2 \bar{\Psi} \) is the basic-state absolute vorticity, \( \Omega \) is the rotation rate of Earth, \( \bar{\Psi} \) is the basic-state stream function, \( K = \sqrt{k^2 + l^2} \) is the total wavenumber, and \( k \) and \( l \) are the zonal and meridional wavenumbers, respectively. The local group velocity \( C_g = (u_g, v_g) \) obtained from Eq. (8) takes the form (Li et al., 2015; Zhao et al., 2015)

\[ u_g = \bar{u}_M + \frac{[(k^2 - l^2) \partial q / \partial y - 2kl \partial q / \partial x]}{K^4}, \]  

(9a)

\[ v_g = \bar{v}_M + \frac{[2kl \partial q / \partial y + (k^2 - l^2) \partial q / \partial x]}{K^4}. \]  

(9b)

The wave ray trajectory is tangential to the group velocity (Lighthill, 1978). The wavenumbers \( k \) and \( l \), which are determined by kinematic wave theory (Whitham, 1960; Shaman et al., 2012), vary with the position of the ray,

\[ \frac{d_g k}{dt} = -k \frac{\partial \bar{\Psi}_M}{\partial x} - l \frac{\partial \bar{\phi}_M}{\partial y} \frac{k \partial^2 q / \partial y \partial x - k \partial^2 q / \partial x^2}{K^2}, \]  

(10a)

\[ \frac{d_g l}{dt} = -k \frac{\partial \bar{\phi}_M}{\partial y} - l \frac{\partial \bar{\Psi}_M}{\partial y} \frac{k \partial^2 q / \partial y \partial x - k \partial^2 q / \partial x \partial y}{K^2}, \]  

(10b)

where \( d_g / dt = \partial / \partial t + C_g \cdot \nabla \). For stationary waves ( \( \omega = 0 \) ), the initial local meridional wavenumber \( l \) is determined from the dispersion relation Eq. (8) for each initial zonal wavenumber \( k \) and a given starting point. Then, the ray trajectory can be numerically integrated from Eqs (9) and (10). The integration was aborted when the local meridional wavelength was calculated as <1000 km.
From Eqs. (9) and (10), it can be seen that the barotropic stationary Rossby wave energy is dominated by the basic zonal flow, basic meridional flow, and absolute vorticity gradient. Notably, the meridional basic flow plays an important role in the dispersion of wave energy particularly over tropical monsoon region where meridional wind can’t be ignored compared with zonal wind. Furthermore, considering the wave ray trajectory is sensitive to the background flow and the atmospheric circulation is subject to multiple factors, it is necessary to extract the influence of heating anomalies on the background flow by partial regression. In this paper, we considered the effects of ENSO and IOD. The basic flow is divided into climatological and abnormal parts, and abnormal wind is partial regressed onto the ISMRI to exclude the effects of ENSO and IOD.

3. Rainfall simulations in GA6 and GA7

Many studies have reported that the tropical monsoons have consequences for rainfall outside the tropics (Nitta, 1987; Hoskins and Rodwell, 1995; Rodwell and Hoskins, 1996; Kripalani et al., 1997; Wang et al., 2001; Ding and Wang, 2005, 2007; Lin, 2009; Lee et al., 2013; Liu and Wang, 2013; Zhao et al., 2019). Since the relationship between ISMR and regional rainfall may be modulated by the influence of tropical SSTs, the impacts of some known tropical SST signals on rainfall anomalies are usually excluded first to better isolate the influence of ISMR on rainfall teleconnections. In the study of Jin et al. (2019), they eliminated the effect of ENSO when they investigated the correlation between the simulated ISMR and rainfall over
the Australian–Asian monsoon region in GA6 and GA7. Although they discussed the likely influence of the IOD on rainfall anomalies in the Australian–Asian region (Ashok et al., 2001; Zhao et al., 2014; Zhao and Zhang, 2016) in GA6 and GA7, their analysis did not remove the effects of the IOD. In this study, we take both the IOD and ENSO into account.

Figure 1 displays the correlations and partial correlations between the ISMRI and the June-July-August (JJA) rainfall over the Australian–Asian monsoon region from GPCP, GA6, and GA7, excluding the impacts of the IOD and ENSO. The partial correlations bear close resemblance to the full correlations. Notably, the rainfall anomalies in the SH particularly over southwest Australia are more evident in GPCP after removing the impacts of ENSO and IOD indicating that the influence of ENSO, IOD and ISMR on the SH rainfall teleconnections are relatively depended. Furthermore, the rainfall teleconnections are in good agreement with the results of Jin et al. (2019; cf. their Fig. 7). In the NH, a wave train-like rainfall teleconnection pattern (Wu, 2002, 2017; Kim et al., 2002), which shows positive correlations over Arabian Peninsula, Northern China and Mongolia, and negative correlations over Central Asia and the Korean Peninsula, is much better captured by GA7 (Figs. 1a, b, c), as reported in Jin et al. (2019, cf. their Fig. 7). In addition, in the NH, the anomalous rainfall pattern correlations between GA7 and observations for the full correlation and partial correlation are 0.496 and 0.431, respectively, but is better than GA6, where the correlation with observations are 0.329 and 0.255, respectively.
In the SH, negative correlations over the subtropical Indian Ocean and positive correlations over tropical western Indian Ocean and southwest Australia and the nearby Indian Ocean (Figs. 1a, d), are evident in observations, as also shown by Jin et al. (2019, cf. their Fig. 7). The anomalous rainfall pattern correlation in the SH between GA7 and observations for the full correlation and partial correlation are 0.251 and 0.068, respectively, but is better and worse simulated in GA6, where the correlations with observations are 0.155 and 0.26, respectively. The decrease in the partial correlation between GA7 and observations is mainly owning to the different influences of ENSO and IOD on the rainfall teleconnection magnitude in GA7 and observation. However, according to the full correlation, the wave-train-like correlation pattern is still better captured by GA7 (Figs.1b, c, d, e). Particularly, GA6 overestimated the positive correlation over Australia and the overestimation is reduced in GA7 (Figs.1b, c, d, e). Overall, the rainfall correlation between GA7 and observations over the Australian–Asian domain (50°S–60°N, 30°–180°E) is still low at 0.31, but is better than GA6, where the correlation with observations is 0.251. In addition, the rainfall teleconnections in the NH are better simulated than that in the SH for both GA6 and GA7. Moreover, we still have to point out that the rainfall correlations with the ISMRI over ISM and northwest of ISM regions are poor simulated in both GA6 and GA7 which need further investigation.

We further evaluate the ISMR intensity to help understand the fidelity of rainfall teleconnections simulated in GA6 and GA7. Figure 2 shows the spatial distribution of precipitation during years of strong and weak ISMR in observations, GA7, and GA6.
Rainfall deficits over the Indian subcontinent during years of strong ISMR are reduced markedly in GA7 simulations. This is accompanied by a much smaller rainfall overestimation in the tropical Indian Ocean in GA7 compared with GA6. Such results are consistent with the findings from Bush et al. (2015) and Willetts et al. (2017), which suggested that excessive rain over the equatorial Indian Ocean warm waters might have contributed to the lack of Indian monsoon rainfall. Our analysis further shows that this may be particularly true in strong monsoon years (Fig. 2h). Similarly, the opposite situation occurred over East Asia and the nearby Philippines Sea. The rainfall over the nearby Philippian Sea and East Asia are worse overestimated and underestimated in GA7 than that in GA6 particularly during the years of strong ISMR (Fig. 2h). Thus, poor rainfall simulation in GA7 over East Asian monsoon region is also a concern for model improvement.

Overall, the rainfall pattern correlations between GA7 (GA6) and observation during years of strong and weak ISMR are 0.875 (0.811) and 0.800 (0.748) over the lower latitude of Australian–Asian domain (30°S–40°N, 30°–180°E). Thus, the rainfall simulation is improved in GA7 compared with GA6. Furthermore, the differences between GA7 and GA6 over the Indian monsoon domain in years of strong ISMR are much more significant than in years of weak ISMR (Figs. 2g, h). These improved rainfall simulations in GA7 during strong ISMR years may help to better understand the link between the improved ISMR and the more realistically simulated rainfall teleconnections in GA7.
4. Circulation anomalies

Circulation anomalies associated with the ISMR are analyzed using regression and partial regression of stream function and wind anomalies at 500 hPa onto the ISMRI (Figure 3). As shown in Fig. 3, two distinct barotropical wave trains originated from the ISM region propagating northward and southward into the NH and SH subtropics are observed in observations. In the NH, the full regressed circulation pattern resembles the circumglobal teleconnection (Ding and Wang 2005). The magnitude of the circumglobal teleconnection decreases sharply and only three centers are observed over Eurasia after removing the signals of ENSO and IOD (Fig. 3d). In the SH, the atmospheric responses also become weaker after removing the signals (Fig. 3d) suggesting the dependent influences of ENSO, IOD and ISMR on the circulation.

Originated from the ISM region, the wave train first propagates westward to the Arabian Peninsula creating a region of abnormally cyclonic circulation, then northeastward to Central Asia, creating a region of abnormally anti-cyclonic circulation, and then eastward to Mongolia and northern China, creating a region of abnormally cyclonic circulation, and finally eastward to the northeast China and Korean Peninsula, creating a region of abnormally anti-cyclonic circulation (Fig. 3d). In the SH, the wave train first propagates southwestward to tropical western Indian Ocean creating a region of abnormally anti-cyclonic circulation, then southward across Indian Ocean creating a region of abnormally cyclonic circulation over the subtropical Indian Ocean and anti-cyclonic circulation over mid-latitude Indian Ocean and southwestern Australia (Fig. 3d). This is consistent with the investigation by Zhao et al. (2019), who noted that an...
equivalent barotropic wave train originating from the Maritime Continent propagates
southward to subtropical Australia. The two tropical cyclonic circulations over Arabian
Peninsula and tropical western Indian Ocean excited by ISMR resemble the opposite
signs of Gill-type responses to tropical diabatic heating (Gill 1980) as discussed in Jin
et al. (2019, cf. their Fig. 10). The atmospheric response patterns over Australia-Asia
monsoon region are observed in GA7, whereas the anomalous anti-cyclonic
circulations over Central Asia and subtropical Indian Ocean are not captured by GA6.
Furthermore, the abnormally cyclonic circulation over midlatitude Indian Ocean is
underestimated in GA6.

Figure 4 shows a map of partial regression of vertical velocity and geopotential
height anomalies at 500 hPa onto the ISMRI removing the signals of ENSO and IOD.
In the regions downstream of the troughs (cyclones) ascending anomalies are observed,
while in the regions downstream of the ridges (anti-cyclones) subsidence anomalies are
observed (Fig. 4). This vertical motions correspond to the westward tilt structure of the
extratropical atmosphere. The anomalous vertical velocity pattern associated with the
ISM bears a strong resemblance to the rainfall pattern shown in Fig. 1. In particular,
the anomalous subsidence motions over Central Asia and Japanese islands which are
not conducive to the formation of precipitation are better simulated in GA7 than that in
GA6 (Figs. 4b, c). The subsidence anomaly over equatorial Indian Ocean and ascending
anomaly over central Australia are overestimated in GA6 but significantly improved in
GA7 (Figs. 4b, c). In addition, the vertical motion is opposite in the south and north
ISM region, which is not well simulated in both GA6 and GA7 (Figs. 4b, c).
Moisture transport at 850 hPa is also examined to gain further insight into the moisture source associated with the ISMR. Figure 5 shows the partial correlation between moist flux transports at 850 hPa and ISMR in observation and GA7, GA6 excluding the effects of ENSO and IOD. The anomalous moisture transports are close to the circulation anomalies in Figure 3 indicating the important role of advection in the moisture transports associated with the ISMR. As shown in Figure 5, the northward anomalous moisture flux transports over East Asia and anti-cyclonic moisture flux transports over subtropical Indian Ocean are better simulated in GA7 contributing to the precipitation increase over northern China and southwest Australia respectively. Particularly, the moisture transports are underestimated over subtropical Indian Ocean and overestimated over central Australia in GA6 which is corresponded to the rainfall anomalies (Fig. 5c). Overall, the influences of ISMR-teleconnection on the vertical motions and moisture transports lead to the formation of rainfall teleconnection. Therefore, the better simulated ISMR-teleconnection helps to improve the presentation of extratropical rainfall in the models.

5. Rossby wave ray tracing and the role of the meridional basic flow

Rossby wave ray tracing in a horizontally non-uniform flow, which describes the pathways of Rossby wave dispersion, is adopted to investigate the link between the improved ISMR and the associated rainfall teleconnections. Technical details about the wave ray tracing analysis can be found in Zhao et al. (2015, 2019). Before describing the wave ray, the background flow is analyzed. Figure 6 shows the composite difference
in full regressed and partial regressed wind anomalies at 250 hPa between strong and weak ISMR years. The partial regressed anomalous winds are similar to that full regressed, but with slight changes in the magnitude of wind anomalies in GA7 and observation suggesting the independent influences of ENSO, IOD and ISMR on the upper tropospheric wind in observation and GA7. As shown in Fig6., the anti-cyclonic circulations over Central Asia and East Asia and a cyclonic circulation over subtropical Indian Ocean (Fig. 6) are in good agreement with the results of Wang et al. (2001, cf. their Fig. 8). Particularly, this anomalous circulation pattern is close to the circulation pattern at 500 hPa associated with the ISMR (Figs. 3e, f) indicating that the response of the extratropical atmosphere to the ISMR is quasi-barotropical. The background flow used to calculate the stationary wave ray trajectories is the superposition of the composite of partial regressed anomalous wind and the climatology wind.

5.1 Rossby wave ray tracing

Figure 7 illustrates the stationary wave ray trajectories of zonal wavenumbers 2–5 emanating from ISMR sources in observations, GA7, and GA6. The wave rays first propagate westward to tropical Africa, then divide to propagate to the NH and SH subtropics (Fig. 7). Evidently, the southern branch of the wave rays in years of strong ISMR is more evident than that in years of weak ISMR, indicating the likely diabatic heating influence of ISMR on the cross equatorial Rossby wave propagation. Furthermore, the wave rays in the SH subtropics are much more than those in the NH in observations (Figs. 7a, b, c), leading to stronger wave trains in the SH (Figs. 3a, b).
This is better captured by GA7 during years of strong ISMR (Fig. 7e) than GA6 (Fig. 7h). On the other hand, both GA6 and GA7 simulate weaker wave propagation in the SH than that observed in years of weak ISMR (Figs. 7f, i), although in GA7, the propagation towards tropical Africa is somewhat closer to observations (Fig. 7f).

The situation is similar for the northern branch of wave rays. The northern wave-ray characteristics simulated in GA7 in years of strong ISMR are much closer to observations than in GA6, with wave rays occurring in the subtropical westerlies over Asia (Figs. 7b, e). However, during years of weak ISMR, the northern branch of the wave rays in both GA7 and GA6 are poorly simulated (Figs. 7f, i), with wave rays being much stronger and further poleward than in observations. Both GA6 and GA7 perform poorly in reproducing the observed characteristics of wave rays in weak ISMR years, during which both model configurations showed a significant dry bias over the Indian monsoon domain in JJA (Fig. 2). Nevertheless, it is not clear whether we can directly associate the poor simulation of wave rays with the underestimation of ISMR. This is because during weak ISMR years, one would expect weak diabatic heating over the Indian monsoon region. However, without considering the diabatic influence of deep monsoon convection on the mean flow, the increase of isolated equatorially asymmetric heating only strengthens the atmospheric response, but not vary the atmospheric patterns (Xing et al., 2014). We need to investigate further to what extent the model's failure to reproduce wave propagation in weak monsoon years is because of the poor simulation of the atmospheric mean flow in the region, or because of the significant lack of rainfall during those years.
5.2 Meridional wind ducts in the upper troposphere

According to the studies by Zhao et al. (2015, 2019) and Li et al. (2015), the meridional basic flow plays an important role in facilitating the propagation of stationary Rossby wave. Furthermore, the interhemispheric propagation of Rossby waves is dominated largely by the meridional flow (Lee et al., 2013; Liu and Wang, 2013; Li et al., 2015; Zhao et al., 2015, 2019). Figure 7 shows the 250 hPa horizontal winds from ERA-interim, GA7, and GA6 in JJA. As shown in Fig. 7a, strong easterly winds prevail at upper levels over the tropical Australian–Asian and African monsoon regions. In tropical North Africa, southerly winds prevail between 10°N and 30°N, whilst northerly winds prevail below 10°N, causing the Rossby wave to first propagate westward and then divide northward and southward over tropical North Africa and beyond. Similarly, the northerly winds over the Indian subcontinent and tropical Indian Ocean also lead the Rossby wave to propagate southward into the SH. The southerly winds prevailing over the western Tibetan Plateau drive the Rossby wave northward into the Asian subtropical westerlies.

The poor simulated meridional propagation of Rossby wave is closely related to the modelling errors of the meridional wind. The significantly weak simulated northerly winds over the upper tropospheric South Asian monsoon domain in GA6 (Figs. 8e, f) are not favorable to the cross-equatorial propagation of Rossby wave. Furthermore, the strength of the simulated meridional winds in Asia in GA6 are stronger than that shown in observations (Figs. 8e, f), especially for the southerly winds over the western Tibetan Plateau. This contributes to the stronger and further poleward propagation of Rossby waves.
wave in GA6 (Figs. 7g, h, i). In contrast, the upper tropospheric meridional winds over the western Tibetan Plateau and south Asian monsoon are more realistically simulated in GA7 (Fig. 8d), especially in years of strong ISMR (Fig. 8h). Therefore, analyzing to what extent the simulation of ISMR influence the meridional wind will help to understand the contribution of improvement of ISMR to the Rossby wave propagation. Furthermore, as discussed by Jin et al. (2019) the SAH is closely linked to the diabatic heating effect of the tropical Indian monsoon, the influence of SAH on the meridional wind will also be considered.

The strength of SAH is defined as the averaged geopotential height of grid within the isoline of 12500 gpm at 200 hPa (Figures 9g, h, i). The multiple regression is used to measure the linear contributions of ISMR and SAH to the meridional wind. Considering the relationship between SAH and ISMR, we removed the linear effect of SAH on ISMR through partial regression. Fig. 9 shows the climatology of SAH and the multiple regression of meridional wind on the ISMRI and SAHI. As shown in Fig. 9, the meridional winds over South Asian monsoon region in GA6 and GA7 is closely related to ISMR. With the increase of ISMR, stronger convective activity enhances the Indian monsoon circulation, the upper northerly wind over South Asian monsoon region enhances (Fig. 8h), making stronger cross equatorial Rossby wave (Fig. 7e). Furthermore, the relationship between anomalous northerly wind over western Tibetan Plateau and ISMR is better simulated in GA7 than that in GA6 (Figs. 9b, c). Moreover, the contribution of SAH to the upper meridional wind over South Asian monsoon region in GA7 are better simulated than that in GA6 (Figs. 9e, f). Therefore, both the
enhancement of ISMR and SAH during years of strong ISMR in GA7 contribute to the
more realistic meridional wind over south Asian monsoon and western Tibetan Plateau,
and hence make more realistic propagation of Rossby wave.

What’s more, the simulation of SAH in GA7 is improved significantly compared
with that in GA6. Due to the dynamic relationship between wind and pressure, the
simulation of wind improves with the improvement of pressure. Particularly, at
midlatitudes, the pressure dominates the wind according to the geostrophic relationship.
As a result, the improvement of SAH in GA7 leads to more realistic climatic mean flow
over South Asia than that in GA6 (Figs. 9g, h, i). In particular, the much stronger
southerly wind over western Tibetan Plateau and south Asian monsoon region in GA6
is mainly owning to the poor simulation of SAH (Fig. 9i). Furthermore, the
improvement of ISMR intensity with more realistic convective heating in GA7
contributes to more realistic meridional wind over South Asian monsoon region.

Nevertheless, it still has to point out that the inter-annual variability of ISMR in
GA7 needs to be improved, and the relationship between SAH and ISMR is
overestimated in GA6 and GA7 with the correlation coefficients of 0.48 and 0.33,
respectively, while 0.13 in the observation. The significant improvement of SAH in
GA7 corresponds to the skillfully simulated ISMR, which may own to the deeper
convection and more realistic diabetic heating are allowed in GA7 (Walters et al. 2019).

6. Summary and discussion

In this study, we have investigated the link between the improved simulation of
ISMR and the associated extratropical rainfall teleconnections in two versions of the
UKMO Unified Model, GA6 and GA7, using Rossby wave ray tracing theory (Li and Li et al., 2012; Li et al., 2015; Zhao et al., 2015, 2019). In a previous UM assessment study, Jin et al. (2019) reported that the reduced Indian monsoon dry bias in UM GA7 at N216 resolution led to more realistic monsoon rainfall teleconnection patterns. However, they did not conduct detailed wave propagation analysis to support these results. Therefore, our study focused on investigating Rossby wave propagation in these two model configurations by using Rossby wave ray tracing in a horizontally nonuniform background flow, as in Zhao et al. (2015, 2019).

Our observational analysis showed that the diabatic heating associated with ISMR can excite two distinct wave trains in the NH and SH subtropics. GA7 can better simulate the teleconnections associated with the ISMR over Australia-Asia monsoon region compared with GA6. The realistic simulated atmospheric teleconnection in GA7 plays an important role in the improvement of rainfall teleconnection by modulating the vertical motion and the moisture transport.

The teleconnection wave train coincides with the pathway of the stationary Rossby wave propagation. Driven by the upper tropospheric easterly flow, the stationary Rossby wave first propagate westward, then separate into northern and southern branches following the meridional wind ducts. The northern branch mainly propagates in the subtropical westerlies over Asia and the southern branch primarily propagates in the SH subtropical westerlies. Compared with GA6, GA7 can better capture the characteristics of Rossby wave propagation pathways in years of strong ISMR, with stronger cross-equatorial propagation and a more realistic northern branch.
of the wave ray tracing trajectories. This was attributed largely to the model skillfully simulating of ISMR and SAH, and their influences on the meridional basic flow over upper South Asia monsoon and western Tibetan Plateau.

Our study may also provide new insights for monsoon teleconnection evaluations by revealing the Rossby wave propagation pathway from the upper tropospheric easterlies. The upper tropospheric meridional winds associated with the monsoon system play an important role in Rossby wave propagation and hence improve the simulation of tropical monsoon teleconnections. Sakaguchi et al. (2016) detected changes in Rossby wave ray trajectories influenced by Asian monsoon rainfall and the associated basic flow using different grid refinements in the Community Atmosphere Model version 4. The teleconnection pathways revealed by Rossby wave ray trajectories provide implications for evaluating and improving the model’s performance of simulating tropical monsoon teleconnections.

The analysis in this paper was focused mainly on the Australian–Asian monsoon region, but further research could be done to evaluate the influence of the tropical Asian monsoon on the weather and climate over other regions. It is also worth noting that significant deficiencies in the modelling of ISMR remain, despite the reduced dry bias in GA7. In particular, the northerly wind ducts over the upper tropospheric South Asian monsoon region in GA7 are poorly simulated. Walter et al. (2019) indicated that the southern branch of the Hadley circulation during JJA in GA7 using an N216 grid was improved significantly compared with GA6 at the same resolution, due to the deeper convection in GA7. Thus, the simulation of convection is important to improve the
We acknowledge that the datasets used in the current analysis come from the atmosphere-only configuration of the UM. It is important to conduct a similar analysis with globally coupled simulations (Williams et al., 2017) to better understand the rainfall teleconnections that could be modulated by air–sea interactions. This will also help us to assess whether current model deficiencies in simulating the Australian–Asian monsoon system can affect the climate and climate change outside the monsoon domain simulated by current CMIP models.

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Figure captions

Figure 1. Correlation map of JJA rainfall with ISMRI for the period 1982–2008 (a) GPCP; (b) GA7; (c) GA6. (d)–(f) Same as (a)–(c), respectively, but for partial correlation excluding the signals of both ENSO and IOD. Dotted areas denote significance at the 95% confidence level. The ‘R’ at the top right of (b)–(c) indicates the pattern correlation (30°–180°E, 50°S–60°N) with (a), and the ‘R’ at the top right of (e)–(f) indicates the pattern correlation with (b) respectively. The black box denotes the Indian summer monsoon domain (70°–90°E, 5°–25°N). The solid black lines represent the pathways of the rainfall teleconnection.

Figure 2. Composites of strong/weak summer monsoon rainfall (JJA) for the period 1982–2008 (unit: mm day\(^{-1}\)). (a), (b) GPCP observations; (c), (d) GA6; (e), (f) GA7; and (g), (h) difference between GA7 and GA6. The black box represents the Indian summer monsoon domain. Cross hatched areas denote significance at the 90% confidence level. Strong (weak) monsoon years are determined based on when the ISMRI (normalized area-averaged summer rainfall anomalies over 70°–90°E, 5°–25°N) is above (below) 0.75 (−0.75).

Figure 3. Map of regression of stream function (shading; units: m\(^2\) s\(^{-1}\)) and anomalous wind (vectors; units: m s\(^{-1}\)) at 500 hPa onto ISMRI (a) ERA-Interim; (c) GA7; (e) GA6. (b), (d), (f) Same as (a), (c), (e), respectively, but for partial regression excluding the signals of both ENSO and IOD. Dotted areas denote significance at the 95% confidence level; only vectors significant at the 95% confidence level are shown.

Figure 4. Map of the partial regression of vertical velocity (shading; units: m s\(^{-1}\)) and geopotential height anomalies (contour; units: m) at 500 hPa onto ISMRI excluding the linear effects of ENSO and IOD (a) ERA-Interim; (b) GA7; (c) GA6. Cross hatched areas denote significance at the 90% confidence level.

Figure 5. Partial correlation map of JJA rainfall (shading; units: mm) and moisture flux at 850 hPa (vectors; units: mm) with ISMRI excluding the signals of ENSO and IOD (a) GPCP; (b) GA7; (c) GA6. Only shading and vectors significant at the 90% confidence level are shown.
Figure 6. Map of regression of anomalous horizontal wind (vectors; units: m s\(^{-1}\)) at 250 hPa onto ISMRI (a) ERA-Interim; (c) GA7; (e) GA6. (b), (d), (f) Same as (a), (c), (e), respectively, but for partial regression excluding the linear influence of ENSO and IOD. Shaded areas denote significance at the 90% confidence level.

Figure 7. Stationary Rossby wave ray trajectories (curves) initiated with zonal wavenumbers 2–5 from ISMR sources (black dots), driven by the 250 hPa horizontal wind, and excluding the influence of ENSO and the IOD. (a)–(c) ERA-Interim wind data; (d)–(f) GA6; and (g)–(i) GA7. Red and green curves represent the stationary Rossby waves propagating in the Southern and Northern Hemisphere, respectively.

Figure 8. 250 hPa climatological zonal winds (contours; unit: m s\(^{-1}\)) and meridional winds (shading; unit: m s\(^{-1}\)) excluding the influence of ENSO and the IOD. (a) ERA-Interim; (b) GA7; (c) GA6; (d) difference between GA7 and GA6. Difference between GA6 and observations of composite meridional winds from years of (e) weak and (f) strong ISMR. Difference between GA7 and GA6 of composite meridional winds from years of (g) weak and (h) strong ISMR. Dotted areas represent significance at the 90% confidence level.

Figure 9. Multiple regression of 200 hPa meridional wind to (a)–(c) ISMRI and (d)–(f) SAHI. (g)–(f) Meridional geostrophic wind (shading; units: m s\(^{-1}\)) and geopotential height (contour; units: m). The solid lines in (g)–(i) represent the location of the climatological SAH, and the yellow and purple thick solid lines in (d)–(f) indicate the composites location of SAH in the years of strong and weak ISMR. Top column is for ERA-Interim, middle column is for GA7, and bottom column is for GA6.
Fig. 1. Correlation map of JJA rainfall with ISMRI for the period 1982–2008 (a) GPCP; (b) GA7; (c) GA6. (d)–(f) Same as (a)–(c), respectively, but for partial correlation excluding the signals of both ENSO and IOD. Dotted areas denote significance at the 95% confidence level. The ‘R’ at the top right of (b)–(c) indicates the pattern correlation (30°–180°E, 50°S–60°N) with (a), and the ‘R’ at the top right of (e)–(f) indicates the pattern correlation with (b) respectively. The black box denotes the Indian summer monsoon domain (70°–90°E, 5°–25°N). The solid black lines represent the pathways of the rainfall teleconnection.
Fig. 2. Composites of strong/weak summer monsoon rainfall (JJA) for the period 1982–2008 (unit: mm day$^{-1}$). (a), (b) GPCP observations; (c), (d) GA6; (e), (f) GA7; and (g), (h) difference between GA7 and GA6. The black box represents the Indian summer monsoon domain. Cross hatched areas denote significance at the 90% confidence level. Strong (weak) monsoon years are determined based on when the ISMRI (normalized area-averaged summer rainfall anomalies over 70°–90°E, 5°–25°N) is above (below) 0.75 (−0.75).
Fig. 3. Map of regression of stream function (shading; units: m² s⁻¹) and anomalous wind (vectors; units: m s⁻¹) at 500 hPa onto ISMRI (a) ERA-Interim; (c) GA7; (e) GA6. (b), (d), (f) Same as (a), (c), (e), respectively, but for partial regression excluding the signals of both ENSO and IOD. Dotted areas denote significance at the 95% confidence level; only vectors significant at the 95% confidence level are shown.
Fig. 4. Map of the partial regression of vertical velocity (shading; units: m s\(^{-1}\)) and geopotential height anomalies (contour; units: m) at 500 hPa onto ISMRI excluding the linear effects of ENSO and IOD (a) ERA-Interim; (b) GA7; (c) GA6. Thick solid lines indicate the zero lines. Cross hatched areas denote significance at the 90% confidence level.
Fig. 5. Partial correlation map of JJA rainfall (shading; units: mm) and moisture flux at 850 hPa (vectors; units: mm) with ISMRI excluding the signals of ENSO and IOD (a) GPCP; (b) GA7; (c) GA6. Only shading and vectors significant at the 90% confidence level are shown.
Fig. 6. Map of regression of anomalous horizontal wind (vectors; units: m s$^{-1}$) at 250 hPa onto ISMRI (a) ERA-Interim; (c) GA7; (e) GA6. (b), (d), (f) Same as (a), (c), (e), respectively, but for partial regression excluding the linear influence of ENSO and IOD. Shaded areas denote significance at the 90% confidence level.
Fig. 7. Stationary Rossby wave ray trajectories (curves) initiated with zonal wavenumbers 2–5 from ISMR sources (black dots), driven by the 250 hPa horizontal wind, and excluding the influence of ENSO and the IOD. (a)–(c) ERA-Interim wind data; (d)–(f) GA6; and (g)–(i) GA7. Red and green curves represent the stationary Rossby waves propagating in the Southern and Northern Hemisphere, respectively.
Fig. 8. 250 hPa climatological zonal winds (contours; unit: m s$^{-1}$) and meridional winds (shading; unit: m s$^{-1}$) excluding the influence of ENSO and the IOD. (a) ERA-Interim; (b) GA7; (c) GA6; (d) difference between GA7 and GA6. Difference between GA6 and observations of composite meridional winds from years of (e) weak and (f) strong ISMR. Difference between GA7 and GA6 of composite meridional winds from years of (g) weak and (h) strong ISMR. Dotted areas represent significance at the 90% confidence level.
Fig. 9. Multiple regression of 200 hPa meridional wind to (a)–(c) ISMRI and (d)–(f) SAHI. (g)–(f) Meridional geostrophic wind (shading; units: m s$^{-1}$) and geopotential height (contour; units: m). The solid lines in (g)–(i) represent the location of the climatological SAH, and the yellow and purple thick solid lines in (d)–(f) indicate the composites location of SAH in the years of strong and weak ISMR. Top column is for ERA-Interim, middle column is for GA7, and bottom column is for GA6.