Does a monsoon circulation exist in the upper troposphere over the central and eastern tropical Pacific?

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ABSTRACT
Considering the central and eastern tropical Pacific (CETP) has important climate impacts, and its seasonal variability is also thought to be important, the authors used the monsoon investigation method named ‘dynamical normalized seasonality’, which can precisely describe the wind vector direction over time, to analyze the upper-tropospheric circulation over the region. The authors discovered that there is a clear reversal of seasonal changes between winter and summer wind, just like the classic monsoon. Accordingly, the authors propose the new concept of the upper-troposphere monsoon over the CETP. The results extend the classical lower-troposphere monsoon region into the upper troposphere.

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1. Introduction

With its significant seasonal variability (Zeng and Zhang 1998; Venkat and James 2003; Li and Zeng 2005) and considerable global climate impact (Li and Zeng 2003; An et al. 2015), the monsoon is one of the main systems of atmospheric circulation. Different definitions of monsoon regions and monsoon indexes have been proposed (Wang, Wu, and Lau 2001; Li and Zeng 2002; Wang et al. 2008; Yoshida and Yamazaki 2010), such as the East Asian summer monsoon, Australian monsoon, and Asian summer monsoon (Li and Zeng 2000; Wang, Wu, and Lau 2001; Zeng and Li 2002; Feng, Li, and Li 2010).

Using the ‘dynamical normalized seasonality’ (DNS) method, Li and Zeng (2000, 2003, 2005) proposed a generalized monsoon system, and then devised the creative concept of the global monsoon (Li and Zeng 2003), which regards the geographically scattered surface monsoon regions as a whole monsoon system and unifies them as one theoretical model. As a result, they showed that the global monsoon could be geographically divided into the tropical monsoon, subtropical monsoon, and temperate–frigid monsoon (Li and Zeng 2003, 2005). Furthermore, they pointed out that in the upper troposphere over the central and eastern tropical Pacific (CETP), there is a significant DNS index maximum value distribution, indicating that it may be a monsoon region. Indeed, the tropical Pacific has always been considered to have a predominant influence on global climate (Cane and Clement 1999; Lea, Park, and Spero 2000; Pierrehumbert 2000; Zhan and Li 2008; Li 2009; Xiao, Li, and Zhao 2012; Zhao, Li, and Zhang 2012; Zhan, Wang, and Wen 2013; Li et al. 2015; Sun, Li, and Ding 2015). Therefore, in this study, we investigated the signals of monsoonal circulation in the CETP, with the expectation to provide a useful supplement to existing monsoon research. In doing so, given that the upper troposphere over the CETP is regarded as a non-traditional monsoon region, we also benefited from the methods and theories of previous research on the South American monsoon (Zhou and Lau 1998) and Southwest Australian monsoon (Feng, Li, and Li 2010).
2. Methodology and data

2.1. Methodology

A monsoon region can be identified by the wind vector direction, measured by the angle in degrees, varying greatly between winter and summer. Taking the East Asian monsoon as an example, the prevailing wind is northwesterly and northeasterly in winter (Chen, Zhu, and Luo 1991; Ding 1994; Huang, Zhou, and Chen 2003; Jhun and Lee 2004), and then turns southeasterly in summer (Lau and Yang 1997; Wang, Wu, and Lau 2001; Ding and Chan 2005). If the angle between the winter and summer wind vector exceeds the critical value of 90° (Webster et al. 1998; Li and Zeng 2000), then the region can be regarded as a monsoon region.

The above concept underpins the DNS method proposed by Li and Zeng (2000, 2002), in which the DNS index is calculated as follows:

\[
\delta = \frac{\|V_1 - V_i\|}{\|\bar{V}\|} - 2,
\]

where \(V_1\) is the climatological wind field in winter (sometimes taken as the wind in January); \(V_i\) is the climatological wind field in summer (sometimes taken as the wind in July); and \(\bar{V}\) is the mean of winter (or January) and summer.

Figure 1. Vertical and horizontal DNS distribution greater than the critical value of 2 (green shading), based on (a) NCEP-2, (b) ERA-Interim, (c) 200-hPa NCEP-2, (d) 300-hPa NCEP-2, (e) 200-hPa ERA-Interim, and (f) 300-hPa ERA-Interim.

Note: The solid blue and red lines denote the westerly isotachs at 0 m s\(^{-1}\) in winter and easterly isotachs at 0 m s\(^{-1}\) in summer, respectively.
(or July) climatological wind vectors at the same point. The constant 2 on the right-hand side of the formula is the determinant criterion. It can be derived that the critical value of \( \frac{\| \vec{V}_1 - \vec{V}_i \|}{\| \vec{V} \|} \) is exactly equal to 2 when the angle between two different vectors is 90° (Li and Zeng 2000). Equation (1) describes that if the angle varies less than the critical 90°, the value of \( \delta \) is negative; otherwise, if it exceeds 90°, then the value of \( \delta \) is positive. The value of \( \delta \) increases as the angle becomes larger at the same location (Li and Zeng 2000).

The norm \( \| A \| \) is defined as follows:

\[
\| A \| = \left( \int_S |A|^2 dS \right)^{1/2},
\]

where \( S \) represents the selected study area, and it can be calculated at a point \((i,j)\) as follows:

\[
\| A_{i,j} \| \approx \Delta S \left[ \left( |A_{i-1,j}|^2 + 4|A_{i,j}|^2 + |A_{i+1,j}|^2 \right) \cos \varphi_j \right. \\
+ \left. |A_{i,j-1}| \cos \varphi_{j-1} + |A_{i,j+1}| \cos \varphi_{j+1} \right]^{1/2},
\]

where \( \varphi \) and \( \Delta S \) are the latitude at point \((i,j)\) and the area element respectively.

Additionally, with the definition of the norm \( \| A \| \), a rigorous mathematical proof can be concluded that the DNS index is actually independent of the \( \varphi_j \), because the formula of the DNS index separately contains the same operational factor in the numerator and denominator centered above and below the division line.

### 2.2. Data

Global monthly NCEP-2 and four-time daily NCEP-1 atmospheric wind field data were obtained from the NCEP–NCAR reanalysis data-set (Kalnay et al. 1996; Kanamitsu et al. 2002), with a horizontal resolution of 2.5° x 2.5° and 17 pressure levels from 1000 to 10 hPa. The pentad results in the study were derived from these daily data. The global monthly wind data were from ERA-Interim (Simmons et al. 2007; Dee et al. 2011), with a 1.5° x 1.5° horizontal resolution and 37 pressure levels from 1000 to 1 hPa.

![Figure 2. Horizontal circulation at 300 hPa: (a) climatology; (b) winter; (c) summer. Notes: Green shading indicates the DNS is greater than the critical value of 2. Wind speed units: m s\(^{-1}\).](image-url)
3. Results

It can be seen that, in the vertical direction (Figure 1(a) and (b)), there is a DNS index maximum area greater than the critical constant of 2 extending from the lower and middle troposphere up to the upper troposphere over the CETP; its core area is between 150 and 400 hPa. The solid blue and red lines delineate the boundaries of the maximum area, which respectively denote the westerly isotachs at 0 m s\(^{-1}\) in winter and easterly isotachs at 0 m s\(^{-1}\) in summer.

The DNS index maximum area right above the tropical Pacific (Figure 1(a) and (b)) stretches down and integrates as one at about 15°N, with the part stretching upward located over the subtropical monsoon. This indicates that this maximum area over the tropical Pacific has the same intrinsic properties as the low-level subtropical monsoons, such as the North American monsoon.

Besides, the DNS index maximum area tends to extend to the Northern Hemisphere above 500 hPa. It can be seen that the horizontal distribution (Figure 1(c)–(f)) of the DNS index maximum area (7.5°S–30°N, 85°–180°W) at specified pressure levels (200, 300 hPa) in the upper troposphere also leans into the Northern Hemisphere; and, at the same time, it presents a dual core in the east and west area, with the east core area being more significant.

According to the definition of a monsoon area (Section 2.1), the DNS index maximum area means that the magnitude of the variation in the prevailing wind direction reaches at least 90°, implying that the area over the CETP may be a monsoon region. Given this strong possibility from the results presented in Figure 1, we next analyze in more depth how the wind vector field varies in the CETP between winter and summer.

Considering the influence of the tropical Pacific, we select the specific domain of (7.5°S–22.5°N, 85°–175°W) as our study region. Hereafter, the CETP refers to this selected region. Figure 2 shows the features of the horizontal circulation at 300 hPa in different pentads. It shows the circulation in earlier stages of the evolution from winter to summer.

Figure 3. Horizontal circulation at 300 hPa in different pentads.
Notes: Green shading indicates the DNS is greater than the critical value of 2. It shows the circulation in earlier stages of the evolution from winter to summer. Wind speed units: m s\(^{-1}\).
the reversal characteristics of the horizontal circulation are basically homogeneous.

However, a number of regional characteristics are apparent (Figure 2(b) and (c)), such as the seasonal variation of the circulation is different between the east (95°–125°W) and west CETP (150°–170°W); the east CETP wind in summer varies much more compared to the west. At the same time, the circulation in summer varies lightly irregularly from about 10°–15°N to the north edge, in particular the marginal circulation variation is not quite so homogeneous because the wind in summer is relatively weak compared to the climatological wind.

To verify the above results, Figures 3 and 4 show the evolution of the horizontal circulation between winter and summer. Still taking 300 hPa as the example, we can see that the wind firstly begins to change from pentad 16 (late March; Figure 3(a)) in the east CETP (95°–125°W), and then the dominant westerly wind begins to decay and turn into weak easterly wind between pentad 20 (early April; Figure 3(b)) and pentad 24 (early May; Figure 3(c)). Furthermore, the wind evolutionary process mainly finishes by pentad 28 (early June; Figure 4(a)) in the east; whereas, at the same time (pentads 24–28), the dominant westerly wind in the west CETP (150°–170°W) begins to decay and turn easterly. Basically, it turns into a weak easterly in pentad 32 (mid-June; Figure 4(b)), and by pentad 36 (early July; Figure 4(c)) the evolutionary process has completely finished across the whole region.

Extending the rough depiction of the evolution shown in Figures 3 and 4, Figure 5 illustrates the process in more detail, over the whole region, and identifies the precise time that the evolutionary process completed. The results clearly show that the seasonal transition first begins in the east ECTP, and then spreads to the north and west. In some areas, the wind direction may change earlier or later (Figure 5), but it always reaches or exceeds 90°. So, generally speaking, the dominant westerly wind in winter turns easterly in summer, and this process clearly demonstrates that the circulation reverses in summer (or July) compared to winter (or January). The results confirm the existence of an upper-troposphere monsoon over the CETP.

Figure 4. Horizontal circulation at 300 hPa in different pentads. Notes: Green shading indicates the DNS is greater than the critical value of 2. It shows the circulation in later stages of the evolution from winter to summer. Wind speed units: m s⁻¹.
4. Discussion and conclusion

This study demonstrates the existence of an upper-troposphere monsoon circulation over the CETP in accordance with the definition of the DNS index, in which the dominant wind direction changes completely from winter to summer. Also shown is that the wind changes in different parts (between the east and west) of the monsoon region with time do not take place at exactly the same pace.

Previous studies state that the monsoons or monsoon regions always involve precipitation; for instance, the East Asian summer monsoon (Wu, Zhou, and Li 2009; Wu et al. 2009; Wang et al. 2008; Li et al. 2011), or other monsoon systems in the lower troposphere (Zhao et al. 2008; Shi, Li, and Wilson 2014). However, since the upper-troposphere monsoon over the CETP is a non-classical monsoon region, there is something unique causing the monsoon circulation to appear entirely in the upper troposphere. So, when it comes to the relationship between the summer monsoon and precipitation, it is less related to this case, meaning we mainly focus on analyzing the circulation character itself.

We studied the seasonal variation of the circulation changing over time, then verified it with the above results, and ultimately confirm the existence of the upper-troposphere monsoon over the CETP. The results expand the traditional monsoon distribution area from the lower troposphere to the upper troposphere.

Disclosure statement

No potential conflict of interest was reported by the authors.

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