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西南季风期间斯里兰卡降水的年代际、年际变化及其与热带印度洋的联系

摘要

本文主要研究了 1979—2016 期间斯里兰卡在西南季风期间降水的年代际、年际变化以及与印度洋海温的联系.首先用经验正交的方法分析了斯里兰卡以及周边地区降水的时空分布,发现前两个模态能够解释超过 70%的方差.其中第一模态为均一模态,且其 PC1 以及斯里兰卡 7 a 滑动平均降水序列都有年代际变化,降水异常在 2000 年前后异常偏多和偏少.通过合成分析发现 2000 年之后降水的异常减少与热带西部、中部印度洋的暖海温异常有关.暖海温异常通过调整经向环流引起了斯里兰卡上空的下沉运动,抑制了降水.在第二模态中,负的信号出现在斯里兰卡大部分地区,只有在斯里兰卡北部海角很小地区出现了正的信号.PC2 表现出了年际变化,且与热带东南印度洋海温异常有显著的关系.通过 Gill-Matsuno 响应,热带东南印度洋海温异常造成热带北印度洋上空的气旋性环流异常,引起了水汽的辐合,从而利于降水.

关键词

降水;斯里兰卡;西南季风;热带印度洋

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0　导读

本文的原文为英文,希望感兴趣的读者进一步关注原文.

斯里兰卡地处低纬,除山区以外的地区四季气温较高且变化幅度较小,但由于受到印度洋季风系统的影响,斯里兰卡在一年之中会经历雨季和旱季,分别为每年的 5—9 月和 11 月—次年 2 月,即西南季风和东北季风盛行时期.前人的研究结果表明:在 1974—2004 年间,斯里兰卡在西南季风时期的降水在逐步增加,并经历了一些严重的极端降水,造成了较大的经济损失,因此研究斯里兰卡在西南季风期间降水的时空变化具有重要意义.

通过经验正交函数分解方法研究了 1979—2016 年斯里兰卡及其周边地区在西南季风期间降水的时空分布变化,前两个模态能够解释超过 70%的方差.第一模态为均一模态,PC1 和斯里兰卡西南季风期间的降水时间序列都表现出了显著的年代际震荡,降水异常在 2000 年前后分别为异常偏多和异常偏少,说明自 21 世纪以来,斯里兰卡的西南季风期间的降水已回落至较低水平,体现了斯里兰卡在西南季风期间降水的一个年代际变化的特征.本文通过对 1979—1998 年和 2000—2014 年两个时段的海洋和大气环流状况进行合成分析,发现自 2000 年之后斯里兰卡在西南季风期间降水的异常减少与热带西部、中部印度洋的海表温度的异常增暖有关:热带西部、中部印度洋在 2000 年之后的异常增暖的海温通过调整经向环流引起了斯里兰卡及其周边区域上空大气的异常下沉运动,抑制了降水条件,导致了斯里兰卡及其周边地区在西南季风期间的降水在 2000—2014 年异常偏少.PC2 显示了斯里兰卡的西南季风期间降水的年际变化,谱分析的结果显示其有一个 5~6 a 的显著周期,通过回归分析本文发现斯里兰卡在西南季风期间降水的年际变化与热带东南印度洋的海表温度异常有显著联系:当热带东南印度洋的海表温度产生异常增暖时,通过 Gill-Matsuno 响应会在热带北印度洋上空的大气产生一个气旋性异常环流,使得水汽在斯里兰卡及其周边区域产生辐合,从而使得斯里兰卡的西南季风期间的降水异常偏多.

本文的研究结果对于斯里兰卡的气候研究以及西南季风期间降水的预报具有参考意义.

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The interdecadal and interannual variations of Sri Lankan precipitation during southwest monsoon and their connections with the tropical Indian Ocean SST

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Abstract The present study investigates the interdecadal and interannual variations of Sri Lankan precipitation during Southwest Monsoon (SWM) and their connections with the Indian Ocean Sea Surface Temperature (SST) over 38 years (1979-2016).Empirical orthogonal function (EOF) analysis is applied to examine the spatial-temporal variations of precipitation in Sri Lanka and surrounding region.The first two leading EOF modes explain exceeding 70% of the total variance.EOF1 shows a monotonous mode.Both PC1 and 7-yr running mean of precipitation in Sri Lanka show clear interdecadal variations with more and less precipitation before and after 2000.The interdecadal variation of precipitation is associated with the warmer SST in the western and central tropical Indian Ocean during 2000-2014,which induces the anomalous downward motion over Sri Lanka through enhancing the meridional circulation,and thus depresses the precipitation over there.For EOF2 mode,negative signals are in most regions of Sri Lanka except in cape of northern Sri Lanka with positive signals.PC2 shows an interannual variation,and is significantly positively related to the SST anomalies in the southeast Indian Ocean.These warm SST anomalies could induce anomalous cyclonic circulation in the north tropical Indian Ocean due to Gill response,which is favourable for convergences of moisture flux and more precipitation in Sri Lanka.This study suggests that the interdecadal variation of precipitation in Sri Lanka is greatly associated with western and central tropical Indian Ocean SST,while the interannual variation is significantly influenced by the anomalous SST in the southeast tropical Indian Ocean.

Key words precipitation;Sri Lanka;southwest monsoon;tropical Indian Ocean

1 Introduction

Sri Lanka is an island located at the southern tip of the Indian subcontinent, which is separated by a pork strait between them.It extends from 5°55′ to 9°51′N in latitude and from 79°42′ to 81°53′E in longitude.Due to its unique location, Sri Lanka is subjected to the great influences of the Indian Ocean monsoon system[1]. Usually, there are two principal monsoon seasons as Southwest Monsoon (SWM; May through to September) and the Northeast Monsoon (NEM,December through to February).In addition,here we consider two inter monsoon periods as First Inter Monsoon (FIM; March through to April) and Second Inter Monsoon (SIM; October through to November).These inter monsoons occur due to the northward and southward migrations of the intertropical convergence zone (ITCZ) over Sri Lanka[2].The nature of the seasonal cycle of monsoon precipitation over Sri Lanka is associated with regional and local topographic influences in the country,such as the Central Highlands.It controls the prevailing moisture-laden monsoon wind and acts as an important physiographical climatic barrier. Two major climatic zones can be distinguished to the west and east of the Central Highlands as the Wet Zone and Dry Zone.The Wet Zone essentially comprises the southwest parts,which are directly exposed to the SWM winds, whereas the rest of Sri Lanka constitutes the Dry Zone, where it gets less SWM precipitation[3]. Mean annual precipitation varies from less than 1 000 mm on the southeast coast to over 4 500 mm on the western slopes of the highlands in the country[1].According to previous studies,the SWM and SIM are the highest contribution for annual precipitation in Sri Lanka[3].

As a result of the increasing SWM precipitation in past decades, the annual average precipitation of Sri Lanka also has increased. According to De Silva[4], the impact of climate change on the Southwest Monsoon precipitation across the country is predicted to increase further. When considering the last two decades of the 20th century, Sri Lanka has faced a number of extreme precipitation events especially during SWM period[5]. High intensity, extreme precipitation events have increased the frequency of flash floods and landslides incidents in Sri Lanka. It is also reported that not only the floods but also the drought conditions have been amplified during 1974–2004[6]. Detailed knowledge about the variations in precipitation pattern is essential for proper water management practices in the country. Thus, understanding the variability of precipitation in both spatial and temporal components may help to improve the ability of forecasting tactics. Understanding the precipitation pattern may be helpful to plan the crop cultivation as well as in water storage designing, and drainage channels system designing for flood mitigation, etc[1]. Nowadays the scientists have paid more attention on finding reasons which may have effect on significant precipitation changes in this region. Few of the studies have already suggested that there is a direct influence of global warming on precipitation variation over the Indian Ocean[7].

Sea Surface Temperature (SST) significantly affects the Asian summer monsoon from intraseasonal to long-term timescales[8]. It is obvious that the precipitation and its trends increase linearly with the increasing SST over tropical monsoon basins. Recently the relationships between SST anomalies and the Asian monsoon precipitation have been subject of many studies. The land surface processes and ocean thermal conditions are significantly influenced by the Indian Monsoon and East Asia Summer Monsoon (EASM, Zubair et al.[9]). The SST anomalies such as El Niño-Southern Oscillation, and wind over the oceanic area would have a marked influence over the weather and climate of small islands like Sri Lanka[10]. Previous researches have suggested that the Sri Lanka must be directed into regional-scale research across the Indian subcontinent and the Bay of Bengal[11-13]. However, few studies have been done to investigate the relationship between the SST and the Sri Lankan precipitation. Rasmusson et al.[14] have found a positive relationship between Pacific SST anomalies and Sri Lankan autumnal precipitation. During summer monsoon season, Arabian Sea SSTs significantly influence the precipitation of Sri Lanka, especially that of the southwestern part of the island[15]. Relatively few studies have been devoted to investigations of longer-term changes in precipitation of Sri Lanka. Therefore this paper is intended to study the relationships between the Indian Ocean SST anomalies and the Sri Lankan summer monsoon precipitation. The purpose of this research is to identify the interdecadal and interannual variations of Sri Lankan precipitation during summer monsoon and their connections with the Indian Ocean SST.

2 Datasets and method

Monthly precipitation data from Global Precipitation Climatology Project (GPCP) the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data available on a 2.5° × 2.5° latitude/longitude grid during 1979 – 2016 are used for this study[16]. The monthly SST dataset used in this study is from Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST, Rayner et al.[17]). It has a horizontal resolution of 1°×1° from 1870 onwards. The atmospheric variables, such as wind, specific humidity and surface pressure data are from NCEP/NCAR reanalysis datasets with a 2.5°×2.5° latitude/longitude grid[18].

Empirical orthogonal function (EOF) analysis, composite analysis, correlation analysis, power spectrum analysis, and regression analysis are applied in the study. The Student's t test is used to examine the confidence level of the correlation and regression analyses.

3 Results

3.1 Variations of precipitation in Sri Lanka

Figure 1 shows the annual cycle of precipitation in

Sri Lanka.Peak of precipitations is observed during the SIM (Oct-Nov) period.Compared with the other three seasons, SWM (May - Sept) persists through longer period (5 months) with higher fluctuation of precipitation.

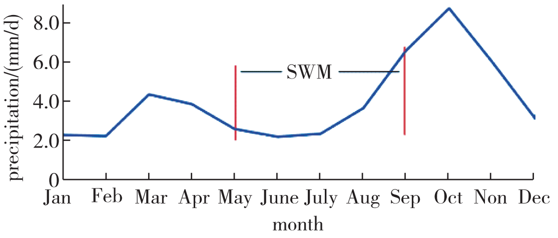

Fig. 1 Annual cycle of precipitation in Sri Lanka (5-10°N, 79-82°E) during 1979-2016

SIM and SWM show major contribution to the Sri Lankan precipitation. Suppia & Yoshino[3] showed that the averaged precipitation received during SWM is 556 mm which contributes 30% to annual precipitation in Sri Lanka.This study focuses on the variations of SWM (summer) precipitation in Sri Lanka.

To illustrate the spatial-temporal variations of precipitation in Sri Lanka, an EOF analysis is applied to the SWM precipitation during 1979 - 2016. The first leading EOF mode explains 57.3% of the total variance and shows a monotonous mode with negative values in Sri Lanka, indicating a coherent variation over Sri Lanka and surrounding area (Fig.2a).

PC1 shows a clear interdecadal variation during SWM with negative values and to be positive around 2000 (Fig.2b). The second leading EOF mode shows relatively less contribution (15% of the total variance), and the most regions in Sri Lanka have negative values, but there are positive values in its northern cape (Fig.2c).Different from PC1, PC2 shows interannual variation in Figure 2d. According to EOF analysis, the SWM precipitation shows interdecadal and interan-

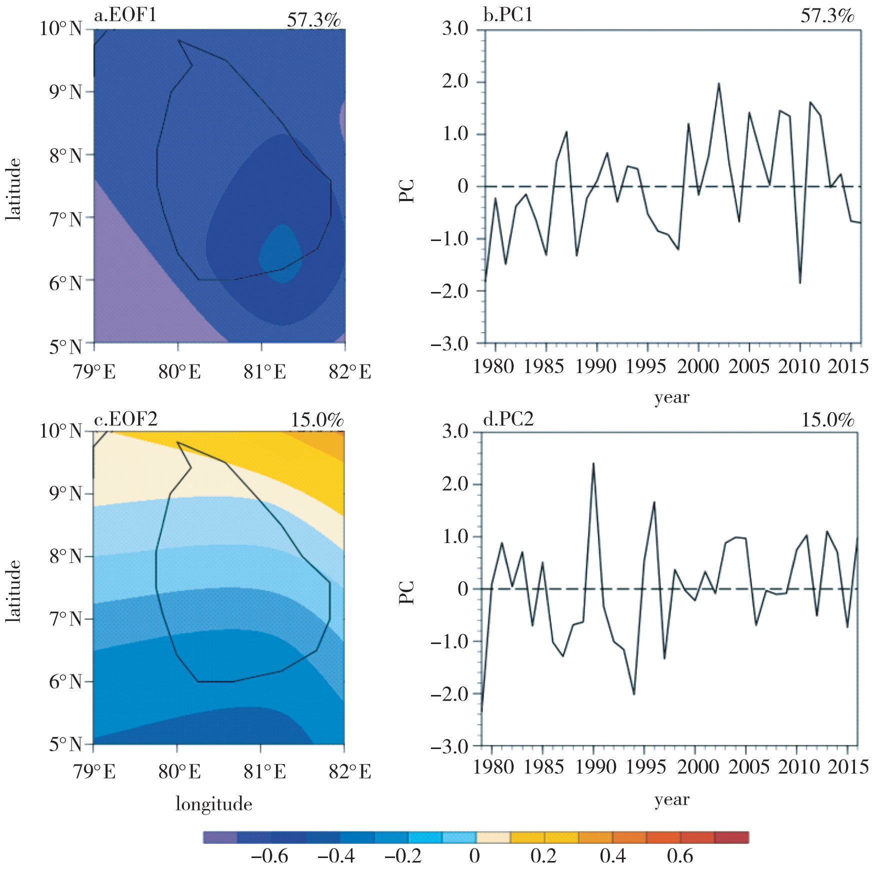

Fig. 2 EOF analysis of SWM precipitation anomalies (unit:mm/month) in Sri Lanka and surrounding region during 1979-2016, (a) and (c) are the first and the second leading modes, respectively, (b) and (d) show the variations of principal component (PC) 1 and 2, respectively (The percentages of variance explained by the EOF1 and EOF2 are given in the top right corner of the figure)

nual variations.In the following,the study examines the connections between precipitation in Sri Lanka and the tropical Indian Ocean SST on interdecadal and interannual timescales,respectively.

3. 2 Interdecadal variation of SWM precipitation in Sri Lanka

The Sri Lankan precipitation index (SPI) is used to represent the SWM precipitation variations in Sri Lanka.It is defined as the area averaged precipitation of Sri Lanka during summer (May − Sep). The SPI variations in Sri Lanka and its 7-year running mean are shown in Figure 3.

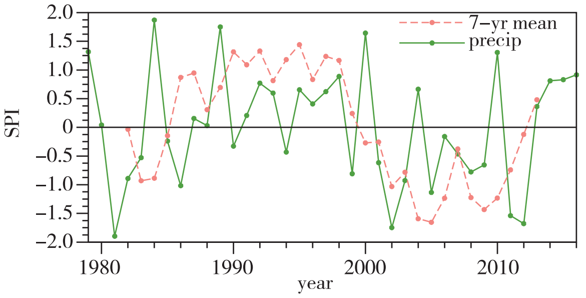

Fig. 3 Time series of normalized Sri Lankan precipitation index (SPI,green line) and its 7-yr running mean (red line). The SPI is defined as the area averaged precipitation of Sri Lanka during summer (May-September)

PC1 (Fig.2b) and 7-year running mean of precipitation (Fig.3) exhibit similar interdecadal fluctuation around 2000.It further indicates that PC1 could well represent the interdecadal variation of SWM precipitation with more and less precipitation before and after 2000. A question is thus raised that why the SWM precipitation shows an interdecadal change around 2000. To answer the question, the present study compares the differences of SST and atmospheric circulation in the Indian Ocean between two time periods (1979−1998 and 2000−2014).

It is found that the SST in Indian Ocean during 2000 − 2014 is significantly warmer than that during 1979−1998,and the warm SST anomalies extend from western to central tropical Indian Ocean (Fig.4).

It is noted that the changes of SST in the southeastern Indian Ocean are not significant on interdecadal timescale (Fig. 4). The warmer SST in the tropical Indian Ocean during 2000 − 2014 could influence the meridional circulation over there.

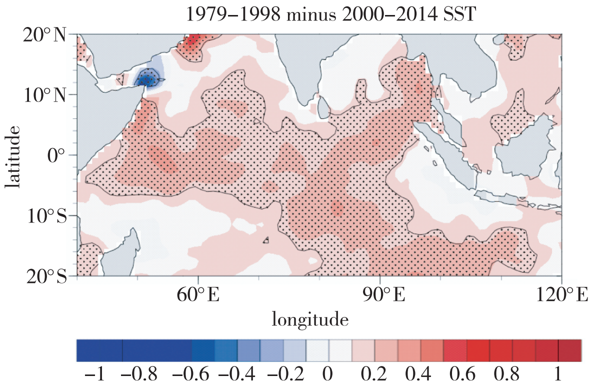

Fig. 4 Differences of SST (℃) anomalies between 2000−2014 and 1979−1998 (2000−2014 minus 1979−1998) in the tropical Indian Ocean during southwest monsoon (summer,May−Sep).The black dots enclosed by black contour represent the 90% confidence level

Figure 5 compares the differences of meridional circulation averaged between 75° E and 82° E between 2000 − 2014 and 1979 − 1998. The stronger upward motions occur south of 5°S,and flow across the equator at higher-level, and then downward motions are seen around 5−10°N,which could depress the precipitation in Sri Lanka during 2000−2014.

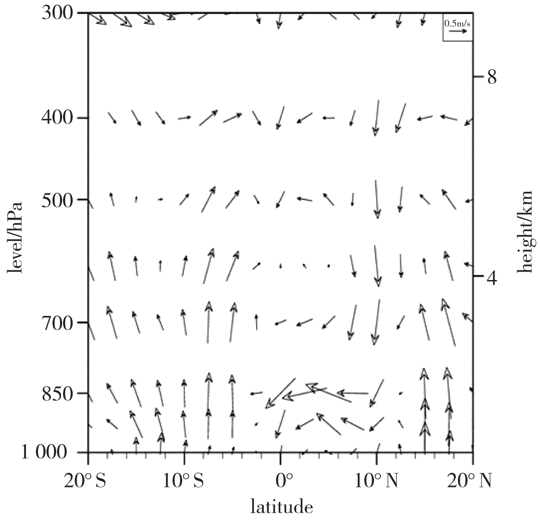

Fig. 5 Differences of meridional winds (m/s) and vertical velocity (0. 01 Pa/s,) along 75−82°E between 2000−2014 and 1979−1998 in SWM (2000−2014 minus 1979−1998). Vertical velocity is multiplied by 100 times

3.3 Interannual variation of SWM precipitation in Sri Lanka

PC2 of EOF analysis of precipitation in Sri Lanka and surrounding region shows an interannual variation (Fig.2d), and is significantly related to the SPI with the correlation coefficient as high as 0.43 (exceeding the 99% confidence level based on the Student's t test). Figure 6 gives the results of power spectrum analysis of PC2. It is seen that PC2 shows interannual variations with about 5 years and 3 years periods. It is indicated that PC2 could represent the interannual variations of precipitation in Sri Lanka to some degree.

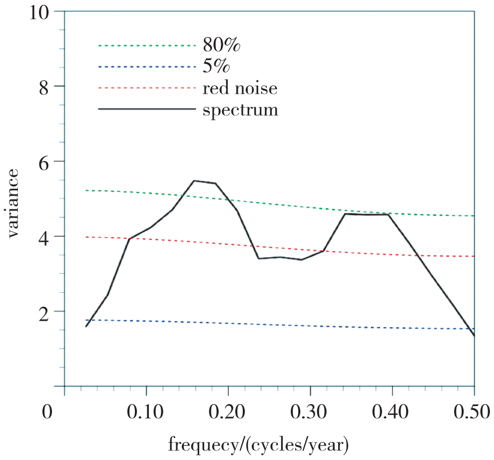

Fig. 6 Power spectrum analysis of PC2 for SWM over 38 years (1979-2016) (Green, red, and blue dashed lines indicate the 80% significance level, the red noise, and the 5% significance level lines, respectively)

Correlation analysis is conducted between PC2 and SST anomalies in Indian Ocean to identify the influences of the Indian Ocean on precipitation in Sri Lanka on interannual timescale (Fig. 7). The significantly positive correlations between SST anomalies and PC2 are seen in the southeast tropical Indian Ocean.

It means that there are more precipitation in most regions of Sri Lanka and less precipitation in the cape of northern Sri Lanka accompanying with warm SST anomalies in the southeast tropical Indian Ocean. In the followings, the mechanism of how the warm SST anomalies in the southeast tropical Indian Ocean impact the precipitation in Sri Lanka is examined.

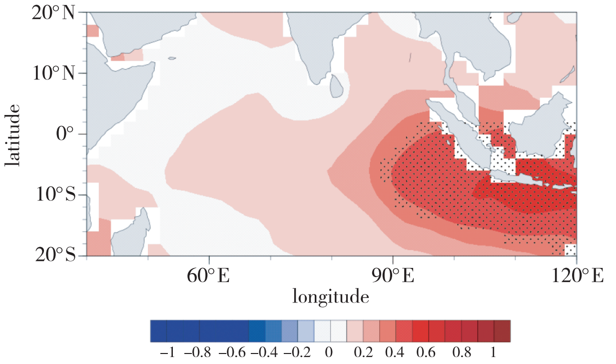

Fig. 7 Correlation of SST anomalies during May-September with PC2 (Black dots indicate significant correlation exceeding the 95% confidence level; the area-mean SST anomalies over the black box 90-120°E and 15°S-0° are defined as the southeast tropical Indian Ocean index (SEIOI))

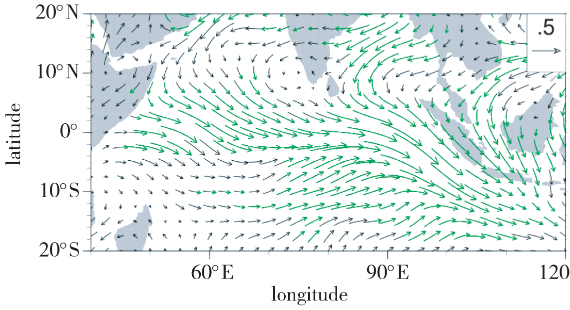

Fig. 8 Regression of wind (m/s) at 1 000 hPa against SEIOI (Green arrows represent the vectors exceeding 90% significance level based on the Student's t test)

Here, the area-mean SST anomalies over a box of 90-120°E and 15°S-0° is defined as the southeast tropical Indian Ocean index (SEIOI) where there are significant relationship with precipitation in Sri Lanka. The large-scale atmospheric circulations associated with SEIOI are shown in Figures 8 and 9. From Figure 8, it is robust that the warm SEIOI could induce strong cyclonic circulation anomalies near to tip of the Indian subcontinent and the Bay of Bengal due to Gill response, which results in significantly anomalous low-level northerly anomalies near Sri Lanka. During southwest monsoon period, climatological wind begins from the Mascarene high at southeast Indian Ocean, and turns into southwesterly when it across the equator[19]. Southwestly prevails in Sri Lanka during SWM. Therefore, under the influences of warm SST anomalies in the southeast tropical Indian Ocean, the southwestly during SWM period is weakening in Sri Lanka (Fig.8).

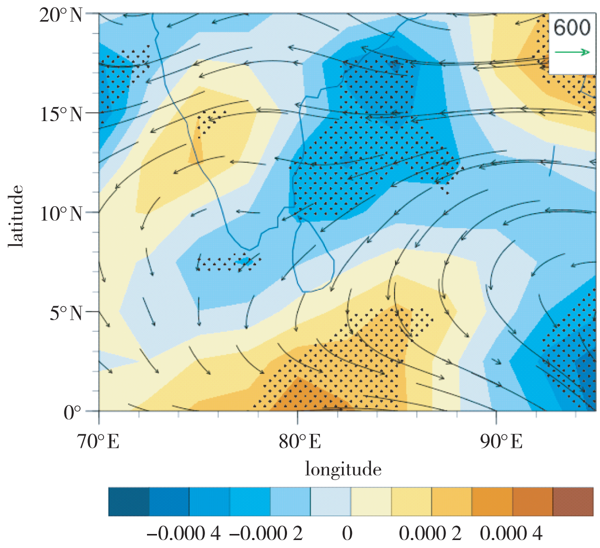

Fig. 9 Regression of moisture flux transport (vector, kg/(m·s)) and its divergent (shading) during SWM against SEIOI(Black dots indicate the moisture convergence and divergence zone exceeding the 90% confidence level based on the Student's *t* test)

According to Bretherton et al.[20], more moisture would be added to the lower troposphere with the increase of SST in surface layer. The present study checks the changes of moisture flux and its divergent associated with SST anomalies in the southeast tropical Indian Ocean. According to results of Kevineetal.[21], the moisture flux is calculated as the following:

$$Q_{\mathrm{div}}=\frac{1}{g}\int_{300}^{P_s}(Vq)\mathrm{d}p=\frac{1}{g}\int_{300}^{P_s}V\cdot\nabla q\mathrm{d}p+\frac{1}{g}\int_{300}^{P_s}\nabla q\cdot V\mathrm{d}p, \qquad (1)$$

Where the right two terms in Eq.(1) are moisture advection and moisture divergence by wind fields, g is the acceleration of gravity, V is two-dimensional wind vector, q is specific humidity, and P_s is surface pressure.

Figure 9 illustrates the variations of moisture flux and its divergent regression by the SEIOI. It is found that the anomalous warm SST in the southeast tropical Indian Ocean could enhance moisture fluxes from the Bay of Bengal into Sri Lanka. The moisture fluxes are convergent over the northern Sri Lanka, which favors more precipitation over there. Based on the large-scale atmospheric circulations and moisture transport, it is suggested that the warm SST anomalies in the southeast tropical Indian Ocean tend to induce more precipitation in Sri Lanka on interannual timescales.

4 Summary and discussion

The present study has investigated the variations of the SWM precipitation in Sri Lanka over last 38 years. The dominant patterns of summer precipitation anomalies in Sri Lanka are studied using EOF analysis. Variance of EOF1 (57.3%) and EOF2 (15%) explains exceeding 70% of the total variance. For the first leading mode of EOF, EOF1 is a monotonous mode. PC1 shows a clear interdecadal change around 2000, which is similar to the change of 7-year running mean of SPI with more and less precipitation before and after 2000. The differences of SST anomalies and meridional circulation are compared between 1979 – 1998 and 2000–2014 to explain the interdecadal variation of precipitation in Sri Lanka. It is found that the SSTs in western and central tropical Indian Ocean during 2000 – 2014 are significantly warmer than those during 1979–1998, while the changes of SST in the southeastern Indian Ocean are not significant on interdecadal timescale. Such significant warmer SSTs in western and central tropical Indian Ocean enhance the meridional circulation along 75–82°E, and thus induce the anomalous downward motion and less precipitation in Sri Lanka. For the EOF2 mode, the most regions in Sri Lanka are covered by negative values, but there are positive values in the northern cape of Sri Lanka. PC2 shows variations on interannual timescale. Such interannual variation of precipitation is greatly associated with the anomalous SST in the southeast Indian Ocean. The warm SST anomalies in the southeast Indian Ocean can result in the anomalous cyclonic circulation in the northern Indian Ocean due to Gill response, which induces moisture flux from the Bay of Bengal into Sri Lanka and moisture convergence in Sri Lanka. These results suggest that the interdecadal variations of precipitation in Sri Lanka are greatly associated with western and central tropical Indian ocean SST, while the interannual variations are significantly influenced by the anomalous SST in the southeast tropical Indian Ocean.

Researchers usually pay attention to the SST and monsoon precipitation in large regions such as Indian subcontinent but miss small islands like Sri Lanka. Many scientists have shown that ENSO-induced SST anomalies persist through summer over the tropical Indian Ocean[22]. Therefore, it is important to continue this research on remote influence of the Pacific SST during SWM to identify the Sri Lankan precipitation variation.

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