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斯里兰卡南部西向沿岸流在西南季风期间的动力学研究

摘要

北半球夏季,北印度洋环流主要受到西南季风流控制,将热带印度洋水体从西向东进行跨海盆输运,然而在斯里兰卡南部沿岸存在一支与西南季风流方向相反的西向沿岸流,即南斯里兰卡沿岸流(SSLCC).本文主要利用ECCO2资料进行南斯里兰卡沿岸流的动力学特征研究.结果表明,SSLCC的形成和孟加拉湾局地环流密切相关.当斯里兰卡穹顶区(SLD)环流偏强时,斯里兰卡南部形成局地气旋式涡旋,斯里兰卡东部沿岸流在SLD西部向南流动,随着气旋式涡旋北部转向西流形成强的SSLCC.相比之下,SLD较弱时,沿岸流仅存在斯里兰卡东部沿岸,斯里兰卡东部沿岸流无法向西转向,SSLCC和西南季风流一起向东流动,其可能的主要原因是局地风应力对SLD产生的强度影响.研究还表明,SLD强度对SSLCC流向和强度有着重要影响.

关键词

孟加拉湾;西南季风流;斯里兰卡;沿岸流;斯里兰卡穹顶区

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0　导读

本文原文为英文,希望感兴趣的读者进一步关注原文.

北印度洋夏季环流主要受热带西南季风流控制,使热带印度洋水体从西向东跨海盆输运.Schott等于1993年观测到一支狭窄的西向流,它将东南向流动的西南季风流(SMC)与斯里兰卡南部海岸分离.Vinayachandran等解释了其主要原因实际是孟加拉湾(BoB)区域风场及其有关的孟加拉湾西边界流向南流动的延伸部分共同导致斯里兰卡周边的陆架陷波变异.然而,该西向流的动力过程仍不清晰,它的季节和年际变化也尚未清楚.因此,本文主要利用ECCO2数据分析1992—2012年南斯里兰卡沿岸流在西南季风期的季节与年际变化特征,探讨其在年际尺度上与BoB地区海洋环流之间的联系,最终揭示斯里兰卡南部西向沿岸流的动力学机制.

统计结果显示,南斯里兰卡沿岸流(SSLCC)具有显著的年际变化:SSLCC异常向西流的年份是1993、2000、2001、2002、2004和2011年,异常向东流的年份是1994、1997、2003和2008年.合成分析结果表明,SSLCC的形成与斯里兰卡穹顶区(SLD)的强度密切相关.SLD增强时,南部海岸有气旋式涡旋(SCV)形成,并逐步加强;同时SLD的强度可以直接影响斯里兰卡南岸西南季风流的偏差.SMC一部分绕着SLD流动,在SLD西侧的流则随着斯里兰卡东部沿岸流(ESLCC)一起向南流.异常强SLD可以迫使该南向流沿斯里兰卡南部海岸向西偏转,此时,这支西向流出现在SCV的北侧.相比之下,当SLD偏弱时,热带海洋环流主要以纬向流动为主,SLD无法驱动南向流动的ESLCC向西偏转流动,只能局限于斯里兰卡的东海岸,而SSLCC伴随着SMC一起向东流动.综上研究,SLD的强度是决定南斯里兰卡沿岸西向流的主要因素,而局地风应力的强度是主导SLD强度加强的可能原因.SSLCC地区的水体质量输运和斯里兰卡东岸(5.5~8°N,82°E)的西边界流速存在显著负相关,即SLD西侧的西边界流越强,则SSLCC异常向西流动,反之亦然.

本文还发现,2011年SLD强度相对较弱,但西向的SSLCC在7月强度很大,表明2011年的个例并不能利用局地风应力强度的作用来进行解释南斯里兰卡沿岸西向流产生机制.因此,今后需要总结归纳西向SSLCC产生的主要因子,并通过数值模拟试验进行机制验证.

Dynamics of westward coastal current during the southwest monsoon in southern Sri Lanka

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Abstract During summertime,the north Indian Ocean circulation is characterized by eastward Southwest Monsoon Current (SMC) which is essential to the transport of water mass in the west and east ocean basins in the tropics.Occasionally,a narrow westward coastal current (hereafter referred to South Sri Lanka Coastal Current,SSLCC), against Southwest Monsoon (SWM) and SMC,exists off the southern coast of Sri Lanka at the same time.In this study,ECCO data is used to examine the dynamics and inter-annual variations of the narrow westward coastal current.It is found that the formation of the westward SSLCC is closely related to local circulation in the Bay of Bengal (BOB).The southward moving East Sri Lanka Coastal Current (ESLCC) which is associated with the western flank of Sri Lankan Dome (SLD) turns to westward along the northern flank of Small Cyclonic Vortex (SCV).The SCV is a cold upwelling dome,originated at the south of Sri Lanka.The strong SLD is the key factor to intensify the SCV which favors the westward SSLCC.This phenomenon is observed in the years of 1993,2002,2004 and 2011.However,the ESLCC turns to eastward with the SMC during the years which have weaker SLD,such as 1994,1997,2003 and 2008.The possible reason is that the SLD is unable to intensify the SCV.The analysis suggests that the strength of SLD plays a significant role for westward SSLCC.

Key words Bay of Bengal;southwest monsoon current;Sri Lanka;coastal current;Sri Lanka Dome

1 Introduction

High-Resolution Global-Ocean and Sea-Ice Data Synthesis model simulations from Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) project were used to analyze the circulation pattern at the south of Sri Lanka (5.5-6°N,80-82°E) during the southwest monsoon.One of the major objectives is to understand the dynamics of Southern Sri Lanka Coastal Current (SSLCC) during the southwest monsoon season.

The circulation along the coast of Sri Lanka is essential to understand the water mass exchange between the Bay of Bengal (BoB) and the Arabian Sea (AS). The circulation pattern of this region undergoes drastic changes with the seasonally reversing monsoon wind system over the Indian Ocean.The monsoon currents which are important for water mass exchange,between south of Sri Lanka and north of the Equator,are westward during winter and eastward during summer[1-2].However,there is considerable salinity difference between the AS and the BoB[3-4].The evaporation over precipitation and river discharge is high in AS and thus the salinity is considerably high in AS with respect to BoB.Low saline water (high saline water) flux from BoB (AS) to AS (BoB) maintains average salinities between the two ocean basins through general circulation[5-6].Thus the understanding of general circulation pattern is important to investigate the water mass exchange between the two basins.General circulation pattern between the two basins is discussed in next paragraphs.

Figure 1a schematically illustrates the prominent surface currents during the Southwest Monsoon (SWM),which has already been described in previous studies[1-2,7].The Southwest Monsoon Current (SMC) flows eastward between equator and southern tip of Sri Lanka as the continuation of Somali Current system from western AS to southeast of AS and flows around the Lakshadweep low of southwest India[1-2,7-8].Subsequently, the equator-ward West Indian Coast Current (WICC) which annually reverse its direction with monsoon reversal[1],merges with the eastward flowing SMC.

In summer, WICC flows southward along the west coast of India which strengthens in July and vanishes during October[1,9]. Then the SMC flows eastward together with WICC in the south of Sri Lanka during SWM which reaches its maximum strength of 60 cm/s in July[2]. The wind strength is much stronger during southwest monsoon period than during northeast monsoon period. Concurrently, East India Coast Current (EICC) flows northeastward along the east coast of India and part of EICC bifurcates southward, against the southward alongshore wind, along with the east coast of Sri Lanka[1,10]. The variability of EICC has been influenced majorly by the coastally trapped Kelvin waves and BoB interior crossing Rossby waves[1,11]. Moreover, interior Ekman pumping, local alongshore winds, remote alongshore winds and remotely forced signal from the equator are the four driving mechanisms of EICC[1,11-13].

During the northeast monsoon, the Northeast Monsoon Current (NMC) flows westward south of Sri Lanka from BoB to AS[1-2,9]. Simultaneously, the EICC flows southwestward along the east coast of India and Sri Lanka and feds the NMC, and part of the NMC supplys poleward flowing WICC along the west coast of India. Southward propagating EICC is intensified by the downwelling coastal Kelvin wave which propagates from Sumatra coast along the boundary of Bay of Bengal as well as crossing southern coast of Sri Lanka to west coast of India[14].

The aforementioned general circulation pattern in BoB and AS can be disturbed by the vortexes/eddies[15-19]. The activities of eddies in the BoB have been previously investigated using drifting data[16], altimetry data[18] and ocean general circulation model (OGCM)[19]. Furthermore, Rath et al.[19] have noted that, SMC becomes stronger around Sri Lanka and the fluctuating geostrophic wind power builds the baroclinic instability which weakens the SMC. Thus eddy starts to interact with the SMC and accordingly the eddy pulses act against the weakening SMC and increase the eddy activities in the Bay of Bengal.

The most fascinating eddy activity in this region is the cyclonic vortex, known as Sri Lanka Dome (SLD), which originated as a consequence of the cyclonic rotation of eastward propagating SMC at around 82−85°E east of Sri Lanka[15,20] during the SWM. In the meantime, the ESLCC flows southward against the local wind[2] along the western flank of SLD which is a cold upwelling dome originated during May, matured at July and decayed during September[15,20-21]. This cyclonic vortex is generated as results of the impact of wind stress (strong cyclonic wind stress curl) and the interaction between the SMC and the SL Island[21]. This has been explained by the well-developed upward isotherm which is induced by cyclonic curl and Open Ocean Ekman pumping[15,20]. The decay of SLD starts around September due to the arrival of Wyrtki jet associated Rossby waves which reflects from the eastern boundary of BoB[15] and freshwater flux from BoB along the east coast of India as EICC advect to the SLD area[21]. Furthermore, part of the SMC circulates as an anticyclonic vortex due to the baroclinic instability of SMC beneath the SLD[19]. Both Anticyclonic vortex (ACV) and SLD participate in the transportation of AS high saline water mass into the BoB[22].

As previously mentioned, the remote forcing (equatorial waves) is one possible reason for the decay of vortexes and the equatorial waves remotely control the circulation pattern in BoB through four coastally trapped Kelvin waves and Rossby waves. Rossby waves radiate westward by coastal Kelvin waves at the eastern boundary of BoB. The first upwelling (downwelling) Kelvin wave occurs during January−March (May−August) and the second upwelling (downwelling) Kelvin wave occurs during August−September (October−December) in the BoB[23]. This westward propagating Rossby waves and coastal Kelvin waves affect the general circulation in Eastern Indian Ocean (EIO) and this westward radiating Rossby wave reaches south of Sri Lanka during SWM[1,11,15,24].

Among all the circulations and dynamics which are discussed in previous sections, Schott et al.[25] found a westward flow at the south of Sri Lanka during summer, which is a surprising finding since this current flows against the SWM winds and the SMC. The eastward monsoon current is separated by the 60-kilometer wide westward flow which has been recognized as carrying the low salinity BoB water according to the ADCP measurements at 5° 38″ N, 80° 31″ E. This westward current wasn' t recorded during most July and August, nevertheless it was recorded during June in ADCP measurements. Furthermore, the westward flow starts approximately at 20 m depth and diminishes around 100 m depth (see, Figs.4c and 4f, Schott et al.[25]). Furthermore, Schott et al.[13] have mentioned that the presence of a narrow westward current just to the south of Sri Lanka between 5.5–6°N latitudes. Additionally, Vinayachandran et al.[17] mentioned the westward flow which separates SMC from Sri Lankan coast. They explained further that this westward current generated by coastally trapped waves travel around Sri Lanka as a result of the wind in the Bay of Bengal and it is an extension of southward-flowing western boundary current of BoB. However, its dynamics remain unexplored and the mechanism that generates the observed narrow westward current in the south of Sri Lanka with annual and seasonal variation is not well understood. This is the main motivation for this study. Moreover, the annual variation of the South Sri Lanka Coastal Current (SSLCC) (Fig. 4) around Sri Lanka during SWM and its relation with eddies are discussed in this paper using ECCO2 model output. Furthermore, this study shows that the westward current is significant in the years which have strong SLD off the east coast of Sri Lanka.

2 Data and methodology

The model output from the NASA Modeling, Analysis, and Prediction (MAP) program funding project called Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2): High-Resolution Global-Ocean and Sea-Ice Data Synthesis is used to examine the currents, temperature and salinity fields in the BoB and South of Sri Lanka for the period of 1992 to 2012. ECCO2 data syntheses are obtained by the least squares fit of a global full-depth-ocean and sea-ice configuration of the Massachusetts Institute of Technology general circulation model (MITgcm) for the available satellite and in-situ data. The ECCO2 nowcast/forecast system produces nowcasts and forecasts of ocean conditions including three-dimensional ocean current/velocities, temperature and salinity structure, surface fluxes, sea surface height, bottom pressure, mixed and mixing layer depths, sea-ice thickness, concentration, density, and eddy transports of mass, temperature, and salt. A cube-sphere grid projection is employed, which permits relatively even grid spacing throughout the domain and avoids polar singularities. Each face of the cube comprises 510 by 510 grid cells for a mean horizontal grid spacing of 18 km. The model has 50 vertical levels ranging in thickness from 10 m near the surface to approximately 450 m at a maximum model depth of 6 150 m (Accessible at: http://ecco2.org).

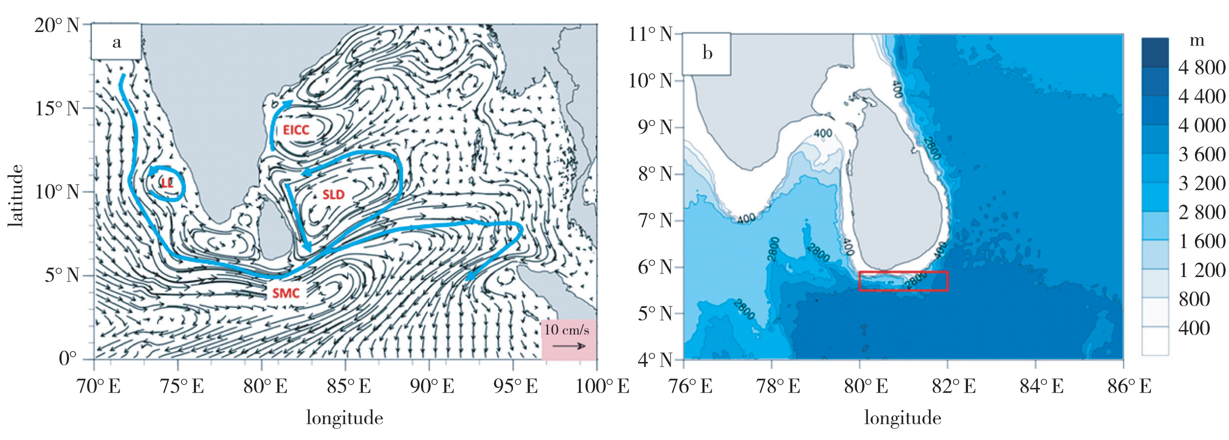

Fig. 1 (a) A schematic representation of the identified current branches during the southwest monsoon, which are indicated by SMC-Southwest Monsoon Current, EICC-East India Coastal Current, SLD-Sri Lankan Dome, and LL-Laccadive Low (upper). Seasonal map of climatological (1992–2012) velocity vector from ECCO2 averaged from June-August (summertime) within upper 100 m depth. The scale vector is 10 cm/s. (b) Indian Ocean bathymetry (in meters) and the study domain (the red box) from ETOPO5 bathymetry data (80–82°E, 5.5–6°N)

In addition to ECCO2 data, bathymetry data from ETOPO5 (see http: // apdrc. soest. hawaii. edu/data/data.php) have been used.

To understand the amount of water mass carried by the SSLCC, the water mass transportation is calculated at the domain from 1992 to 2012 using the equation[26]:

$$\text{Watermass Transports} = V\int_{x_1}^{x_n}\int_{z_1}^{z_n} \mathrm{d}x\mathrm{d}z , \qquad (1)$$

Where, V is the zonal velocity, x is the latitude distance and z is the depth.

3 Results and discussion

During the boreal summer the circulation around Sri Lanka is illustrated in Figure 1 a which suggests that the zonal current (SMC) flows eastward south of Sri Lanka. To understand the annual variation of zonal velocities in the selected domain (80–82°E, 5.5–6°N in Fig.1b), the depth-time section of climatological zonal velocities are displayed in Figure 2. The climatological zonal velocities are eastward during SWM (June–Sep) and westward during the rest of the year. The westward strength of climatological zonal velocities is stronger than the eastward ones. Thus, the annual westward flow is prominent beneath Sri Lanka. Though, the summer monsoon winds are much stronger than the winter monsoon in the Indian Ocean[10]. However, Schott et al.[1], Shankar et al.[2], and Schott et al.[25] mentioned about the narrow westward current which flows against SMC just south of Sri Lanka during the boreal summer. Accordingly, the detailed view of zonal velocities are discussed from 1992 to 2012 (Fig.3).

Understanding the variation of westward current is essential to explore the water mass exchange between West and East Indian Ocean basins during summertime. Figure 3 explicates the SWM seasonal variation of zonal current in the domain. According to general understanding of the monsoon circulation, the zonal flow is eastward in the manner of SMC during the SWM (Fig.2). It is agreeable with the wind-driven circulation during the SWM. However, the inter-annual variation of SSLCC shows some deviations than the general explanation of summer monsoon circulation around Sri Lanka (Fig.3). The SMC flows eastward as usual during the years of 1994, 1995, 1997, 1999, 2003, 2006, 2007, 2008 and 2009, and consecutively becomes weaker. Among the aforementioned years, 1994, 1997, 2003 and 2008 have strong eastward zonal velocities greater than 20 cm/s. However, the zonal velocities show westward tendency during several years. This impressive phenomenon is detected during 1993, 2002, 2004 and 2011. This concurs with ADCP observation of Schott et al.[25] where they observed westward flowing narrow current that separates the eastward flowing SMC from the coast of Sri Lanka at 5°38.8′N and 80°31.0′E during 1993. It is strengthening from the 20 m depth and diminishesat about 100 m depth. Thus the ECCO2 model output analysis agrees with that observation in 1993. An examination of the time series for velocities during the period of 1992–2012 show that the relatively strong velocities which exceed 20 cm/s are noted during 2000, 2001, 2002, 2004 and 2011 within 20–60 m depth range. Likewise, the strongest eastward (westward) ve-

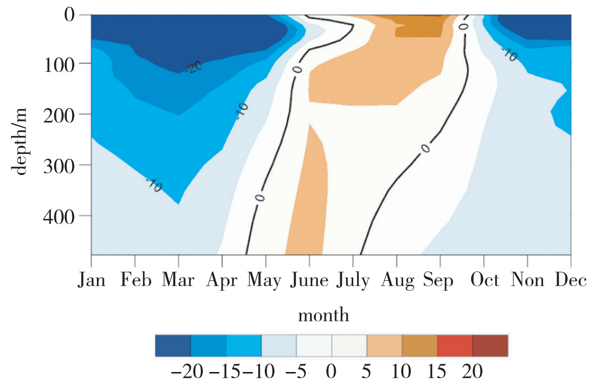

Fig. 2 Climatological cycle of zonal velocities over the region (80–82°E, 5.5–6°N), velocities are in cm/s and depth is in meter

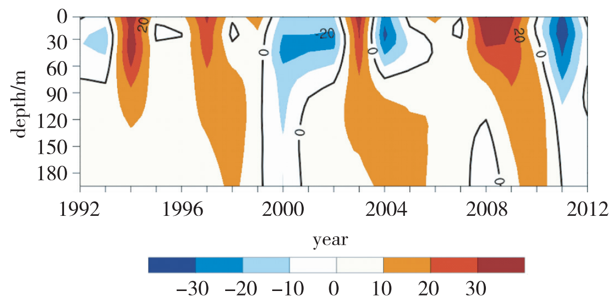

Fig. 3 Time series of zonal velocities in summertime over the domain (80–82°E, 5.5–6°N), with velocities in cm/s and depth in meter

locities are observed in 1994, 2008, and 2009 (2004 and 2011) within this domain.

To evaluate the variability of SSLCC, the current vectors are overlaid over the current speed for selected years during the month of July (Fig.4). The years of 1993, 2000, 2001, 2002, 2004 and 2011 are climatologically averaged to understand the circulation pattern and current speed during the westward SSLCC while the years of 1994, 1997, 2003 and 2008 are averaged to explore the circulation pattern and speed during the eastward SSLCC (Fig.4). This yearly difference shows that the vortexes/eddies have a significant contribution to the generation of westward flow. The SMC forms meander south of Sri Lanka during SWM[19]. These meanders can be classified as cyclonic (anti-clockwise) and anti-cyclonic (clockwise) vortexes and the systematic representation of these vortexes are illustrated in Figure 5. However, the position and existence of these vortexes change in yearly as well as throughout summer. Two of these vortexes are cyclonic and one is anti-cyclonic. The cyclonic vortexes are located to the north of SMC and east of Sri Lanka. The cyclonic vortex located to the east of Sri Lanka is known as SLD (Fig.5). The other cyclonic vortex which is located to the south of Sri Lanka is named as Small Cyclonic Vortex (SCV) (Fig. 5). The reason behind the formation of SCV might be the westward SSLCC. A part of the SMC circulates as SLD[15] and another part bends as the Anticyclonic Vortex (ACV)[19]. These are the major vortexes which engage with summertime circulation south of Sri Lanka (Fig.5). SLD reaches its mature level during July[15,21]. Thus the discussion is carried out in July.

When SSLCC flows westward, the strong SWM wind (Fig.6) and much prominent SLD (Fig.4) can be observed. During this period of time, the southward-flowing ESLCC merges with the western flank of SLD and turns westward along the southern coast of Sri Lanka. The SCV appears as the effect of strong SLD, creating a barrier between the southern coast of Sri Lanka and SMC. According to Schott et al.[1], a narrow westward current presents from 5.5°N to 6°N just beneath the southern coast of Sri Lanka. The climatological section analysis of ECCO2 model data also matches with the previous findings. The analysis suggests that the strength of the western flank of SLD and strength of SMC directly affect SSLCC. When the SLD strengthens, the strength of the southward-flowing ESLCC (western flank of Sri Lankan Dome) also increases and favors the westward SSLCC. The generality of these results is checked using independent speed of SLD westward flank in the east coast of Sri Lanka (Fig.7b). The zonal velocity of SSLCC is highly correlated with the speed of SLD western flank which suggests that the strength of SLD can be used to predict the westward bias of SSLCC

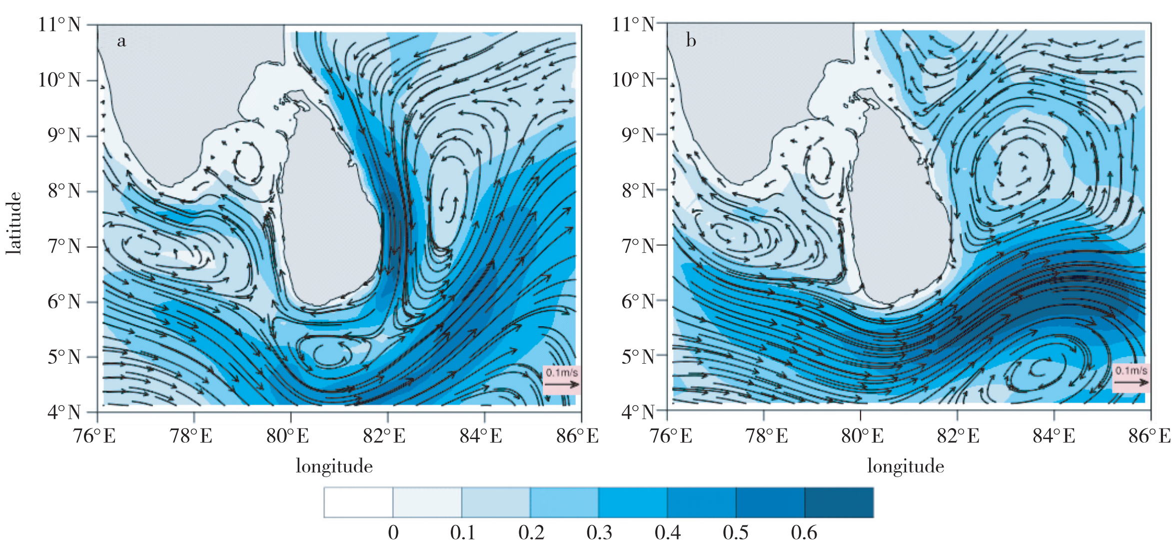

Fig. 4 Climatological current vectors overlaid over current speed (shading, in m/s) at the 40 m depth (a) in 1993, 2000, 2001, 2002, 2004 and 2011, (b) in 1994, 1997, 2003 and 2008 during July, the scale vector is 0.1 m/s

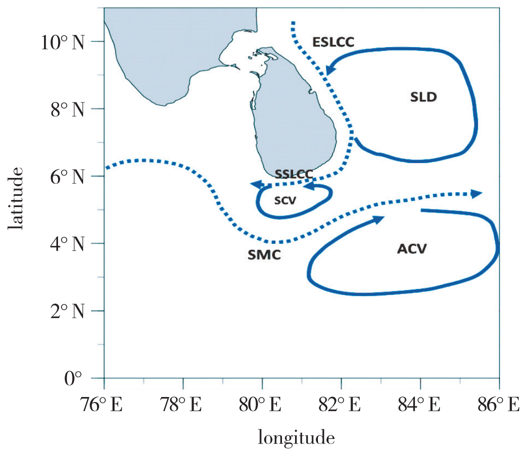

Fig. 5 A systematic representation of the identified current branches during the southwest monsoon

in SWM. The negative correlation indicates that the highest speed of SLD western flank tends to turn SSLCC towards west against strong SMC.

When the SLD gains less strength than SMC, the SLD is confined to the east of Sri Lanka. In this period the wind stress is relatively weak (Fig.6). Thus, the SLD doesn't extend to south of Sri Lanka. In this case, SMC doesn't generate meanders in south of Sri Lanka and the SLD doesn't intensify the SCV. Thus, SSLCC flows eastward together with SMC. As aresult of the weakening SLD, the ACV becomes stronger and northeastward. Due to the weakening SLD, the ESLCC bifurcate as, upper part towards the north and rest southward along the western flank of SLD. According to Fig.7b, the lower speed of SLD western flank tends to SSLCC towards east accordingly SMC during the SWM.

The hypothesis that the strong SLD causing the westward flow of SSLCC during SWM, has been clarified further by the time series of water mass transportation in the domain and the speed of western flank between 5.5–8° N, 82° E during summertime (Fig. 7a). The highest speed of western flank drives the westward current just beneath the southern Sri Lanka coast. However, this hypothesis deviates in 2011. The speed of western flank is not stronger (0.2 m/s) but the maximum westward transportation (11.9S_v) has been noted. Except 2011, there is a strong relationship between the strength of western flank of SLD and the westward water mass transportation. Thus, the strong SLD can drive the westward flow just beneath the southern Sri Lankan coast. Further studies are needed to determine the factors which affect the origin of SLD and small cyclonic eddy besides the wind stress and wind stress curl. The deviation in 2011 clearly indicates that there can be other factors which can impact on the formation of SLD and SCV.

4 Summary and conclusions

Schott et al.[25] observed the narrow westward current which separates eastward flowing SMC from

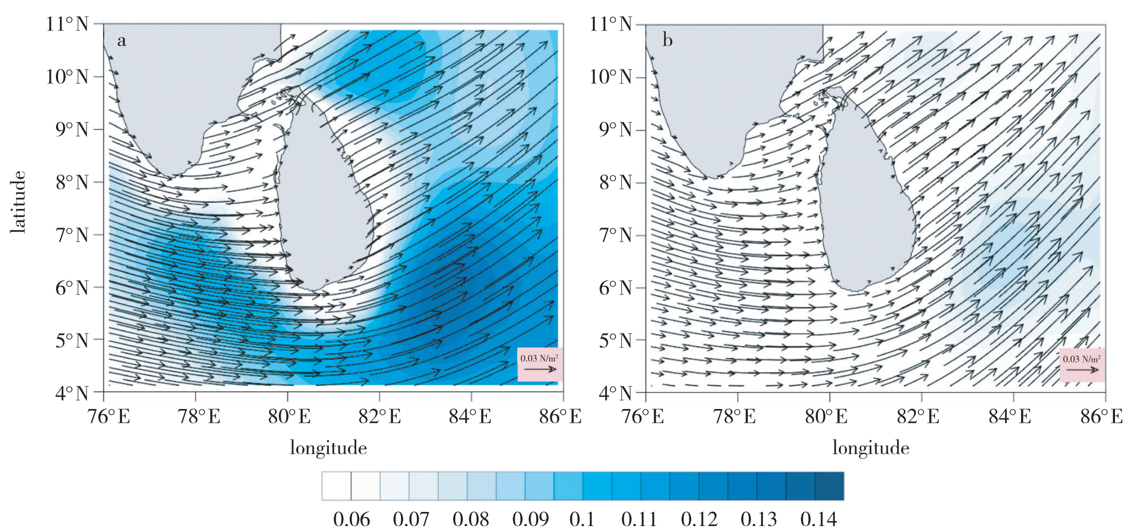

Fig. 6 Climatological wind stress vectors overlaid over wind stress speed (shading, N/m^2) for (a) in 1993, 2000, 2001, 2002, 2004 and 2011, (b) in 1994, 1997, 2003 and 2008 during July. The scale vector is 0.03 N/m^2

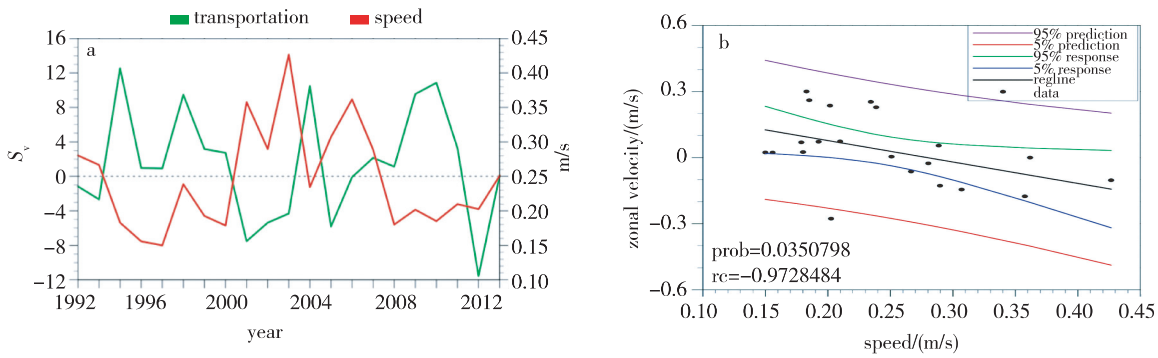

Fig. 7 (a)The volume integrated water mass transportation (green line; unit: S_v(1 $S_v = 10^6$ m^3/s); positive (negative) values indicate eastwards (westward) flow), and the volume integrated current speed (red line; unit: m/s) between 5.5–6°N, 82°E, and 0–100 m during July; (b) The scatter diagram of zonal velocity of SSLCC against the speed of SLD western flank with fitted regression line, 95% prediction limits (outer lines) and 95% confidence limits on μ_{Y1X0} and 95% confidence limits (response) on μ_{Y1X0}

southern Sri Lankan coast at mooring position 5°38.8′ N, 80°31.0′ E in 1993. Dynamics of the SSLCC has been studied for the years of 1992 to 2012 using ECCO2 reanalysis data during the SWM period to understand the mechanism which drives the current against the strong southwest monsoon wind. The narrow westward current (South Sri Lanka Coastal Current, SSLCC) originates as the result of the strength of SLD just beneath the southern coast of Sri Lanka. Consequently, the SLD extends to southern Sri Lanka and intensify the generation of SCV at the south of Sri Lanka. The strength of SLD can directly affect the deviation of SMC from southern Sri Lankan coast. The SMC flows eastward at south of Sri Lanka and part of the SMC circulates around SLD, afterward, it flows southward through the western flank of SLD along the east coast of Sri Lanka. The strong SLD can force this southward flow to turn to the west along the southern coast of Sri Lanka (Fig. 7b). This westward flow takes place on the northern flank of SCV. Another part of the SMC bends as the anticyclonic vortex at the southeast of Sri Lanka. However, relatively weak SLD cannot turn the southward flowing ESLCC westward and SSLCC flows eastward along with the SMC (Fig.7b). The SSLCC depends on the strength of SLD and the strength of wind stress intensify the strength of SLD over this area. Remarkable phenomenon is noted in 2011 and the strength of SLD and westward current cannot be explained by the wind stress. The strength of SLD is relatively low, however, the SSLCC could transport maximum water mass towards west during July. Thus, further studies are needed to determine the factors which have impacts on strong SLD and the extension of SLD south of Sri Lanka.

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