Polar Science 25 (2020) 100537

Contents lists available at ScienceDirect

Polar Science

journal homepage: http://www.elsevier.com/locate/polar

The linkages between Antarctic sea ice extent and Indian summer monsoon rainfall

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A R T I C L E I N F O

Keywords:
Sea ice extent in the Indian ocean sector
Teleconnection
High and low ice phase
Mascarene high
Indian summer monsoon rainfall

A B S T R A C T

Teleconnection between the Antarctic sea ice and the tropical climate has been extensively investigated. This study examines the interannual relationship between the variability of sea ice extent in the Indian Ocean sector (20–90°E) and Indian summer monsoon rainfall under the influence of the Mascarene High. Sea ice extent during April-May-June (AMJ) appears to have a significant correlation with the summer monsoon rainfall over Peninsular India region during June-July-August-September from 1979 to 2013. Composites of mean sea level pressure (MSLP), 500 hPa geopotential height, and 850 hPa wind anomalies during high and low ice phases show a positive relation between the sea ice extent and the Mascarene High, revealing that high (low) ice phase corresponds respectively to the strengthening (weakening) of the Mascarene High as well as an increase (decrease) in Indian summer monsoon rainfall. During the respective high (low) ice phase years, positive (negative) MSLP anomalies were found, particularly over the Mascarene High region, associated with the eastwards (westwards) shifts of its climatology locations. Similar features were observed at 500 hPa geopotential height anomalies. In addition, strong anticyclonic (cyclonic) anomalies in the Mascarene High region were found in 850 hPa winds, which led to corresponding strong (weak) south westerlies and thus respective positive (negative) Indian summer monsoon rainfall anomalies.

1. Introduction

Antarctic sea ice extent is an extremely important feature in southern polar regions (Wadhams, 2009). It is also known as an essential factor in the climate system. Its variability influences global systems, regionally and remotely (Yuan and Martinson, 2000; Zhang, 2007; Liu et al., 2002; Oza et al., 2017), including both the physical and biological systems (Massom and Stammerjohn, 2010). Over the past decade, the interaction between Antarctic sea ice extent and tropical climate had been studied extensively by various researchers. Many previous studies have confirmed the relationship between sea ice variability and atmospheric circulation in the Southern Hemisphere (Simmonds and Budd, 1991; Simmonds and Wu, 1993; Simmonds and Jacka, 1995; Godfred-Spenning and Simmonds, 1996; Simmonds, 2003; Pezza et al., 2008), particularly under the influence of El Niño Southern Oscillation or ENSO (White and Peterson, 1996; Turner, 2004; Schneider et al., 2012). In addition, Antarctic sea ice extent has also been strongly linked to other climate variability indices related to the tropical Indian Ocean Sea Surface Temperature (SST) (Yuan and Martinson, 2000; Rai and Pandey, 2006; Rai et al., 2008) and tropical Pacific precipitation (Yuan and Martinson, 2000) on different timescales. For example, Rai and Pandey (2006) identified that SST over the southeast Indian Ocean has a strong relationship with sea ice variability. In a different study, Liu et al. (2011) revealed that southwestern Indian Ocean SST (50°– 70°E, 10°–25°S) has a possible impact on the interannual sea ice concentration anomalies from 1979 to 2009. Their results demonstrate that sea ice concentration in the Antarctic Peninsula, Ross Sea shelf, and the Indian Ocean sector is mostly affected by changes in the western Indian Ocean SST.

Indian summer monsoon is known as one of the most significant phenomena in the global climate framework. The event usually commences in June and ends in September. The intensities of the rainfall

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https://doi.org/10.1016/j.polar.2020.100537
Received 23 October 2019; Received in revised form 14 May 2020; Accepted 21 May 2020
Available online 21 June 2020

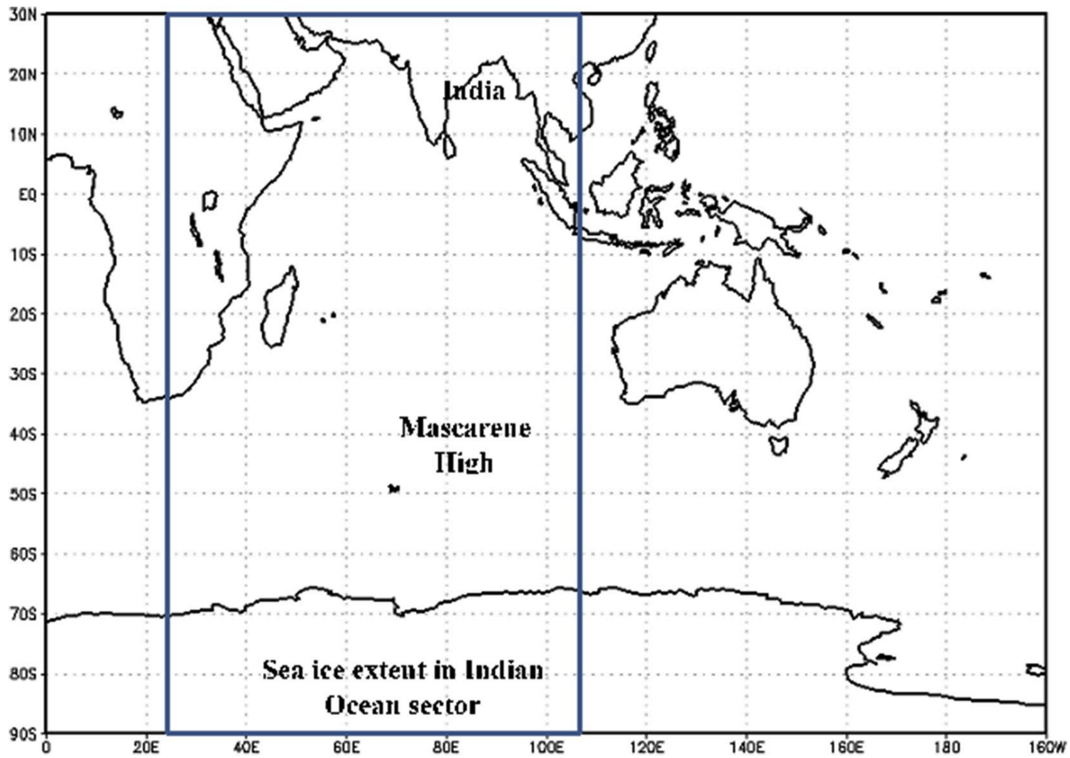

Fig. 1. Area of the study.

have significant environmental and social impacts (Clift and Plumb, 2008). According to Sarthi et al. (2012), this monsoon occurs due to the land sea temperature difference that creates a variation of lower and upper wind circulations over the India regions and the variability of the Indian summer monsoon rainfall is controlled by the Mascarene High (Han et al., 2017). Theoretically, the center of the Mascarene High is located around 30°S and 60°E, near the Mascarene Islands over the southern Indian Ocean (Krishnamurti et al., 2013). However, in several studies the location of Mascarene High has been variously defined. For example, Manatsa et al. (2014) characterized the intensity of the Mascarene High over the region 25°– 35°S, 40°– 105°E based on the maximum isobaric ridge of the climatological mean sea level pressure (MSLP). Ohishi et al. (2015) defined the Mascarene High as a region of high pressure anomaly within 10°– 50°S, 40°– 120°E in austral summer (November to January), while Morioka et al. (2015) defined it to be between 30°– 35°S, 80°– 90°E. However, research related to the Mascarene High variability is still minimal and some researchers have suggested that the Mascarene High intensity is determined by the circumpolar low over higher southern latitudes (Xue et al., 2004).

In previous study, Dugam and Kakade (2004) noted that the sea ice extent over Antarctica was inversely correlated with Indian summer monsoon rainfall during the boreal winter. Prabhu et al. (2009) stated that there was a positive correlation between the sea ice extent and the Indian summer monsoon rainfall: the sea ice extent in the western Pacific Ocean sector had a strong connection with the Indian summer monsoon rainfall during March in the same year. To date, there is no physical explanation behind the relationship between the sea ice extent in the Indian Ocean sector of Antarctica and Indian summer monsoon rainfall and this topic is still in their infancy. Literature regarding the links between Antarctic sea ice and the Asian monsoon, particularly over the India regions, is also limited. Most of the existing literature focus on sea ice and the East Asia monsoon (Xue et al., 2003; Wu et al., 2009; Guo et al., 2014) and also African rainfall (Stuut et al., 2004). However, the physical processes of the teleconnection between the sea ice and the tropics are still not clear (Liu et al., 2011).

In this paper, we investigate the linkage between the interannual variability of sea ice extent in the Indian Ocean sector and the variability of Indian summer monsoon rainfall, that is modulated by the variabilities in the Mascarene High. This study focuses on the sea ice extent in the Indian Ocean sector because this sector experiences the second largest amount of increasing sea ice extent (after the Ross Sea sector) and accumulates 55 $\times$ 10^3 km^2 per decade in all seasons (Turner et al., 2015). However, it should be noted that the trend in the sea ice extent is only significant in the Ross Ice sector (Yuan et al., 2017). Furthermore, this sector is less studied compared to other sectors such as the Ross, the Weddell and Bellingshausen Seas (Comiso et al., 2011; Murphy et al., 2014) and frequently the analysis of the sea ice is on the whole Antarctica (Rai et al., 2008; Prabhu et al., 2009) instead of any specific sector.

This paper is organized as follows. The various forms of data used and the methodology adapted in the study are discussed in Section 2. Sections 3 until 6 provide the characteristics of the sea ice extent in the Indian Ocean sector and Indian rainfall, seasonal correlation between sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall, the influence of sea ice extent on the Mascarene High and also the role of Mascarene High towards Indian summer monsoon rainfall respectively. Section 7 provides the summary of the study.

2. Data and methodology

The monthly sea ice extent data, obtained from satellite passive-microwave data of the Scanning Multichannel Microwave Radiometer and the Special Sensor Microwave Imager, for a 35 year period from January 1979 to December 2013, were used to investigate the variability of sea ice extent. These data are available from the U.S. National Snow and Ice Data Center. In this study we use sea ice extent data over the Indian Ocean sector, located from 20°to 90°E. In addition, monthly mean reanalysis datasets of climate parameters were obtained from the European Centre for Medium-range Weather Forecasting Reanalysis. The period of the data is from January 1979 to December 2013 with a spatial resolution of 0.75° $\times$ 0.75° latitude–longitude grids. The mean sea level pressure (MSLP), geopotential height at 500 hPa, and zonal and

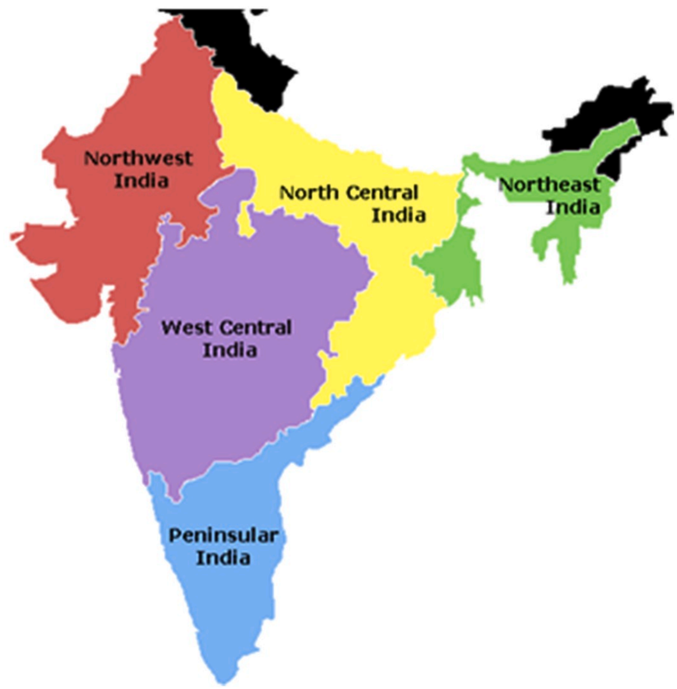

Fig. 2. Sub-regions of India: Northwest (NW), Central north (CN), Northeast (NE), West Central (WC) and Peninsular (Pen). Retrieve from http://www.monsoondata.org/hist/region.html.

meridional winds at 850 hPa were used to examine atmospheric features during the sea ice extent phase. Monthly rainfall for all Indian subcontinent (Al) as well as India sub-regions such as Northwest (NW), Central North (CN), Northeast (NE), West Central (WC), and Peninsular (Pen) India were obtained from the Indian Institute of Tropical Meteorology (definitions of the geographical region of India is shown in Fig. 2). The available rainfall data span from January 1874 to December 2014. To examine the pattern of the Indian summer monsoon rainfall distribution over the India region during the expansion phases of the sea ice extent in the Indian Ocean sector, monthly Global Precipitation Climatology Project data with a spatial resolution of 2.5° × 2.5° latitude–longitude grids were used. These data are from January 1971 to December 2013.

The sea ice extent index in the Indian Ocean sector is defined by the normalized values of the sea ice extent in the Indian Ocean sector. Similar methodology was used for Indian summer monsoon rainfall index. The definition of Temporal Mascarene High (TMH) index will be explained in Section 6. In addition, three-month composite anomalies of sea ice extent in the Indian Ocean sector, which include January-February-March (JFM), February-March-April (FMA), March-April-May (MAM), April-May-June (AMJ), May-June-July (MJJ) and June-

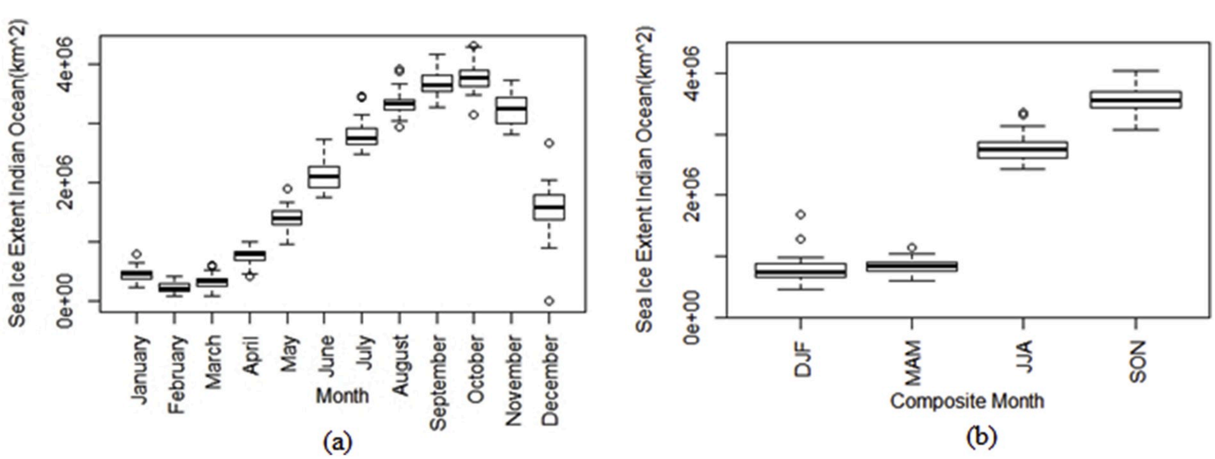

Fig. 3. Boxplot illustrates a) long term monthly average b) composite month (December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON) of the sea ice extent in Indian Ocean sector (km^2) from 1979 to 2013. The thick black line represents the median value and the circles show outliers. The upper and lower whisker line of each boxplot represents the maximum and minimum value of the sea ice extent.

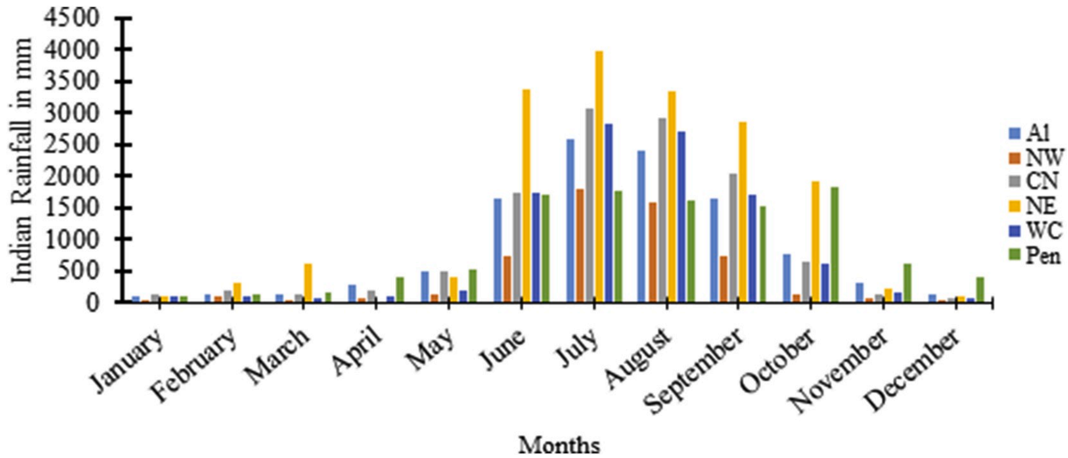

Fig. 4. Interannual variability of Indian rainfall for all India and its sub-regions in mm averaged from 1979 to 2013. All India (Al), Northwest (NW), Central north (CN), Northeast (NE), West central (WC), Peninsular (Pen).

July-August (JJA), were also prepared to investigate the seasonal impacts of sea ice extent on the Indian summer monsoon rainfall. Correlation, partial correlation, composite, and phase analysis were used to analyze and identify the teleconnection between sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall. In this study, the region 35°–47° S, 65°–90° E was selected to represent the Mascarene High region. The map location of the study area is shown in Fig. 1.

3. Characteristic of the sea ice extent in the Indian Ocean sector and Indian rainfall

3.1. Sea ice extent in the Indian Ocean sector

Long term monthly and seasonal sea ice extents in the Indian Ocean sector were analyzed for the period of January 1979 to December 2013. Boxplot in Fig. 3 illustrates long term monthly average and composite month of the sea ice extent in Indian Ocean sector from 1979 to 2013. The thick black line represents the median value and the circles show outliers. The upper and lower whisker lines of each boxplot represent the maximum and minimum value of the sea ice extent, respectively. Fig. 3a illustrates strong monthly variations of the sea ice extent in the Indian Ocean sector with a distinct minimum value in February and maximum in October (Parkinson and Cavalieri, 2012). The sea ice starts to increase from March. Similarly, as evident from Fig. 3b the seasonal cycle of the sea ice extent in Indian Ocean sector for the period 1979–2013, shows the lowest and highest amount of sea ice extent for 35 years are during DJF and SON.

3.2. Indian rainfall

Fig. 4 displays the interannual variability of rainfall over India. The highest contribution of Indian rainfall occurred in June, July, August and September during the Indian summer monsoon period. Each sub-region receives different amount of rainfall during this period. NE India region experiences highest interannual rainfall compared to other sub-regions. This is followed by CN, WC, Pen, and NW. As stated by Parthasarathy et al. (1993), central and northeastern region received more than 80% of yearly amount of rainfall during the summer monsoon event. On the contrary, northwest India only receives 50%–75% of annual monsoon rainfall. This indicates that the intra-seasonal variations of Indian summer monsoon rainfall are large and over the entire India region. Moreover, the position of inter tropical convergence zone (ITCZ) also affects the variabilities of the large-scale rainfall over this region during the summer monsoon (Rajeevan et al., 2012).

Table 1
Correlation coefficient between sea ice extent in the Indian Ocean during different composite month January-February-March (JFM), February-March-April (FMA), March-April-May (MAM), April-May-June (AMJ), May-June-July (MJJ), June-July-August (JJA) and Indian summer monsoon rainfall at different sub-regions of India (All India (Al), Northwest (NW), Central north (CN), Northeast (NE), West central (WC), Peninsular (Pen) India) from 1979 to 2013 (* is statistically significant at $p < 0.05$).

Composite month of sea ice extent in Indian Ocean sector		Indian summer monsoon rainfall at different sub-regions					
		Al	NW	CN	NE	WC	Pen
	JFM	0.02	-0.02	0.23	0.05	-0.09	0.38*
	FMA	-0.2	0.05	-0.39*	-0.17	-0.15	-0.21
	MAM	0	0.1	0.02	-0.34*	0.17	0.07
	AMJ	0.08	0.13	0	-0.03	0.04	0.44*
	MJJ	0.08	0.13	-0.03	-0.11	0.11	0.31
	JJA	0.05	0.11	-0.06	-0.13	0.14	0.21

4. Seasonal correlation between the sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall

In order to investigate the impact of sea ice extent in the Indian Ocean sector on Indian summer monsoon rainfall event, the correlation of both time series at different composite months and sub-regions of India is computed. The period of the analysis consists of 35 years from 1979 to 2013. Table 1 shows the correlation coefficients between the sea ice extent in the Indian Ocean sector during different composite months and Indian summer monsoon rainfall over the various sub-regions of India. From the analysis, it is perceivable that sea ice extent in the Indian Ocean sector during AMJ has the strongest positive correlation with the Indian summer monsoon rainfall over the Peninsular India with a statistically significant correlation coefficient of $r = 0.44$ ($p < 0.05$) (see also Fig. 5). The FMA and MAM composite month of sea ice extent in the Indian Ocean sector correlates negatively with Indian summer monsoon rainfall over the central north and northeast India. It is well-known that the variability of Antarctic sea ice is influenced by the variability of the Southern Annular Mode (SAM), ENSO, and also the Indian Ocean Dipole (Raphael et al., 2011). In a previous study, Turner et al. (2015) revealed that SAM has an important role in sea ice extent variability in the Indian Ocean sector. Therefore, we removed the influence of SAM. Even after removing the SAM influence, the partial correlation is still significant with the value of 0.38 ($p < 0.05$). Similar results were also noted for the ENSO and the Indian Ocean Dipole (not shown), in which both have

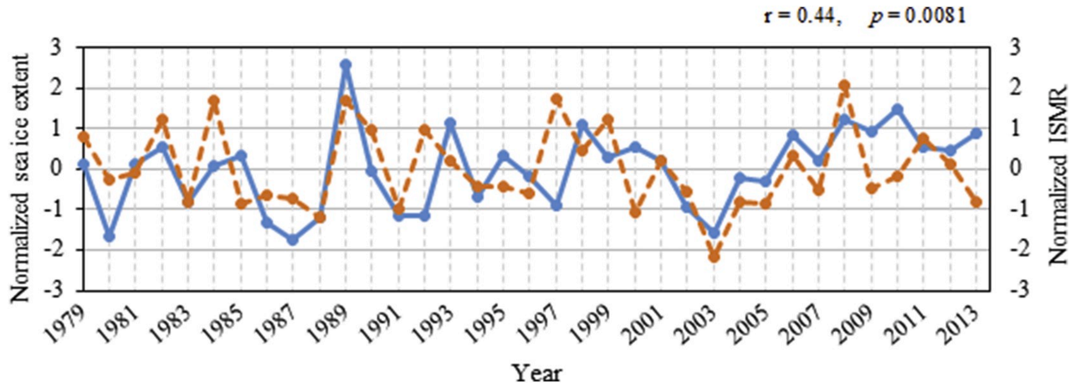

Fig. 5. Correlation between normalized time series of the AMJ sea ice extent in the Indian Ocean sector (blue solid line) and Indian summer monsoon rainfall, ISMR (orange dashed line) over the Peninsular India region from 1979 to 2013, statistically significant at 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

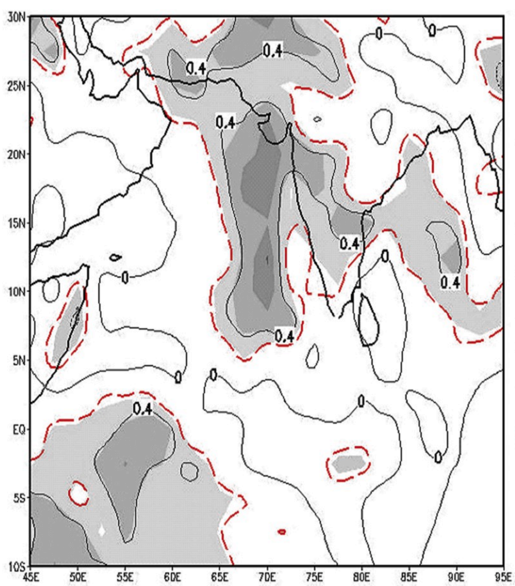

Fig. 6. Correlation between the AMJ sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall over India region from 1979 to 2013. Dashed line in red is statistically significant at 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

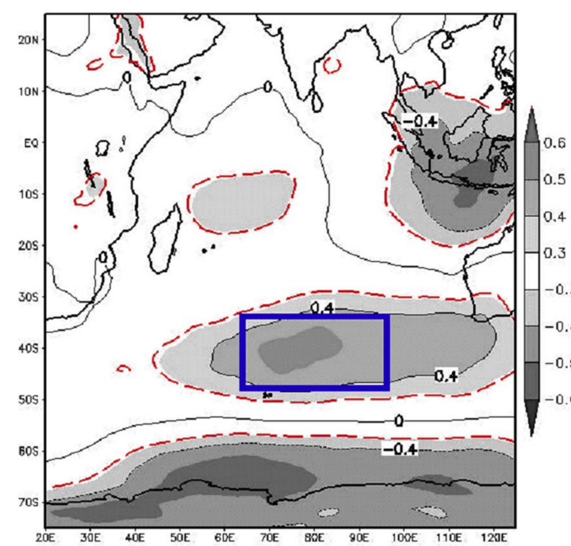

Fig. 7. Spatial correlation between AMJ sea ice extent in the Indian Ocean sector and MJJ MSLP (hPa) from 1979 to 2013. Dashed line in red is statistically significant at 95%. The blue box is defined as Temporal Mascarene High (TMH) area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

insignificant impact towards the variability of the sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall.

The spatial correlation between the AMJ sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall from 1979 to 2013 is further examined to gain a better insight for spatial relation (Fig. 6). Result shows a high positive correlation (shaded regions) over the Peninsular India region, which is consistent with the correlation analysis above. Rainfall over the Indian subcontinent is influenced by complexities associated with geography, topography, and differential land-use pattern. The western, eastern, and southern parts of the subcontinent are surrounded by the Arabian Sea, Bay of Bengal, and the Indian Ocean, respectively and the Himalaya is situated in the northern part. All of these features play a major role in deciding the climate of the India and its sub-regions. Therefore, Indian summer monsoon rainfall has large spatial and temporal variations. During the summer monsoon, west Peninsular region receives higher precipitation because it is located on the windward side of the mountain range of Western Ghats, while northern and central India known as rain-shadow areas receive precipitation less than 500 mm (Kumar et al., 1995; Fukushima et al., 2019). Francis and Gadgil, 2006 also showed that during southwest monsoon period, west coast of Peninsular India receives more rainfall. Overall when the sea ice extent in the Indian Ocean sector increases, the Indian summer monsoon rainfall tends to increase. The high and low sea ice phase years were categorized when the sea ice extent in the Indian Ocean sector index is greater than 1 (less than −1) standard deviation. The high ice phase years (1989, 1993, 1998, 2008, 2009, 2010) and the low ice phase years (1980, 1986, 1987, 1988, 1991, 1992, 2003) are tagged.

5. Composite analysis: influence of the sea ice extent in the Indian Ocean sector on the Mascarene High

The positive relationship between the sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall was also found in an earlier study (Prabhu et al., 2009). To investigate further the influence of the sea ice extent in the Indian Ocean sector on Indian summer monsoon rainfall, the correlations between sea ice extent in the Indian Ocean sector and MSLP from 1979 to 2013 were analyzed. The correlation between the AMJ sea ice extent in the Indian Ocean sector and MSLP during MJJ is highest over the southern Indian Ocean between 30° S and

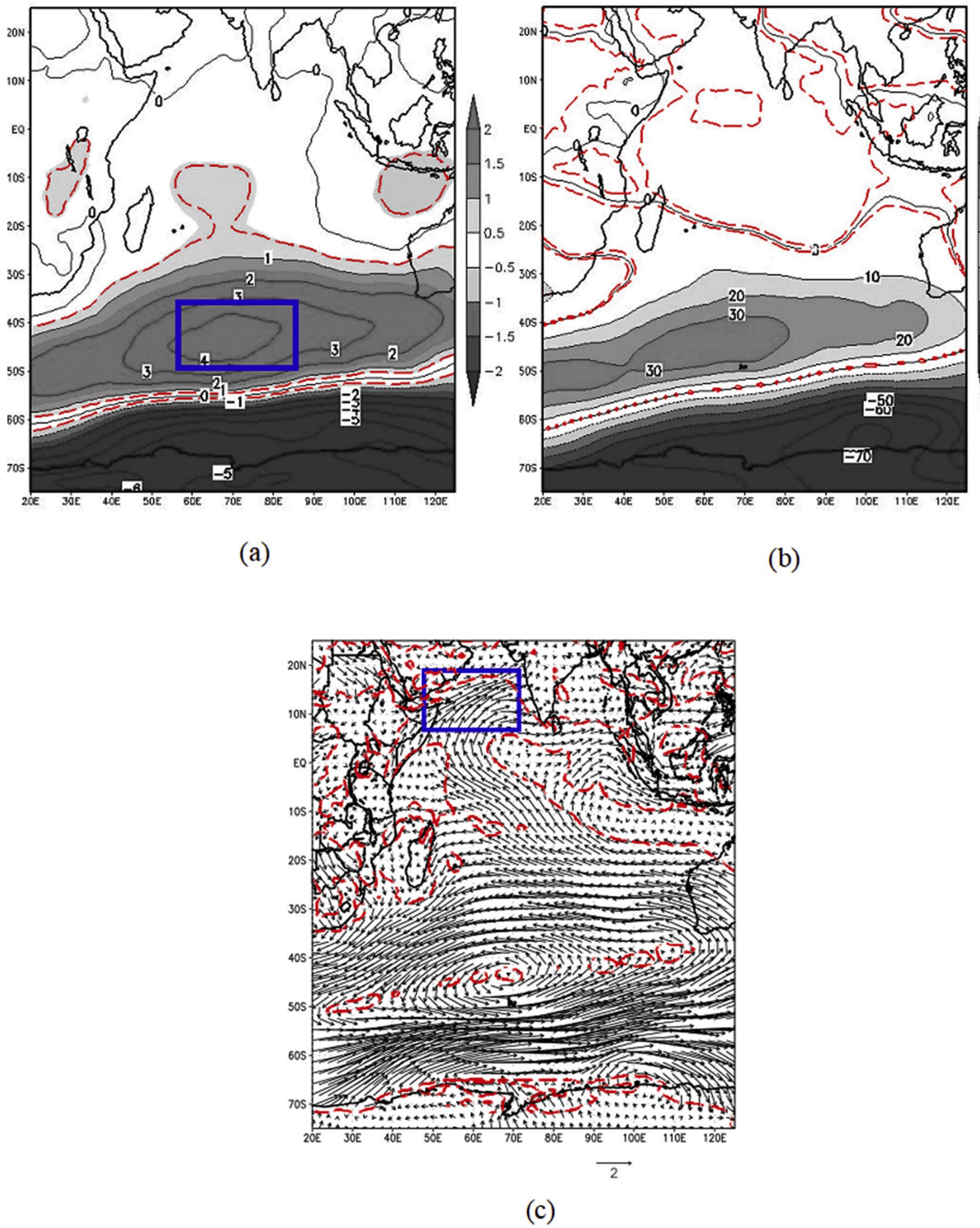

Fig. 8. Composite difference (high ice phase – low ice phase) anomalies of MJJ a) MSLP, *hPa* b) 500 hPa geopotential height, *m* c) wind vector at 850 hPa, ms^{-1}. The blue box: maximum positive MSLP anomaly, the blue box: Area corresponds to Somali jet. Dashed line in red is statistically significant at 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

50° S (Fig. 7). In contrast, negative correlations are found over the Antarctic continent and some part of Southeast Asia.

We further examined the composite difference (high minus low ice phase) of MSLP, 500 hPa geopotential height, and wind vector at 850 hPa anomalies during MJJ months. The composite difference of MSLP anomaly (Fig. 8a) clearly illustrates a positive anomaly between the latitude belt of 35°S to 50°S, while a negative anomaly exists over the Antarctic region. Also, the positive value indicates an intensification of the MSLP over the southern Indian Ocean, inclusive some of the Mascarene High region. However, this inclusive region does not represent the entire Mascarene High system. In addition, the two phases are associated with a longitudinal movement of the Mascarene High. The location of the Mascarene High is located more eastwards from its climatological position during the high ice phase. As proposed by Manatsa et al. (2014), when the location of Mascarene High is anomalously displaced to the east of its normal position, enhanced convection

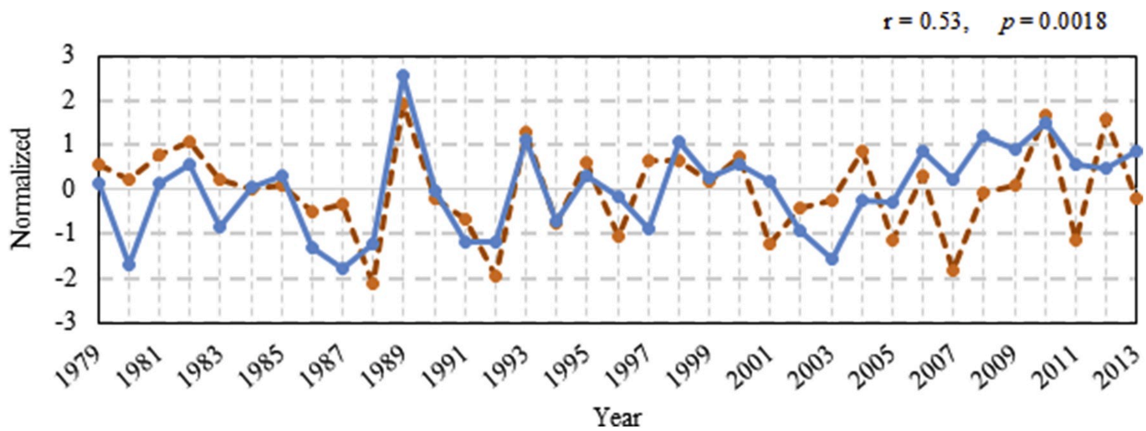

Fig. 9. Correlation between the normalization of AMJ sea ice extent in the Indian Ocean sector (blue solid line) and the Temporal Mascarene High (orange dashed line) from 1979 to 2013, statistically significant at 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

occurs over the western equatorial South Indian Ocean. A similar pattern also appears at 500 hPa geopotential height (Fig. 8b), indicating a barotropic feature. The positive anomaly was observed over the southern Indian Ocean, where the major ridge extended to the east of the southern Indian Ocean, while the negative anomaly was observed over the Antarctic continent. The contour line of the geopotential height anomaly also was much closer to each other, indicating tighter gradient during the high ice phase.

As the MSLP anomaly over the southern Indian Ocean increases, the wind anomaly at 850 hPa shows a very strong anticyclonic anomaly at 30°to 50°S (Fig. 8c). The northern branch of this strong anticyclonic wind anomaly produces a stronger westerly wind as it crosses the equator, enhancing the Somali jet, during the high ice phase years. Lau et al. (2000) and Wang et al. (2001) indicated that Mascarene High over the southern Indian Ocean and the Somali jet are some of the major circulation systems that control the Indian summer monsoon. Lau et al. (2000) showed that the large-scale flow in the low-level interhemispheric gyre circulation (IGC) over the southern Indian Ocean is connected with the Somali jet to the westerlies across the Indian subcontinent. They also stated that major fluctuations of the Asian summer monsoon are controlled by the IGC and western Pacific subtropical high. The intensified Somali jet transports a large amount of water vapor towards western Ghats, resulting in heavy rainfall over the western India region (Shi et al., 2016). This is consistent with the Li and Li (2014) study, where the anticyclonic anomalies at 850 hPa over the Mascarene High, intensified southwesterly near the Somali coast known as Somali jet and intensified Indian summer monsoon. Also, similar statement was given in the study of Xue et al. (2004) and Rao et al. (2017), who showed that with the intensification of Mascarene High, the Somali jet along with the Indian monsoon westerlies is enhanced. Over high latitudes, there is strong westerly wind and out-flow winds from the Indian Ocean sector, which contributes to the expansion of the sea ice (Jena et al., 2018) during the high ice phase years. According to the Stammerjohn et al. (2008), this is also due to the enhanced Ekman drift in the ocean that facilitated northward advection of the sea ice by the strong westerly winds. Therefore, it can be concluded that the sea ice extent in the Indian Ocean sector has an association with the variability of the Mascarene High, with strengthening (weakening) during the high (low) ice phase years, that subsequently influences the speed of the Somali jet.

6. The role of Mascarene High on Indian summer monsoon rainfall

The variability of the Mascarene High plays a key role in determining the intensity of Indian summer monsoon rainfall through a modulation of the strength of the Somali jet, by which the large amount of moisture is transported towards the India region. As is widely known, the Mascarene High is one of the factors that influences the intensity of Indian summer monsoon (Wu et al., 2012; Ahasan et al., 2014). The intensification of the Mascarene High leads to strengthening of the Somali jet and Indian monsoon westerlies (Xue et al., 2004; Li and Li, 2014).

In order to provide a better understanding of role of the Mascarene High in influencing the Indian summer monsoon rainfall, a Temporal Mascarene High (TMH) index was developed. The TMH index is defined by the normalization of MSLP during MJJ over the TMH region (Fig. 7). The TMH region (35°– 47° S, 65°– 90°E) shows the highest value of correlation coefficient. The time series of correlation coefficient between the AMJ sea ice extent in Indian Oceans sector index and TMH index for 35 years was 0.53 with statistically significant $p < 0.05$ (Fig. 9). Based on the correlation coefficient value, the selected TMH region is the best area to represent the Mascarene High region.

The link between the Mascarene High and Indian summer monsoon rainfall has been studied for many decades (Krishnamurti and Bhalme, 1976). The impact of the TMH on the Indian summer monsoon rainfall was examined further using the composite difference of the velocity potential at 850 hPa and 200 hPa (positive TMH minus negative TMH index). The aim of this analysis is to identify the convergence and divergence anomaly patterns over the India region during the strengthening and weakening phases of the Mascarene High which determine the descending and ascending of air. The positive TMH (negative TMH) index years were categorized based on greater than 1 (less than −1) standard deviation. The positive TMH index years were 1982, 1989, 1993, 2010 and 2012 while the negative TMH index years included 1988, 1992, 1996, 2001, 2005, 2007 and 2011.

Fig. 10 illustrates the composite difference of velocity potential and divergence wind at 850 hPa and 200 hPa between positive TMH and negative TMH index years. At 850 hPa (Fig. 10a), a strong convergence occurs over the Arabian Sea and west of Peninsular India. On the other hand, at 200 hPa a strong divergence anomaly appears over almost the same region (Fig. 10b). This vertical motion indicates a strong ascending motion of air, which leads to the development of clouds and heavy rainfall (Dike et al., 2014) over the region. Consistent results appear in the composite anomaly of rainfall (Fig. 11), where positive values of rainfall over the west coast of Peninsular India and Bay of Bengal are shown. This finding is consistent with Saeed et al. (2011) and Sinhaa et al. (2013), who stated that the west coast of Peninsular India receives heavy rainfall during the Indian summer monsoon rainfall event while less rainfall anomaly appears at the east central of the India. As mention above, this is due to the Himalaya mountain that hinders rainfall from reaching the regions and also the region is affected by the northeast monsoon.

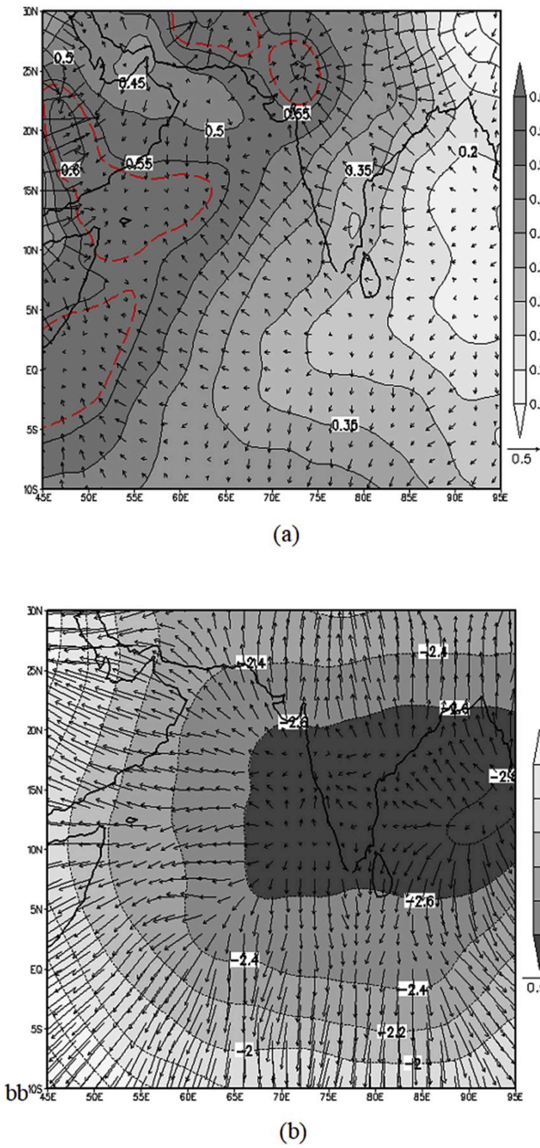

Fig. 10. Composite difference (positive TMH index – negative TMH index) of velocity potential (shaded contour) and divergent wind (vectors) anomalies during Indian summer monsoon rainfall at a) 850 hPa (10^{6} m^2/s) and b) 200 hPa (10^{6} m^2/s). Dashed line in red is statistically significant at 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

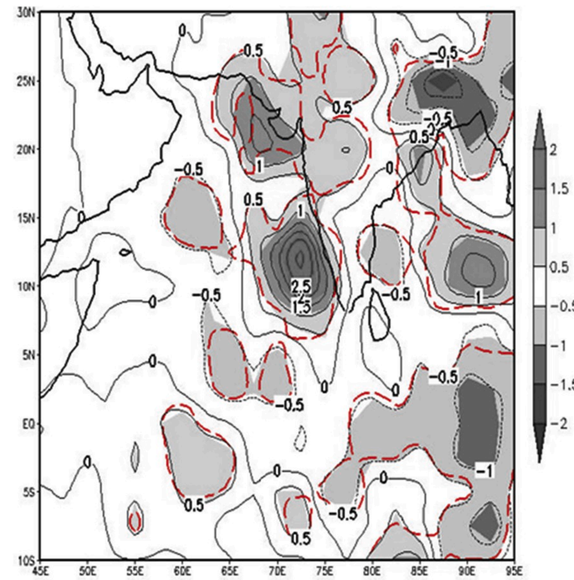

Fig. 11. Composite difference (positive TMH index – negative TMH index) of Indian summer monsoon rainfall anomaly (mm/year). Dashed line in red is statistically significant at 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

7. Summary and discussion

The linkage between interannual variability of sea ice extent, particularly over the Indian Ocean sector, and Indian summer monsoon rainfall is examined in this study for the period 1979–2013. The correlation analysis shows that AMJ sea ice extent in the Indian Oceans sector is significantly positively correlated with the Indian summer monsoon rainfall over Peninsular India with correlation coefficient, $r = 0.44$ (statistically significant $p < 0.05$) for 35 years. Consistent with the spatial correlation analysis, the high positive correlation is also shown over the west Peninsular India region.

The linkage on how sea ice extent in the Indian Ocean sector influences the Mascarene High is further analyzed using the composite analysis of the climate parameters. The composite anomaly of MSLP shows that there is a strengthening (weakening) of pressure in the Mascarene High region during the high (low) ice phase years. In addition, the center of the Mascarene High is also shifted eastwards (westwards) from its climatology position during the high (low) ice phase years. Similar features were found at 500 hPa geopotential height anomaly. In the lower troposphere (850 hPa), a very strong anticyclonic (cyclonic) anomaly appears over the Mascarene High region during the high (low) ice phase years. The possible reason for this positive connection between sea ice in the Indian Ocean sector and Mascarene High is due to the change of the circulation variabilities that occur at upper and lower levels during the high and low ice phases. According to Parise et al. (2015), there is a poleward shift and strengthening of the polar jet, as well as northward expansion and weakening of subtropical jet at the upper level during the increase of the sea ice. Meanwhile, at the lower level, decrease and increase of MSLP over the high and mid latitudes are found. Consistent with Smith et al. (2017) and Bader et al., 2013 studies, who stated that there is a poleward shift of Southern Hemisphere mid-latitude tropospheric jet in response to increased Antarctic sea ice extent and an equatorward shift of the jet during the occurrence of less ice.

The highest positive correlation between the AMJ sea ice extent in the Indian Ocean sector and MJJ MSLP was used to define the TMH domain (35°– 47° S, 65°–90°E). The correlation coefficient between the AMJ sea ice extent in the Indian Ocean sector index and TMH index for 35 years is 0.53 with statistically significant $p < 0.05$. The positive TMH index or strengthening of TMH years shows a strong convergence (divergence) anomaly at 850 hPa (200 hPa) over the Arabian Sea, west Peninsular India, and also south west of Australia. As a result, higher rainfall occurs over west of India. Opposite feature is found for the negative TMH index or weakening of the TMH years, when strong divergence (convergence) anomaly covers almost entire the India region at 850 hPa (200 hPa). This leads to clear skies and dry weather.

As a conclusion, during the high ice phase, the Mascarene High is intensified, and strong anticyclone winds appears over the region. Thus, enhanced south westerlies lead to more clouds and rainfall over the west coast of Peninsular India region during the Indian summer monsoon. While during the low ice phase years, the Mascarene High is weakening and the opposite features appear, in which the air descends from the troposphere to the surface, causing dry weather in central India and the surrounding areas. A schematic diagram of the proposed mechanism is shown in Fig. 12. The teleconnection from the Antarctic sea ice extent may not be limited to the tropics; it may extend beyond to other parts of

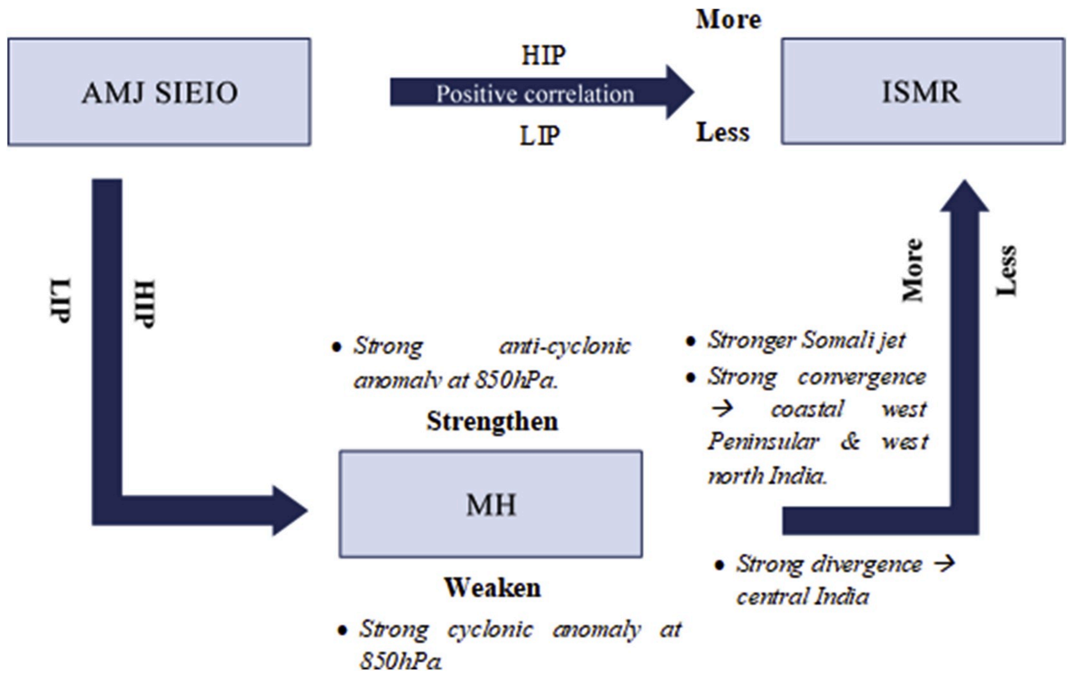

Fig. 12. Schematic diagram of the proposed teleconnection (SIEIO: sea ice extent in the Indian Ocean sector, HIP: high ice phase, LIP: low ice phase, MH: Mascarene High, ISMR: Indian summer monsoon rainfall).

the Northern Hemisphere. This study clearly indicates that there is a strong connection between the sea ice extent in the Indian Ocean sector and Indian summer monsoon rainfall via modulating the Mascarene High. In order to identify the factor or to understand more about the mechanism, especially in terms of dynamics, the interaction of the atmosphere and ocean component should be taken into account. Therefore, simulation using climate models will be performed in future work.

Acknowledgments

This study is funded by the Ministry of Sciences Technology and Innovation Flagship Grant: FP1213E037. It is also strongly supported by the Academic Sciences of Malaysia, Sultan Mizan Antarctic Research Foundation, Malaysian Antarctic Research Program and the Vice Chancellor of the University Malaya. Fundamental Research Grant Scheme (FRGS) FP059-2019A and FIO-UM Joint Center of Marine Science and Technology Fund are also acknowledged. Seong-Joong Kim is supported by the Korean Polar Research Institute (KOPRI) project (PE20070). We would like to thank Muhammad Yunus bin Ahmad Mazuki from National Antarctic Research Center in helping us to improve the quality of the figures in the reviewed manuscript during the movement control order in Malaysia due to the covid-19 global pandemic.

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