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What caused the interdecadal shift of the ENSO impact on dust mass concentration over northwestern South Asia?

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Abstract. The change of large-scale circulation, especially El Niño-Southern Oscillation (ENSO), play an important role in the interdecadal variability of dust activities over the dust source and downwind regions. However, the detailed factors that lead to the interdecadal variability of the ENSO impact on dust activities over the northwestern South Asia remain less clear, although previous studies have discussed the response of the interannual dust activities over the northwestern South Asia to the ENSO circle. Based on the linear regression model and MERRA-2 atmospheric aerosol reanalysis data, this study investigated the interdecadal variability of the ENSO impact on dust activities as well as the associated possible atmospheric drivers under two different warming phases over the northwestern South Asia. Results indicated that the relationship between ENSO and surface dust mass concentration (DUSMASS) experienced an obvious shift from the accelerated global warming period (1982–1996) to the warming hiatus period (2000–2014). The change of Atlantic SSTA pattern weakened the impact of ENSO on dust activities over the northwestern South Asia, while that of Indian Ocean SSTA pattern and PDO tended to strengthen ENSO's effect. Both the Atlantic and Indian Ocean SSTA patterns were modulated by the duration of ENSO events (i.e., continuing and emerging ENSO). The Eurasian continent and Indian Ocean thermal contrast was less likely to cause the shift of ENSO–DUSMASS relationship. This study provides new sights to numerical simulation involving the influence of atmospheric teleconnections on the variability of dust activities and their influence mechanisms.

Keywords: Surface dust mass concentration; ENSO–DUSMASS relationship; interdecadal change; large-scale atmospheric circulation; northwestern South Asia

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1 Introduction

Dust aerosol is attracting an increasing concern due to its adverse impacts on human health (Bozlaker et al., 2013; Chen et al., 2004; Erel et al., 2006; Kaiser and Granmar, 2005; Poulsen et al., 1995; Sanchez de la Campa et al., 2013; Schulz et al., 2012) and environmental problems (Avila, 1998; Behrooz et al., 2017; Razakov and Kosnazarov, 1996). The Northwest Indian subcontinent, which is the most arid and semiarid area of South Asia, suffers heavy and frequent dust storms in summer due to extremely dry climate and strong winds (Jin and Wang, 2018). Those dust storms can travel long-distance to North India and the Arabian Sea, degrading air quality (Mahowald et al., 2010) and modifying ocean biogeochemistry processes (Richon et al., 2018; Singh et al., 2008). Particularly, dust aerosols can change local radiation budget, circulations, and Indian summer monsoon rainfall through absorption and scattering of solar radiation. The mineral dust over the northwestern South Asia is closely associated with the long-term variation of global climate (Banerjee et al., 2019; Bollasina et al., 2011; Jin et al., 2018). To better understand such feedback, and so that to give early warning to reduce disasters and losses caused by dust events, it is important to find out the controlling factors of the surface dust mass concentration (DUSMASS) and its long-term variation.

ENSO, as a periodic fluctuation in sea surface temperature (SST) and the air pressure across the equatorial Pacific Ocean, is as the primary large-scale driver of dust loading over the global dust source region (Trenberth et al., 2014). The Niño index significantly impacts the dust activity over the South Asia either indirectly through dust transport from Southwest Asia and/or directly through precipitation effect on dust emission (Banerjee et al., 2019; Bollasina et al., 2011; Jin et al., 2018).

An interdecadal climate regime shift was observed in the large-scale boreal winter circulation pattern over the North Pacific in the mid-1970s (Graham, 1994; Nitta and Yamada, 1989; Trenberth and Hurrell, 1994). Another remarkable climate change was observed in the early 21st century, i.e., an accelerated global warming prevailed before late 1990s and a warming hiatus dominated after that (Easterling and Wehner, 2009; Fyfe et al., 2011, 2013). After 2013, the global warming came to an end due to a persistent warm condition over the equatorial Pacific between Mar. 2014 and May 2016 (Hu and Fedorov, 2017). Concurrent with the Pacific climate shift, the large-scale circulation pattern and their atmospheric teleconnection also exhibit interdecadal change. Statistically 1980–1999 was characterized by a predominance of eastern equatorial Pacific (EP) and continuing (CT) El Niño event (McPhaden et

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al., 2011; Yang and Huang, 2021), while the central equatorial Pacific (CP) and emerging (EM) El Niño became more frequent since the beginning of the 21st century (Yang and Huang, 2021). The tropical Pacific and Indian Ocean SST showed a rapid shift from a cold to warm state around the late 1970s. This climate regime shift altered the links of ENSO with Indian summer monsoon rainfall (ISMR) (Kumar et al., 1999). The changes of the teleconnection relationship at the turning point of mid-1970s have been well documented, while that occurred around the early 21st century, particularly the effect of ENSO on DUSMASS over the northwestern South Asia, is insufficiently analyzed.

The impact of ENSO on DUSMASS over the northwestern South Asia experiences interdecadal shift. In the context of global warming (Deser et al., 2017; Kosaka and Xie, 2016), the relationship between El Niño and monsoon experiences interdecadal change. The correlation between El Niño and rainfall over India turned to be insignificant from the late 1970s, simultaneously, the relationship between ENSO and monsoon also weakened around this turning point (Kumar et al., 1999). Two influence mechanisms are proposed to explain this weakened ENSO–monsoon relationship. One is the varied location of Walker circulation that adjusts the monsoon rainfall over Indian region, the other is the temperature change over Eurasia that modulates the land-sea thermal gradient. Besides, the impact of Atlantic Ocean pattern on the monsoon circulation over the Indian Ocean became stronger since late 1970s as the influence of the tropical Pacific has reduced (Kucharski et al., 2007; Sabeerali et al., 2019; Srivastava et al., 2019). This in-turn impacts the circulation responsible for dust uplift and transport. Several studies show that the dust activities over the northwest Indian Ocean were also affected by the Indian Ocean dipole, which modulated the ENSO-related moisture (Banerjee and Kumar, 2016). However, Agrawal et al. (2017) indicated that whenever the relationship of ISMR with IOD is weaker (stronger), it becomes stronger (weaker) with the ENSO index. The two types of ENSO are also found to differ in their links with ISMR, i.e., the central equatorial Pacific El Niño (CP El Niño) shows higher correlation with Indian droughts than the eastern equatorial Pacific El Niño (EP El Niño) (Kumar et al., 2006). In addition, the Pacific Decadal Oscillation (PDO) is reported to amplify the effect of ENSO when it is in phase with ENSO (Roy et al., 2003).

In short, ENSO primarily influences the DUSMASS over the northwestern South Asia by impacting the winter precipitation and the subsequent soil moisture, but the effects of ENSO on ISMR experienced remarkable interdecadal change and many factors may cause this transition. Till now, however, the interdecadal variability in the links of DUSMASS over the northwestern South Asia with ENSO has not

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been investigated in detail compared to the North African and West Asian counterpart (Yu et al., 2015). In addition, though many factors were proved to influence the short-term (e.g., interannual scale) variation of the relationship between ENSO and dust activities over South Asia, their effects on the long-term (e.g., interdecadal scale) change were still unclear. Cai et al. (2014) pointed out that global warming will have a significant impact on ENSO. The extreme El Niño events will become more frequent under the changes of atmospheric convention in the next half of the 21st century. Thus, understanding the physical mechanism of the shift of the ENSO–DUSMASS relationship is of profound implications for the forecast of dust trend in the future climate change scenario.

Many of the past researches on dust events were based on the aerosol optical depth (AOD) data provided either by observational data at meteorological stations, which are sparsely distributed in the key dust sources, or by satellite remote sensing with limited coverage and bias caused by cloud contamination and uncertainty in retrieval algorithms, respectively (Zhang and Reid, 2009). Due to these limitations, some of conclusions on the effect of ENSO events on dust activities remained contradictory. The current study used the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) (Gelaro et al., 2017) atmospheric aerosol reanalysis data. The MERRA-2 can provide high-quality dust aerosol variables related to emission, transport, and deposition process benefiting from the integrated multiple satellite systems and ground-based AERONET (Randles et al., 2017). Another advantage of MERRA-2 is its continuity in both temporal and spatial coverage (Gelaro et al., 2017). Those are of great significance to explore the interactions between DUSMASS and large-scale atmospheric circulation.

This study aims to investigate the large-scale atmospheric factors that contribute to the interdecadal variability of the ENSO impact on DUSMASS over the northwestern South Asia. The paper is organized as follows. Section 2 describes the datasets and methods. Section 3 presents factors that influence the interdecadal change of the relationship between DUSMASS and wintertime Niño-3 index. Section 4 discusses the deficiency and prospect of this study. The conclusions are given in Sect. 5.

2 Data and methods

2.1 Study area

The main dust source over South Asia is a large arid region in the northwestern part of the Indian

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subcontinent, which stretches from India to Pakistan. Most of the dust aerosols over this region come from the Thar desert. The southeastern part of the Thar desert lies between the Aravalli Hills. The desert extends to the Punjab Plain in the north and northeast, to the alluvial plains of the Indus River in the west and northwest, and to the Great Rann of Kutch along the western coast. The desert presents an undulating surface, with high and low sand dunes separated by sandy plains and low barren hills. The soils are mainly consisted by desert soils, red desertic soils, sierozems, the red and yellow soils of the foothills, the saline soils of the depressions, and the lithosols (shallow weathered soils) and regosols (soft loose soils) found in the hills. The subtropical desert climate here results from persistent high pressure and subsidence. The prevailing southwest monsoon winds from Indian Ocean that bring rain to much of the Indian subcontinent in summer tend to bypass the Thar to the east. The soils are generally infertile and overblown with sand due to severe wind erosion (Augustyn et al., 2019). The amount of annual rainfall in the desert is low, ranging from about 100 mm or less in the west to about 500 mm in the east. Almost 90 % of the annual rainfall occurs in the season southwest monsoon, from July to September. While the prevailing wind is dry northeast monsoon during other seasons. Dust storms and dust-raising winds are common from May to July (Chauhan, 2003). Thus, the DUSMASS used in this study is averaged from June to July and May is neglected to weaken the disturbance of seasonal climatological differences. Analysis is carried out over the dust source in the northwestern South Asia (65°–82° E, 24°–32° N in Fig. 1). All variables involving spatial average are taken from this region unless stated otherwise.

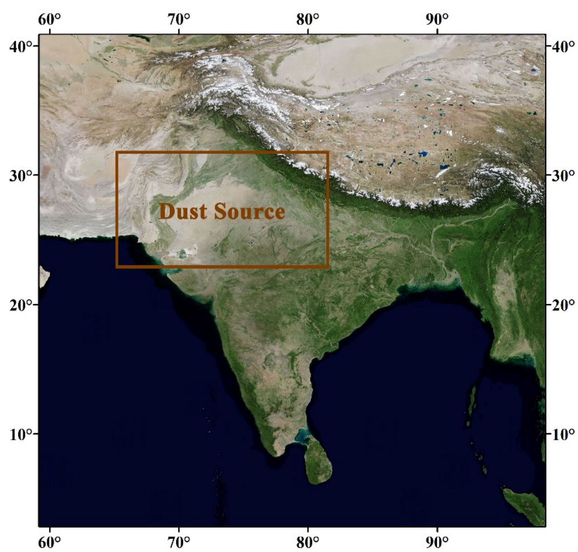

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Figure 1: Geographical map of South Asia (© Google Maps 2021). The dust source over the northwestern South Asia is marked with brown rectangle.

2.2 Datasets

2.2.1 Dust concentration

Surface dust concentrations from 1982 to 2014 were provided by Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). MERRA-2 is produced via the Goddard Earth Observing System-Data Assimilation System (GEOS-DAS, version 5.12.4) based on GEOS-5 climate model and the Gridpoint Statistical Interpolation (GSI) analysis scheme (Gelaro et al., 2017). Extensive satellite data are integrated into MERRA-2 to estimate dust concentration (Rienecker et al., 2011; Veselovskii et al., 2018). The dust products were comprehensively validated using the results of ground-based observation, satellite measurements, and numerical simulation (Rienecker et al., 2011). They have been widely applied to researches on global environment and climate change (He et al., 2019; Randles et al., 2017). The variable "Dust Surface Mass Concentration" (DUSMASS) with a spatial resolution of 0.625°×0.5° (longitude×latitude) used in this study is from the dataset of "tavgM_2d_aer_Nx".

2.2.2 Land and sea surface temperature

To explore the possible influence of SST variability on the South Asian dust activity, we used three SST datasets from 1981 to 2014: (1) The National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) version 5 (Huang et al., 2017) that is available at 2°×2° spatial resolution is used for analysis, (2) Centennial in situ Observation-Based Estimates (COBE) version 2 SST data at 1°×1° spatial resolution (Hirahara et al., 2014) and (3) Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1.1) dataset produced by the Met Office, starting from 1870 up to the present with a horizontal resolution of 1°×1° (Rayner et al., 2003) are used for comparison. While the land-sea thermal contrast was calculated from the Hadley Centre Climate Research Unit Temperature version 5.0.1.0 (HadCRUT5) data from 1981 to 2014, which are a blend of the Climatic Research Unit land-surface air temperature dataset (CRUTEM5) and the Hadley Centre sea-surface temperature (HadSST4) dataset (Osborn et al., 2021). The longitude and latitude of SST index involved in this study were shown in Table 1.

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Table 1: Longitude and latitude of SST index used in this study.

Acronyms	Full Name	Longitude and Latitude	Involved Ocean
Niño-3	——	150°–90° W, 5° S–5° N	Pacific
Niño-3.4	——	170°–120° W, 5° S–5° N	Pacific
Niño-4	——	160° E–150° W, 5° S–5° N	Pacific
ASGI	Atlantic SSTA gradient index	North: 60°–30° W, 0–20° N South: 20° W–10° E, 0–20° S	Atlantic Ocean
TWISSTA	Tropical western Indian ocean SSTA	50°–70° E, 10° S–15° N	Indian Ocean
PDO	Pacific decadal oscillation	117.5° E–77° W, 20°–66.5° N	Pacific

2.2.3 Large-scale climate indices

Three monthly Niño indices Niño-3, Niño-3.4, and Niño-4 from 1981 to 2014, which monitor the SST anomalies averaged across the eastern equatorial Pacific, Pacific from dateline to the South American coast, and central equatorial Pacific, respectively, were used to analyze their links with DUSMASS over the northwestern South Asia. Kinter et al. (2002) pointed out that Nov.–Jan. is the peak season for El Niño/La Niña, thus the average Niño index from (–1) Nov. to (0) Jan. was used. Only one Niño index that shows the highest correlation coefficient was retained in this study, i.e., Niño-3. The large-scale climate indices, such as PDO, was also used to explore the potential factors that contributed to the interdecadal shift of ENSO–DUSMASS relationship. All those indices were from the Climate Predict Center of National Oceanic and Atmospheric Administration (NOAA/CPC).

2.3 Method

In this study, we compared the impact of ENSO on DUSMASS over the northwestern South Asia under two different warming epochs, and investigate the potential global change drivers to the shift of ENSO–DUSMASS relationship. The global warming is separated into the accelerated warming period from 1982 to 1996 and the warming hiatus period from 2000 to 2014. The year 2014 was added to the warming hiatus period to keep the length of those two periods consistent. This classification is not controversial since the ENSO year stated in this study spanned from antecedent November to current

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January.

2.3.1 Contribution of factors to relationship

The contribution of Z (Indian Ocean SSTA variance, Atlantic SSTA gradient index, or Eurasian continent and Indian Ocean thermal contrast) modifying ENSO–DUSMASS relationship was defined as: sliding regression of Z onto Niño-3 index multiplies by sliding regression of DUSMASS onto Z with Niño-3 removed (Yang and Huang, 2021).

2.3.2 Signal removal method

The residual time series based on the linear regression method were used to remove the ENSO signal in the oceanic SSTA pattern, (Yang and Huang, 2021), as shown in Eq. (1):

$$\xi_{remove} = \xi - Z \times \frac{cov(\xi, Z)}{var(Z)} \tag{1}$$

Where ξ and Z is the time series of oceanic SSTA (such as Atlantic and Indian Ocean) and ENSO, respectively, cov indicated the covariance between two variables, and var indicates the variance of ENSO.

2.3.3 Coupled spatial pattern analysis

The maximum covariance analysis (MCA) is a useful tool for isolating the most coherent pairs of spatial patterns and their associated time series by performing an eigenanalysis on the temporal covariance matrix between two geophysical fields (Storch and Zwiers, 1999). The MCA method was used to analyze the coupled patterns between DUSMASS and oceanic SSTA.

2.3.4 Definition of different types of ENSO

Following Yeh et al. (2009), an El Niño event is defined as CP El Niño if Niño-4 > Niño-3 and Niño-3.4 > 0.5°C, and as EP El Niño if Niño-4 < Niño-3 and Niño-3.4 > 0.5°C. Similarly, a La Niña event is referred to as CP La Niña if Niño-4 < Niño-3 and Niño-3.4 < –0.5°C, and as EP La Niña if Niño-4 > Niño-3 and Niño-3.4 < –0.5°C. According to this method, the CP El Niño years during 1982–2014 include 1988, 1991, 1995, 2003, 2005, 2007, and 2010; CP La Niña years include 1984, 1989, 1999, 2001, 2011, and 2012; EP El Niño years include 1983, 1987, 1992, and 1998; EP La Niña years include 1985, 1996, 2000, and 2008.

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Following Yang and Huang (2021), the EM and CT ENSO were defined based on the Niño-3 index. For CT ENSO, the Niño-3 index follows the rule of $[[(-1)\text{Oct.}–(0)\text{Jan.}]_{mean}>0.5\ (<–0.5)\text{STD}\ \&\ [(0)\text{Mar.}–(0)\text{May}]>0.5\ (<–0.5)\text{STD}\ \&\ [(0)\text{Jun.}–(0)\text{Sep.}]>0\ (<0)]$ or $[[(-1)\text{Oct.}–(0)\text{May}]>0.75\ (<–0.75)\text{STD}\ \&\ [(0)\text{Jun.}–(0)\text{Sep.}]_{mean}>0.5\ (<–0.5)\text{STD}]$. To acquire more available samples in the study period, all the ENSO years that were not defined as CT ENSO were identified as EM ENSO year in this study, which was different from Yang and Huang (2021). Based on this definition, the CT El Niño years during 1982–2014 include 1982, 1983 and 1987; CT La Niña years include 1984, 1985, 1989, 1996, 1999, 2000, and 2011; EM El Niño years include 1995, 1998, 2003, 2005, 2007, and 2010; EM La Niña years include 2008 and 2012.

The effect of ENSO type on the correlation between ENSO and DUSMASS was partly analyzed through the duration and intensity of Indian Ocean SSTA following the ENSO events. We calculated the correlation between the variance of monthly Indian Ocean SSTA from (–1) Sep. to (0) May and DUSMASS. It is found that the maximum correlation between the Indian Ocean SST and Niño-3 SST occurs in the central Indian Ocean rather than in the Arabian Sea SST (Clark et al., 2000). Therefore, the variance of monthly Indian Ocean SSTA was calculated over the central Indian Ocean (tropical western Indian ocean, TWISSTA) (50–70° E, 10° S–15° N). The EP ENSO tends to onset in spring (Mar.–May) and reaches the mature phase in winter, then decays near Apr. of the second year. Whereas the onset of CP ENSO appears in summer and reaches the peak around Dec. –Jan., then decays in early spring of the second year (Kao and Yu, 2009). Consequently, monthly Indian Ocean SSTA was taken from (–1) Sep. to (0) May.

In this study, "(0) month" represents the year concurrent with the year when DUSMASS is acquired and "(–1) month" represents the preceding year.

3 Results

3.1 Observed interdecadal change of the impact of Niño-3 index on DUSMASS

In the present study, we found that the ENSO–DUSMASS relationship experienced an interdecadal transition at around 1999/2000. Based on the 15-year sliding correlation from 1982 to 2014 (Fig. 3 (b)), the ENSO–DUSMASS relationship was weak before the end of 1990s and became stronger after that. Specifically, the winter Niño-3 index ((–1) Nov.–(0) Jan.) presented a weakly negative relation with

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DUSMASS during the accelerated warming period (1982–1996), while exhibited a significant negative correlation ($P < 0.01$) during the warming hiatus stage (2000–2014). The varied correlation was not influenced by the lengthen of sliding windows or the type of Niño index, and was confirmed by multiple datasets of SST (not shown).

3.2 Factors influencing the interdecadal change of the impact of Niño-3 index on DUSMASS

3.2.1 Tropical Atlantic SSTA pattern

With the global climate change observed in early 2000s, the ENSO-related tropical Atlantic SSTA experienced an obvious transition, i.e., from an Atlantic Niña pattern during 1982–1996 to an Atlantic Niño pattern during 2000–2014 (Fig. 2), which is also reported by Yang and Huang (2021). The tropical Atlantic SSTA pattern was a crucial factor for the restoration of ENSO–ISMR relationship since the late 1990s (Yang and Huang, 2021), thus, it could also disturb the impact of ENSO on dust activities over the northwestern South Asia. In order to validate the connection between the Atlantic SSTA and the DUSMASS–Niño-3 relationship, an Atlantic SSTA gradient index (ASGI) was used to describe the SSTA pattern shift in the tropical Atlantic, which represented the difference of averaged SSTA between tropical North Atlantic and tropical South Atlantic (marked by two rectangles in Fig. 2). The Atlantic Niña pattern develops and is most sensitive to ENSO in spring (Tokinaga et al., 2019), thus the SST averaged from Mar. to May was used in this section.

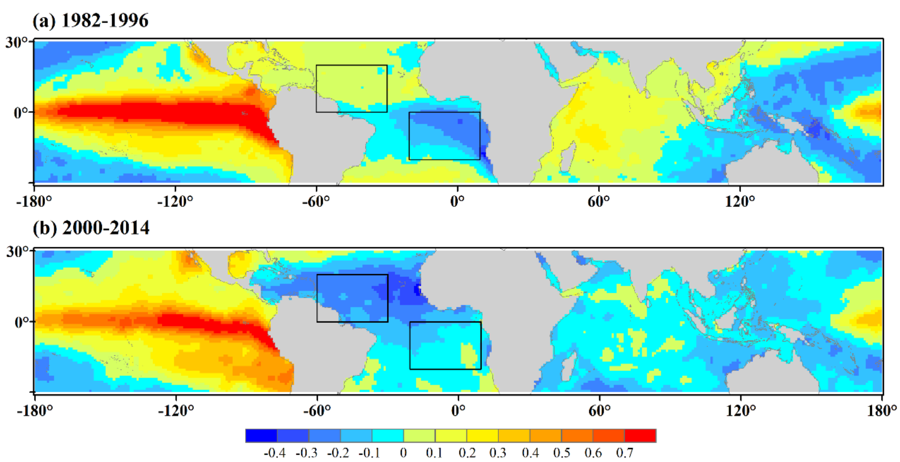

Figure 2: Regression of tropical SSTA onto Niño-3 index. Black rectangles denote the regions to define ASGI. The range of the upper one is 60–30° W, 0–20° N and that of the lower one is 20° W–10° E, 20–0° S. (Similar with Fig. 2 (c)–(d) of Yang and Huang (2021) but with different time spans)

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Based on the 15-year sliding correlation during 1982–2014 (Fig. 3), the relationship between Niño-3 and ASGI witnessed a reversal at the early 2000s, simultaneously, the correlation between Niño-3 and DUSMASS exhibited the similar change. However, the significance of correlation between Niño-3 and DUSMASS in the two warming phases (1982–1996 and 2000–2014) was opposite to that between Niño-3 and ASGI, i.e., the correlation between Niño-3 and ASGI passed the 99 % confidence level during 1982–1996 and it did not pass the 95 % confidence level during 2000–2014, while the correlation between Niño-3 and DUSMASS showed a contrary trend with a higher correlation coefficient appeared in 2000–2014. Additionally, Figure 4 proved that during 1982–1996, ASGI weakened the DUSMASS–Niño-3 relationship while the contribution of ASGI was close to 0.0 during 2000–2014. All these clarified that the weakening of the influence of ASGI on Niño-3 index promoted the effect of Niño-3 index on DUSMASS.

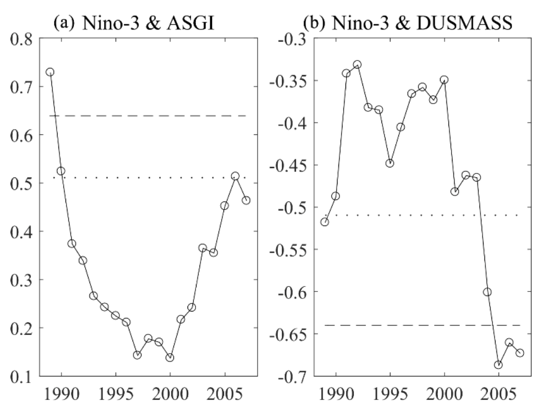

Figure 3: The 15-year sliding correlation between (a) Niño-3 and Atlantic SSTA gradient index (ASGI), (b) Niño-3 index and DUSMASS during 1982–2014. The x-axis denotes the middle year of the period under analysis. The horizontal dashed line and dotted line indicate the 99% and 95 % confidence levels respectively.

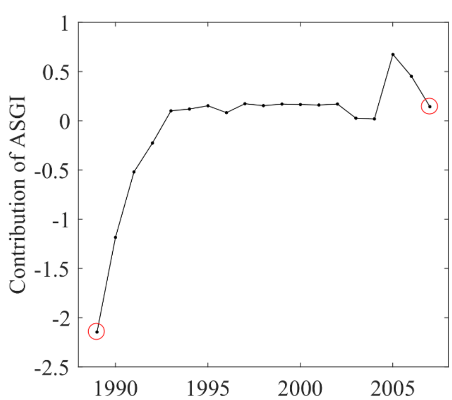

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Figure 4: Sliding contribution of Atlantic SSTA gradient index (ASGI) to ENSO–DUSMASS relationship. The two circles represented the 15-year window spanning from 1982 to 1996 and 2000 to 2014, respectively. The x-axis denotes the middle year of the period under analysis.

To illustrate the spatial coupling pattern of Atlantic SSTA and DUSMASS, the MCA method was utilized. Figures. 5 (a)–(b) showed the correlation between DUSMASS and tropical Atlantic SSTA of the first MCA mode with ENSO-related signals removed. It is clear that the DUSMASS presented remarkable decrease over northern and northwestern India, meanwhile, the tropical Atlantic SSTA displayed an apparent dipole pattern with negative in the south and positive in the north.

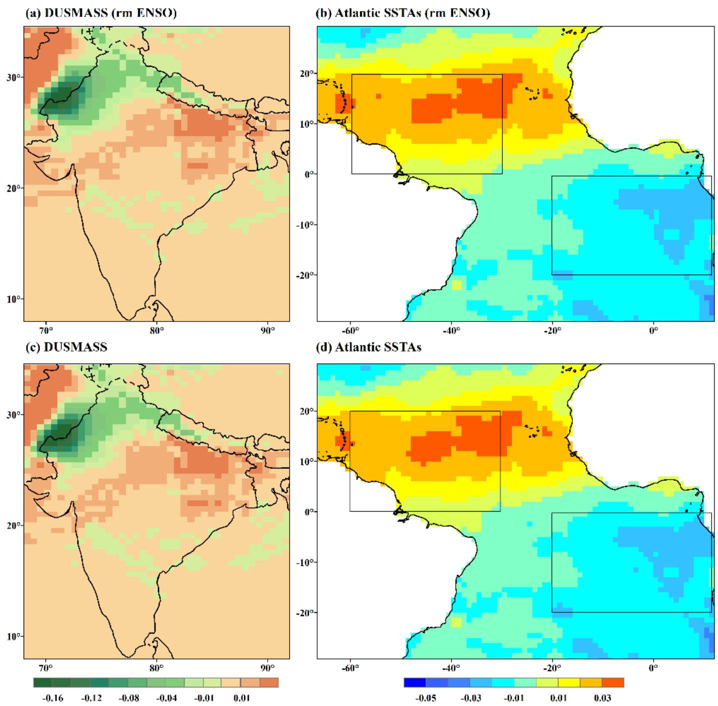

Figure 5: Spatial correlation between tropical Atlantic SSTA and DUSMASS of the first mode of the MCA analysis in 1982–2014. The first MCA mode of (a) the DUSMASS, and (b) the tropical Atlantic SSTA with ENSO-related signals removed. (c)–(d) As in (a)–(b), but for the original series including the ENSO signal.

The MCA results with ENSO-related signals removed were similar with that including the ENSO-related signals (Figs. 5 (c)–(d)), demonstrating that ENSO exhibited no significant impact on the spatial coupling between DUSMASS and Atlantic SSTA. Besides, the regression of DUSMASS onto ASGI was close in 1982–1996 and 2000–2014 (not shown), which were both insignificant, suggesting no apparent interdecadal transition in the relationship between DUSMASS and Atlantic SSTA in recent decades. This manifested that the shift of the relationship between DUSMASS and ENSO was not due to the

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interdecadal transition in the relationship between DUSMASS and Atlantic SSTA.

The MCA result indicated that the colder tropical South Atlantic could suppress dust storm over the northwestern South Asia but the warmer tropical South Atlantic could enhance the dust concentration. As reported previously (e.g., Kucharski et al., 2009, 2008, 2007; Kucharski and Joshi, 2017; Sabeerali et al., 2019; Yadav, 2016, 2009), the warm tropical North Atlantic and clod tropical South Atlantic were conducive for ISMR, which was bridged by the large-scale monsoon circulation (Rong et al., 2010), Rossby wave train (Yadav, 2009), Asian jet (Yadav et al., 2018), Kelvin wave response (Sabeerali et al., 2019), and an abnormal westerly. Considering the relationship between ISMR and tropical Atlantic SSTA, the Atlantic Niña pattern that was linked to ENSO in 1982–1996 (Fig. 2 (a)) tended to suppress dryness and weaken the positive relationship between DUSMASS and ENSO, while the Atlantic Niño pattern in 2000–2014 would decrease the north-south Atlantic SSTA gradient and offset the effect of Atlantic Niña pattern, which weakened the dryness's response to Atlantic and enhanced the ENSO–DUSMASS relationship. Accordingly, the correlation between ENSO and DUSMASS strengthened together with the change of Atlantic SSTA pattern.

It was reported that the interdecadal shift of tropical Atlantic SSTA pattern was a response to the multi-year ENSO events (Tokinaga et al., 2019). The multi-year ENSO event, which was also called as continuing ENSO (CT ENSO), was a situation where the summer ENSO SSTA continued from the preceding year. Another type of ENSO, which was called as emerging ENSO (EM ENSO), was characterized as late Atlantic SSTA response that started from June. The CT ENSO primarily dominated during 1982–1996, while 2000–2014 was dominated by EM ENSO (Yang and Huang, 2021). The impact of the two types of ENSO on the shift of the DUSMASS–Niño-3 relationship were examined. Table 2 showed that ASGI was significantly correlated with Niño-3 in the CT ENSO years, which was not observed in the EM ENSO years. Simultaneously, DUSMASS was significantly related to Niño-3 only in the EM ENSO years. The composite correlation changes for CT and EM ENSOs resembled that for ENSOs in 1982–1996 and 2000–2014, indicating that the shift of Atlantic SSTA pattern plays an important role in modulating the DUSMASS–Niño-3 relationship.

Table 2: Correlation between ASGI and Niño-3 as well as DUSMASS in two different phases (* and * indicate the correlations that are significant on a 0.1 and 0.01 level, respectively).**

R	CT ENSO	EM ENSO	1982–1996	2000–2014

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ASGI & Niño-3	0.78 (***)	0.19	0.73 (***)	0.46 (*)
DUSMASS & Niño-3	-0.60 (*)	-0.75 (***)	-0.51 (*)	-0.67 (***)

Apart from the south-north dipole pattern of the tropical Atlantic SSTA, the switch in the intensity and location of North Atlantic SST tripole pattern was also responsible for the change of Niño-3–DUSMASS relationship (Banerjee et al., 2021). Compared with the global warming hiatus period, the North Atlantic SST exhibited higher correlation with dust activities over South Asia in the context of global warming, which was teleconnected through the precipitation and westerly anomalies over the Indo-Gangetic plain (Banerjee et al., 2021). Therefore, the impact of Niño-3 on DUSMASS was weakened during 1982–1996 when an accelerated global warming was witnessed, while the impact was stronger during 2000–2014 when a warming hiatus prevailed.

3.2.2 Variation of Indian ocean SST

Previous studies have recognized the covariability between the western Pacific and Indian Ocean (Kug et al., 2005; Wang et al., 2003; Watanabe and Jin, 2002). ENSO can affect the Indian Ocean SST in the form of Walker circulation and the Indian Ocean variability can also modulate the ENSO variability (Kug et al., 2005; Wu and Kirtman, 2004; Yu et al., 2002). It is known that ENSO mainly influences the monsoon rainfall of South Asia through changing the SST of Indian ocean (Krishnamurthy and Kirtman, 2003; Srivastava et al., 2019). During CT ENSO years, the ENSO event in summer primarily starts from the preceding winter, while in EM ENSO years, the ENSO event mainly emerges in late spring (Yang and Huang, 2021). Correspondingly, the associated Indian Ocean SST oscillation also varies in these two different ENSO years. In order to explore whether the different types of La Niña impacted the DUSMASS over the northwestern South Asia through adjusting the duration of the temperature anomaly, we compared the SST and the variance of the monthly SSTA from (–1) Sep. to (0) May over the tropical western Indian ocean (central Indian Ocean, 10° S –15° N, 50–70° E).

Figure 6 showed that the variances in the EM La Niña years were generally larger than that in the CT La Niña years, while the variances in the EM El Niño years were generally smaller than that in the CT El Niño years. The monthly tropical western Indian ocean SSTA in CT and EM ENSO years were seen in Fig. S1, which showed that the monthly SSTA from preceding Sep. to following May appeared as persistent positive and negative anomalies in EM El Niño and CT La Niña years, respectively, while

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those in EM La Niña and CT El Niño years experienced monthly and/or seasonal oscillatory. Concurrently, the difference of DUSMASS in El Niño and La Niña years was obvious in the EM ENSO period with higher values appeared in La Niña years (Fig. 7). However, in the CT ENSO period, no significant difference was observed between El Niño and La Niña years. Therefore, it is hypothesized that the EM ENSO conditions, which was associated with higher Indian Ocean SST variance, were more favorable to trigger the variation of DUSMASS. Yang and Huang (2021) reported that 1982–1996 was primarily dominated by CT ENSOs while EM ENSOs primarily controlled during 2000–2014. Combined with abovementioned hypothesis, the correlation between DUSMASS and Niño-3 should be higher in the later period 2000–2014, which was consistent with the interdecadal change of this relationship.

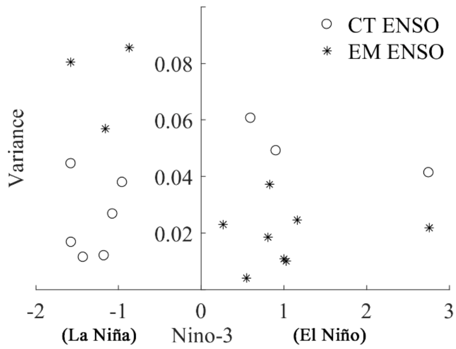

Figure 6: Scatter diagram between Niño-3 index and the variance of the monthly SSTA from (–1) Sep. to (0) May over the tropical western Indian ocean (50–70° E, 10° S–15° N) separately for continuing (CT) and emerging (EM) ENSO.

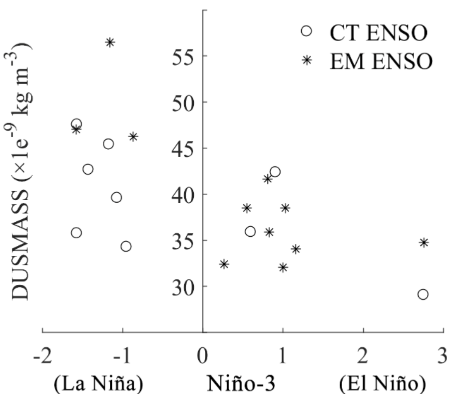

Figure 7: Scatter diagram between DUSMASS and Niño-3 index separately for continuing (CT) and emerging (EM) ENSO.

Unlike the weakening effect of tropical Atlantic SSTA pattern on the DUSMASS– Niño-3

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relationship, the Indian Ocean SSTA variance, as a response to the type of ENSO, tended to strengthen this relationship since the impact of Indian Ocean SSTA variance was synchronous with that of Niño-3. The correlation coefficient between the variance of Indian Ocean SSTA and DUSMASS turned from 0.15 ($P>0.1$) during 1982–1996 to 0.57 ($P<0.05$) during 2000–2014, which was different from the insignificant regression of DUSMASS onto ASGI in those two periods. To quantify the role of Indian Ocean SSTA variance in modifying the DUSMASS–Niño-3 relationship, we calculated the contribution of SSTA variance to the relationship as shown in Fig. 8. The contribution of Indian Ocean SSTA variance was close to 0.0 in 1982–1996 and approached to 1.0 in 2000–2014, which further confirmed the strengthening effect of Indian Ocean SSTA in the later period.

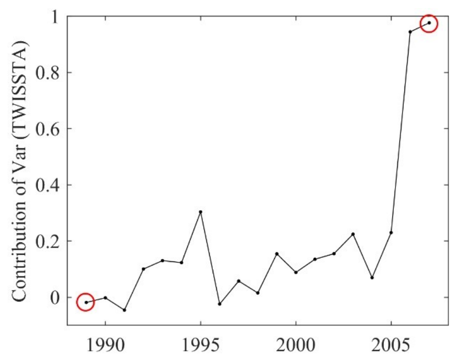

Figure 8: Sliding contribution of tropical western Indian Ocean SSTA (TWISSTA) variance to ENSO–DUSMASS relationship. The two circles represented the 15-year window spanning from 1982 to 1996 and 2000 to 2014, respectively. The Niño-3 index was multiplied by –1 considering that the higher variances in the later period corresponded to the negative phase of ENSO.

Apart from the CT ENSO and EM ENSO, the response of Indian Ocean SSTA was also different between CP ENSO and EP ENSO (Hu et al., 2018). It was reported that the onset of EP ENSO appears in spring and decays near Apr. of the second year, while the CP ENSO tends to onset in summer, reaches their peak intensity around December–January, and decays in early spring of the second year. The duration of the CP ENSO is about eight months shorter than that of the EP ENSO (Kao and Yu, 2009). Especially for the El Niño event, the maximum negative SSTA appears in the winter of year (+1) in the CP El Niño while a stronger cold anomaly appears in the winter of year (+2) in the EP El Niño, indicating a slow and strong cooling after the EP El Niño but a quicker and weaker cooling after the CP El Niño (Hu et al., 2012). In order to explore whether the different types of ENSO impacted the DUSMASS over northwestern South Asia through adjusting the Indian Ocean SST, we compared the SST and DUSMASS

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in CP and EP ENSO conditions.

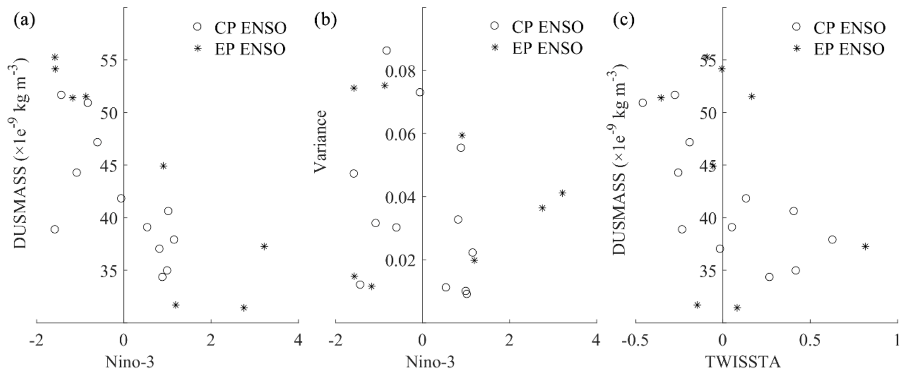

Figure 9: Scatter diagram between (a) Niño-3 and DUSMASS, (b) Niño-3 and TWISSTA variance, and (c) TWISSTA and DUSMASS separately for CP and EP ENSO.

Figure 9 (a) showed that the DUSMASS was generally larger under La Niña conditions than that under El Niño conditions. Specifically, the mean DUSMASS in EP La Niña years was higher than that in CP La Niña years, however, this difference was not significant. In addition, no remarkable difference in Indian Ocean SSTA variance was observed under the two types of ENSO, as shown in Fig. 9 (b). The correlation analysis (not shown) revealed that the significant interdecadal variability of Niño-3–TWISSTA and DUSMASS–TWISSTA relationship was spotted in winter (averaged from (–1) Dec. to (0) Feb). Nevertheless, the TWISSTA under two types of ENSO and the DUSMASS in varied TWISSTA exhibited no significant differences (Fig. 9 (c)), indicating that the variation of TWISSTA and the response of DUSMASS to TWISSTA was not modulated by the types of EP and CP ENSO. The results demonstrated that the transition of EP and CP ENSO exhibited no significant contribution to the shift of the DUSMASS–Niño-3 relationship.

3.2.3 Eurasian continent and Indian Ocean thermal contrast

Kumar et al. (1999) pointed out that in El Niño events before 1980, colder Eurasian temperature anomalies coupled with positive Pacific SST anomalies coincides with negative ISMR anomalies. The inverse connection between ENSO and Indian summer monsoon is maintained. While in the El Niño events during 1981–1997, the increased premonsoon surface temperatures over Eurasia far exceeded the warming in the Indian Ocean. The stronger lad-sea thermal contrast is conducive for a stronger monsoon, which overrides the influence of El Niño. The Eurasian temperature anomalies could also disturb the impact of ENSO on DUSMASS over the northwestern South Asia since monsoon and rainfall are crucial

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factors to trigger dust storms. To isolate the role of Eurasian continent temperature anomalies in modulating the effect of ENSO on DUSMASS over the northwestern South Asia in the recent climate change (i.e., from an accelerated global warming during 1970s–1990s to a warming hiatus during 1998–2014), we compared the Eurasian continent (60°–100° E, 30°–45° N) and Indian Ocean (60°–100° E, 10° S–10° N) thermal contrast in those two periods and calculated its contribution to the change of ENSO–DUSMASS relationship.

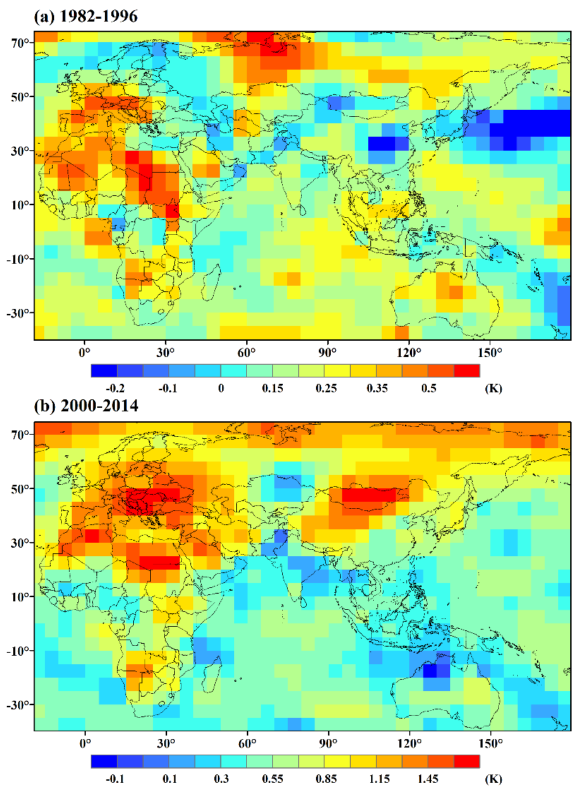

Figure 10: Spatial distribution of summer surface temperature anomaly separately for 1982–1996 (a) and 2000–2014 (b).

Figure 10 displayed the spatial distribution of summer surface temperature. Compared to the spatial distribution of surface temperature during 1982–1996, the warming over Eurasian continent was significantly stronger than that over tropical Indian Ocean during 2000–2014, which indicated higher land-sea thermal contrast in the later period. The strong land-sea thermal contrast can significantly impact the drought conditions over the arid regions in the northwestern South Asia through adjusting the south Asian monsoon, moisture transmission, and precipitation (Kinter et al., 2002; Kumar et al., 1999).

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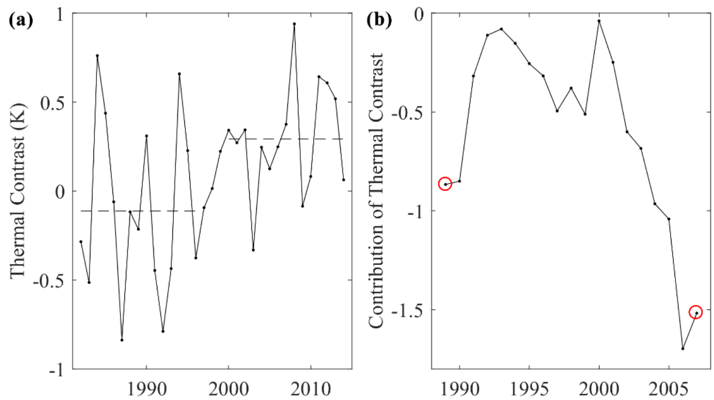

Figure 11: Time series of summer Eurasian continent and Indian Ocean thermal contrast. The dotted lines denote the average values from 1982 to 1996 and from 2000 to 2014, respectively; (b) Sliding contribution of Eurasian continent and Indian Ocean thermal contrast to ENSO–DUSMASS relationship. The circles represented the 15-year window spanning from 1982 to 1996 and from 2000 to 2014, respectively.

As shown in Fig. 11 (a), the Eurasian continent and Indian Ocean thermal contrast during 2000–2014 was higher than that in 1982–1996. As a result, the negative contribution of the thermal contrast grew stronger in the later period compared with that in the first period. The enhancement of thermal contrast's effect mitigated the impact of Niño-3 index on DUSMASS, and this should have led to higher correlation coefficient in 1982–1996 rather than in 2000–2014, which conflicted with the observed interdecadal transition of DUSMASS–Niño-3 relationship. Thus, the change of Eurasian continent and Indian Ocean thermal contrast cannot explain the difference of DUSMASS–Niño-3 relationship in the varied warming phases.

3.2.4 Phase shift of Pacific Decadal Oscillation

It is suggested that the PDO can influence the interannual variability of ISMR by enhancing the ENSO–ISMR relationship when ENSO and the PDO are in-phase, while weakening the relationship when they are out of phase (Dong et al., 2018; Krishnamurthy and Krishnamurthy, 2014). However, it is unclear whether the PDO is responsible for the shift of the ENSO–DUSMASS relationship. Table 3 listed the years with different phases of ENSO and PDO as well as years when ENSO and PDO are in (out of) phase separately. The correlation coefficient between Niño-3 and DUSMASS and significance level were also given. It demonstrated that the PDO significantly strengthened the correlation between Niño-3 and DUSMASS as the coefficient turned from –0.34 ($P>0.1$) when PDO and Niño-3 were out of phase to –0.71 ($P<0.01$) when they were in-phase.

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The 200 hPa velocity potential trend in the positive PDO years exhibited a decrease (divergence) over the western tropical Pacific and an increase (convergence) over the tropical Indian Ocean and Indian subcontinent (across 40°–100° E), as shown in Fig. 8 (a) of Huang et al. (2020). The upper-level convergence over India and the adjacent seas corresponded to the anomalous descending motion, which suppressed ISMR and consequently stimulated the dust storms over South Asia. Meanwhile, two anomalous anticyclones developed to the northwest and southwest of India due to the depressed convection (Huang et al., 2020). The westerlies on the northern flank of the northwest anticyclonic anomalies advected relatively drier air from the Eurasian continent (Parker et al., 2016) to the west of north-central India. Those situations were in favor of dust generation, in addition, the eastward transport of dust from Southwest Asia by the westerlies contributed about half of the dust concentration over the Indo-Gangetic plain (Banerjee et al., 2019). While in the negative PDO years, anomalous ascent appeared over India, which enhanced ISM convection and rainfall, as shown in Fig. 8 (b) of Huang et al. (2020). Similarly, two anomalous cyclones established to the west of India. The easterlies over the northern Indian subcontinent transported wet air from the Bay of Bengal into the east of north-central India, which increased rainfall and reduced dust emissions over the northern India (Huang et al., 2020). The descending and ascending flows over the Indian subcontinent in the negative and positive phase of PDO coincided well with that in the La Niña and El Niño periods, respectively. Hence, PDO can significantly strengthen the effect of ENSO when they were in-phase.

Table 3: List of individual and combined wintertime ENSO–PDO years during 1982–2014.

Events	Phase	
	Positive	Negative
ENSO	1983, 1987, 1988, 1991, 1993–1995, 1998, 2003, 2005, 2007, 2010, 2015, 2016, 2019	1982, 1984–1986, 1989, 1996, 1997, 1999–2001, 2006, 2008, 2009, 2011, 2012, 2014
PDO	1981–1988, 1996–1998, 2001, 2003–2006, 2010, 2014–2019	1989, 1991, 1995, 1999, 2000, 2002, 2008, 2009, 2011, 2012
ENSO×PDO	1983, 1987–1989, 1998–2000, 2003, 2005, 2008–2012	1982, 1984–1986, 1991, 1995–1997, 2001, 2006, 2014

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R (Niño-3 & DUSMASS)	–0.71 (P<0.01)	–0.34 (P>0.1)

Table 3 revealed that most of years (8 out of 14) when ENSO and PDO were in-phase appeared in the second period, i.e., 2000, 2003, 2005, and 2008–2012. Meanwhile, most of years (8 out of 11) when ENSO and PDO were out of phase appeared in the first period, i.e., 1982, 1984–1986, 1991, 1995, 1996, and 1997. Simultaneously, the winter Niño-3 exhibited lower correlation with DUSMASS in the first period when most of ENSO years were accompanied with anti-phase PDO. In addition, the quantitative contribution of PDO shown in Fig. 12 further confirmed that the PDO strengthened the impact of ENSO on DUSMASS in 2000–2014 while the contribution was close to 0.0 in 1982–1996. All those demonstrated that the phase shift of PDO plays an important role in modulating the revolution of DUSMASS–Niño-3 relationship.

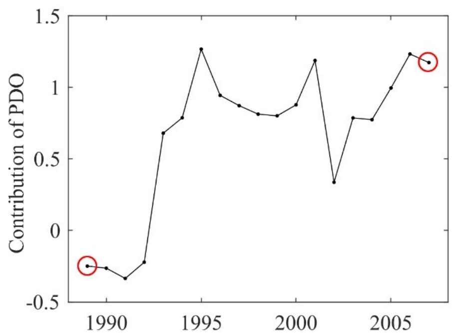

Figure 12: Sliding contribution of PDO to ENSO–DUSMASS relationship. The two circles represented the 15-year window spanning from 1982 to 1996 and 2000 to 2014, respectively.

4 Discussion

4.1 Uncertainty in analyzing the contribution of the influence factors

The schematic diagram of the interdecadal shift of the ENSO impact on DUSMASS was shown in Fig. S2. It illustrated that all the SSTA patterns in Atlantic Ocean, Pacific Ocean, and Indian Ocean play important roles in changing the ENSO–DUSMASS relationship. The contributions of those abovementioned factors to the interdecadal shift of this relationship were analyzed based on the linear regression model. However, the linear regression model would definitely bring uncertainty to the results (Guo et al., 2017) and may not be sufficient to verify the causal relationship between the factors and the ENSO–DUSMASS relationship. The numerical models are thus suggested to more accurately quantify

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the contribution of those factors to the shift of ENSO–DUSMASS relationship, which will be included in our future research. However, it is undeniable that this study provides new sights to the dust storm-related numerical simulation by taking account of the teleconnections and their influence mechanisms.

In addition, while analyzing the effects of different types of ENSO event in Sect. 3.2.2, we compared the variance of the difference in SST over the tropical western Indian ocean between two adjacent months, as shown in Figs. 6, 7, and 9. It showed that only eight EP and EM ENSO years were identified and the number of CP and CT ENSO years were also insufficient. The statistical results acquired from the insufficient number of samples could also be explained by the random events (Pallikari, 2004). In order to verify this conclusion, we calculated the interannual correlation between the variance of SST difference and DUSMASS from 1982 to 2014. Even so, the significant interannual correlation does not guarantee the significant link between different types of ENSO. Therefore, longer time series with valid samples (EP, CP, CT, and EM ENSO years) are needed to further validate the influence of ENSO types on the ENSO–DUSMASS relationship in the future. Alternatively, using numerical model to simulate the teleconnection pattern of ENSO over South Asia under different types of ENSO is also favorable.

It is possible that the interdecadal variability of ENSO–DUSMASS relationship results from anthropogenic land-use management (Kumar et al., 1999), which should be considered in the future researches.

4.2 Difference in varied seasons and ENSO types

In this study, we analyzed the effect of wintertime ((–1) Nov.–(0) Jan.) ENSO on DUSMASS. It is noteworthy that the correlation between summertime ((–1) Jun.–(–1) Aug) ENSO and DUSMASS also exhibited remarkable interdecadal variability in the context of global warming, i.e., the correlation coefficient shifted from –0.24 ($P>0.1$) during 1982–1996 to –0.81 ($P<0.001$) during 2000–2014. It is known that lead-lag interaction and feedback are common among the large-scale atmospheric teleconnections, and the teleconnection pattern in other oceans usually lags behind the atmospheric circulation of Pacific Ocean (Trenbeth et al., 2002). Regarding this, the summertime ENSOs were obtained from the antecedent year, i.e., (–1) Jun.–(–1) Aug. The impact of summer and winter ENSO on the following summer DUSMASS would be confused when the lag effects were taken into account. Therefore, only wintertime ENSO impacts were displayed in this study, which could be the superimposed effects of summertime and wintertime ENSO. The precise numerical simulation is needed to further

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isolate the seasonal difference in detail.

The CT ENSO refers to the summer ENSO that primarily starts from the preceding winter, whereas the EM ENSO refers to the ENSO event that emerges in late spring (Yang and Huang, 2021). Similarly, the onset of EP ENSOs tends to occur in spring while that of CP ENSOs appear in summer. Besides, both CT and EP ENSOs dominate in 1979–1997, while the EM and CP ENSOs become more frequent in 2000–2018 (Kao and Yu, 2009; Yang and Huang, 2021). Thus, it is likely that the CT (EM) ENSOs may coincide with EP (CP) ENSOs. However, the years defined as CT (EM) ENSO years using Yang and Huang (2021)'s method were not consistent with the EP (CP) ENSO years and they were crossed among different types of ENSOs, indicating that the CT (EM) ENSOs were independent of the EP (CP) ENSOs. Yang and Huang (2021) suggested that the impact of ENSO on ISMR is significant when EM ENSOs dominated, while it is weak when CT ENSOs prevailed. It is further demonstrated that the transition of EP and CP ENSO exhibits no significant contribution to the shift of relationship between ISMR and ENSO since the 21st century. Those are also true for the revolution of ENSO–DUSMASS relationship.

5 Conclusions

In the study, we investigated the interdecadal change of the ENSO impact on DUSMASS over the northwestern South Asia from 1982 to 2014 as well as factors that contribute to the shifts of the responses of DUSMASS to the wintertime ENSO. It was found that the ENSO–DUSMASS relationship shifted from weak negative relation during 1982–1996 to significant negative correlation during 2000–2014. The change of Atlantic SSTA pattern weakened the impact of wintertime ENSO on dust activities over the northwestern South Asia, while that of Indian Ocean SSTA pattern and PDO tended to strengthen ENSO's effect. Both the Atlantic and Indian Ocean SSTA patterns were modulated by the duration of ENSO events (i.e., continuing and emerging ENSO). The Eurasian continent and Indian Ocean thermal contrast cannot explain the shift of ENSO–DUSMASS relationship. The current results are based solely on the linear regression, and further studies integrating numerical models and longer time series are needed to validate the results. Nevertheless, our study indeed found multiple large-scale factors that could impact the interdecadal interaction between ENSO and dust activities over the northwestern South Asia. Considering the large-scale circulation forecast is relatively easier, the results in this study could provide new insight to the prediction of dust storm trend in the near future based on the variability of ENSO–

DUSMASS relationship.

Data availability

The data can be downloaded for free from the corresponding website which were listed in the text.

Author contribution

L.S. designed the study, performed the analysis with feedback from J.Z. and F.Y., and wrote the paper that was reviewed by J.Z., F.Y., D.Z., J.W., X.M., and Y.L.. All the authors discussed the results.

Competing interests

The authors declare that they have no conflict of interest.

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