

Middle East Dust as an Important External Driver of the Indian Ocean Dipole

Corresponding Author: Professor Jing Li

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Liu et al. estimated that dust aerosols from the Middle East regions act as a dominant external driver of the Indian Ocean Dipole. In particular, they show that summertime dust over the 1980-2020 period accounts for ~36% of interannual IOD variance, surpassing the El Niño-Southern Oscillation as the main driver during boreal autumn, using satellite observations and reanalysis. In addition, they perform CSEM v1.2 with the Parallel Ocean Program (POP2) and Community Atmosphere Model simulations (CAMS 4.3) to show that reduced summertime Middle East dust enhances warming in the western Indian Ocean during boreal autumn and induces easterly winds that shoal the eastern thermocline. This tilts of the thermocline, deepening it in the west and shoaling it in the east, and reinforces the SST gradient through the Bjerknes and wind–evaporation–sea surface temperature (WES) feedback, amplifying a positive IOD pattern, and vice versa.

Overall, the central findings are scientifically interesting and clearly relevant to Indian Ocean climate variability, particularly the assessment that summertime Middle East dust explains a large fraction of IOD interannual variance, potentially surpassing ENSO's influence during boreal autumn. However, characterizing Middle Eastern dust aerosols as the dominant external driver of IOD variability is currently overstated. A more explicit differentiation between the impacts of Middle Eastern dust and those of Central and East Asian dust emissions is required, as both may modulate the IOD. Furthermore, additional forcings and modes of variability, including anthropogenic aerosols, greenhouse gases, the Madden–Julian Oscillation (MJO), and the Pacific Decadal Oscillation (PDO), can also affect IOD variability during boreal autumn. These contributions should be carefully separated and quantified before making the strong claim that Middle East dust is the dominant external driver of the IOD.

Dust variability can both drive and respond to IOD variability. However, this bidirectional relationship does not yet appear to be well constrained in the authors' analysis of dust–IOD interactions, partly because of substantial uncertainty in the representation of dust emissions in the global climate model CESM v1.2 (Kok et al., 2022; main text reference 18). Given this known bias, the authors should more clearly justify their choice of CESM v1.2 with CAMS 4.3 for this study and explain how this underestimate might affect their conclusions regarding dust–IOD interactions.

Prior work has linked anthropogenic aerosols and greenhouse gases to Indian Ocean warming and IOD-like patterns, and has also shown that Middle East and West Asian dust influences the South Asian monsoon and Arabian Sea SST (see Banerjee and Kumar, 2016; Jin et al., 2014; Zheng and Hoteit, 2025). Also, It has been shown that Indian summer monsoon rainfall responds positively to Middle East dust (Jin and Yang, 2014). These findings from previous studies should be discussed explicitly in the main manuscript.

-Banerjee, Priyanka, and S. Prasanna Kumar. "ENSO modulation of interannual variability of dust aerosols over the northwest Indian Ocean." *Journal of Climate* 29, no. 4 (2016): 1287-1303.

-Jin, Qinqian, Jiangfeng Wei, and Zong-Liang Yang. "Positive response of Indian summer rainfall to Middle East dust." *Geophysical Research Letters* 41, no. 11 (2014): 4068-4074.

-Zheng, Yiling, and Ibrahim Hoteit. "Asymmetric impacts of Indian Ocean Dipole on summer climate over Arabian

General comments:

-Please use other reanalysis datasets (e.g., ERA5-CAMS, NAAPS) and satellite dust AOD products to check if the observed dust AOD pattern variability is reliable. In particular, since MODIS DOD has known bias, please cross-validate with IASI-DAOD or other independent datasets (such as CALIPSO).

-Line #72: MISR only provides aerosol data from approximately year 2000 onward, whereas the caption of Fig. 1 states the MISR non-spherical aerosol optical depth data from 1980 to 2023. This should be corrected. If other datasets are combined for the pre-MISR period, this should be clearly mentioned in the figure caption.

-In Fig. 1a, it is not clear whether the regression is performed on climatological means or on individual years. I assume the regression is currently done for individual years, comparing dust during JJA with other meteorological values during SON.

-The rationale for using different time periods for the datasets is unclear, such as most satellite dust DOD cover 2003–2023, while dust station data spans 1980–2023. The manuscript should clarify the reason and discuss any resulting limitations and uncertainties in the analysis.

Lines 117-120: "Reduced Middle East dust emissions are statistically linked to atmospheric and oceanic states resembling pIOD events, suggesting that decadal variations in dust loading likely exert an important, previously underappreciated influence on tropical Indian Ocean climate." It is not clear whether the authors remove ENSO-related variability from SST fields (in Fig. 1 and Extended Figs 1–5) before computing the IOD index. Also, there are several confounding factors that can also influence the IOD, such as the MJO and the PDO. The manuscript should detail how these confounding factors are accounted for or removed in the dust–IOD statistical analyses. Please cite that previous work here, especially when stated as "previously underappreciated influence on tropical Indian Ocean climate."

Lines #31-35: The use of summertime station-based dust-frequency observations to scale annual-mean dust mass density in CESM v1.2 needs further justification. Could you please clarify why the other seasons were not considered? This could potentially underestimate the true annual mean dust mass density. The authors should also clarify this methodological choice and its possible implications.

Line # 142- "Both the spatial configuration and the intensity of these anomalies strongly indicate that SMED acts as an external forcing capable of generating pronounced interannual variability in the TIO". This conclusion is currently overstated, as the authors are not investigating the impact of other aerosols on IOD changes. How do PDO and MJO manifest in changes in IOD, since they are also affected by dust forcing, which in turn can affect the positive and negative phases of IOD?

Lines # 57-60, Supplementary Information (extended Fig. S6). Why, in the extended Fig. 6a, are they not including the SMED versus DMI sim? It would be good to plot the correlation coefficient and also the SVD analysis for this simulation run. As shown in Fig. S6b, the observations are quite off for the SMED and DMI patterns from 2010 onwards. What could be the reason for that?

Line 474: Please cite the methodology and relevant references related to the implementation of Singular Value Decomposition Analysis.

Lines #212-215; "Once transported, these aerosols exert a strong radiative forcing by absorbing solar radiation, which heats the upper troposphere, while simultaneously reducing the amount of shortwave radiation reaching the ocean surface".

-It depends on the dust mineralogy as well; without constraining that over SMED, it is perhaps uncertain to quantify that. Authors should also consider providing the heating rate map rather than showing changes in surface radiative flux. That is important for assessing how much the radiative heating rate changes. To correctly determine vertical radiative heating rates, authors could consider the vertical profiles of dust extinction. Authors should also use the CALIPSO data or the CESM-based vertical profile of the dust extinctions to identify changes in heating rates.

-Please explain why the TIO low cloud fraction is decreasing, and the high cloud fraction is increasing in the reduced-dust over SMED scenarios. How are authors constraining the other aerosols in the CESM v1.2 setup? Are authors only changing dust aerosol, or are they also changing other aerosols, such as sea salt aerosol in CESM v1.2 setup?

Lines #225-227 "These changes significantly affect cloud dynamics, driving a decrease in low-level cloud cover and an increase in high-level clouds over the western TIO (Fig. 3c, d)." Figure S8 and Figure 3 show otherwise. I see an enhanced low cloud fraction from the CSEM runs over the Western TIO. Please explain.

Lines #227-230: This needed a detailed investigation of the cloud feedback; the authors should cite past work for this statement here: "The transformation of cloud fields further modifies the radiative budget by increasing both longwave and shortwave radiation, thereby amplifying the warming signal over the western TIO in synergy with the direct radiative effects of reduced dust."

Lines 232-237: Did the authors run the CESM v1.2 simulation from 1980 to 2020, or from 2010 to 2020?

Line 288 and other places: "Furthermore, analysis of the month-to-month evolution of the IOD signal (figures omitted)". The figure not shown does not look ideal. Please consider including all referenced figures in the supplementary materials.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

Please find my comments in the attachment.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

The manuscript investigates the role of mineral dust aerosols from the Middle East in modulating interannual variability of the Indian Ocean Dipole (IOD). Using a combination of satellite observations, reanalysis datasets, and climate model experiments, the authors demonstrate that variations in summer dust emissions between 1980 and 2020 explain approximately 36% of the observed interannual IOD variance—exceeding the influence of the El Niño–Southern Oscillation (ENSO) during boreal autumn. Overall, the paper identifies a previously underappreciated dust–IOD teleconnection, emphasizing the importance of aerosol forcing in seasonal prediction and long-term climate projections. Overall, the work is novel, and supported by comprehensive analysis. However, the manuscript is not always easy to follow, as several figure captions and axis labels lack clarity and may cause confusion for readers. I recommend publication after revision to address the points detailed below.

Major comments:

1. The paper explains how dust emission reduction over Middle East causes a positive anomaly in solar radiation reaching to the western Indian ocean surface. However, it does not clearly discuss how this enhanced radiative energy translates into a positive SST anomaly, considering the ocean's large heat capacity. Please expand on this physical mechanism. Is the ~2-month lag used in the analysis related to the ocean mixed-layer adjustment timescale?

2. Please explain why there is a positive net LW flux at surface over the western Indian ocean in the case of dust deduction? Moreover, for both SW and LW, why the flux anomaly over eastern Indian ocean is always opposite to the western part?

Specific comments:

3. Line 88, 'reversing the regression coefficients to represent dust reduction' is very confusing, I figured out its meaning when I looked at the figure caption of Fig. S3, it means you take the negative values of the regression coefficient. Please modify the sentence, and also clarify it in the caption of Fig.1.

4. Fig S3, you mentioned 'regression coefficient' and 'correlation coefficient' in the figure caption, are they the same? Please clarify what you used and keep them consistent.

5. In Fig1 (e), please clarify that the grey dashed line is the mixed layer depth anomaly, right? It is not just mixed layer depth. Also, please clarify the grey dashed line is corresponding to the y-axis on the right. Otherwise, it's too confusing.

6. Line 93, '0.5K per standard deviation of dust variability', please clarify the meaning of this term. Authors use different dust proxies, e.g., dust AOD, column mass density, and dust frequency, what are their standard deviation of dust variability, respectively.

7. Line 336, 'suppress eastern upwelling', should that be suppress eastern downwelling?

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have addressed my major concerns, and the revised manuscript is substantially improved. I thank the authors for their careful and thorough revisions. I have one remaining minor point, concerning consistency between the limitations now stated in the manuscript and the stronger framing used in the title and abstract. The newly added limitations paragraph (Lines 465–481, beginning "While this study demonstrates a robust statistical linkage between SMED and IOD variability...") is a valuable and welcome addition.

In light of these acknowledged uncertainties, the wording “dominant external driver” in the title appears stronger than what can be conclusively supported. I recommend softening this language to better align with the paper’s own caveats, for instance, removing “dominant” from the title, abstract, and conclusion and replacing it with wording such as “important.” One possible revision to the title is “Middle East Dust as an Important External Driver of the Indian Ocean Dipole.” Related phrasing in the abstract and conclusion should be adjusted accordingly (e.g., Line 416: “exerts a dominant control”). With this minor wording adjustment, I recommend the manuscript for publication.

(Remarks on code availability)

<https://zenodo.org/records/15684742>

Regarding the post-processing Matlab code posted on Zenodo (<https://zenodo.org/records/15684742>): for accessibility and ease of use by international readers, I recommend that the in-code comments be provided in English (or at least include English translations alongside any non-English comments). This would make the scripts much easier to follow and reproduce for the broader community. Thank you.

Reviewer #2

(Remarks to the Author)

The authors did a great job in addressing my comments and questions. I have no further suggestions.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

The authors have addressed the reviewers’ comments well. The responses are clear, and the revisions have improved the manuscript. I do not have any remaining major concerns, and I believe the paper is now suitable for publication in Nature Communications. I recommend acceptance in its current form.

(Remarks on code availability)

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Response to the review of “Middle East Dust as a Dominant External Driver of the Indian Ocean Dipole” (NCOMMS-25-75253-T).

Responses to Review 01 ’s comments

Summary:

Liu et al. estimated that dust aerosols from the Middle East regions act as a dominant external driver of the Indian Ocean Dipole. In particular, they show that summertime dust over the 1980-2020 period accounts for ~36% of interannual IOD variance, surpassing the El Niño-Southern Oscillation as the main driver during boreal autumn, using satellite observations and reanalysis. In addition, they perform CSEM v1.2 with the Parallel Ocean Program (POP2) and Community Atmosphere Model simulations (CAMS 4.3) to show that reduced summertime Middle East dust enhances warming in the western Indian Ocean during boreal autumn and induces easterly winds that shoal the eastern thermocline. This tilts of the thermocline, deepening it in the west and shoaling it in the east, and reinforces the SST gradient through the Bjerknes and wind–evaporation–sea surface temperature (WES) feedback, amplifying a positive IOD pattern, and vice versa.

Overall, the central findings are scientifically interesting and clearly relevant to Indian Ocean climate variability, particularly the assessment that summertime Middle East dust explains a large fraction of IOD interannual variance, potentially surpassing ENSO’s influence during boreal autumn. However, characterizing Middle Eastern dust aerosols as the dominant external driver of IOD variability is currently overstated. A more explicit differentiation between the impacts of Middle Eastern dust and those of Central and East Asian dust emissions is required, as both may modulate the IOD. Furthermore, additional forcings and modes of variability, including anthropogenic aerosols, greenhouse gases, the Madden–Julian Oscillation (MJO), and the Pacific Decadal Oscillation (PDO), can also affect IOD variability during boreal autumn. These contributions should be carefully separated and quantified before making the strong claim that Middle East dust is the dominant external driver of the IOD.

Reply: We are grateful to the reviewer for his/her insightful and very valuable suggestions, which have significantly contributed to the enhancement of our manuscript. We have carefully addressed the comments and made the necessary revisions, hoping that the updated version meets the journal's standards. Our responses to each of the comments and suggestions are as follows. The referee's original comments are shown in blue. Our replies are shown in black. The corresponding changes in the manuscript are shown in *Italic black*.

1. Dust variability can both drive and respond to IOD variability. However, this bidirectional relationship does not yet appear to be well constrained in the authors' analysis of dust–IOD interactions, partly because of substantial uncertainty in the representation of dust emissions in the global climate model CESM v1.2 (Kok et al., 2022; main text reference 18). Given this known bias, the authors should more clearly justify their choice of CESM v1.2 with CAMS 4.3 for this study and explain how this underestimate might affect their conclusions regarding dust–IOD interactions.

Reply: We thank the reviewer for this insightful comment regarding the bidirectional nature of dust–IOD interactions and the known uncertainties in modeled dust emissions. We agree that this complexity requires careful consideration.

The core reason for our model choice is to isolate the climatic impact of dust without the complication of dust emission response to climate. Therefore, we required a model framework that allows dust aerosol concentrations to be prescribed, creating a one-way forcing. Moreover, the prescribed dust field used in our study has been validated by previous studies (Buchard et al., 2017; Che et al., 2022).

(1) Choice of CAM version: We selected the Community Atmosphere Model version 4.3 (CAM4.3) because it supports prescribed dust mixing ratios. This capability is essential for our experimental design. In contrast, later versions (CAM5 and CAM6) feature more complex aerosol–climate interactions where dust is computed online based on evolving meteorological and surface conditions, making it difficult to prescribe fixed values of dust loading.

(2) Choice of CESM version: Consequently, we used CESM v1.2, which is compatible with CAM4.3. The newer CESM v2 is exclusively coupled with CAM6, which employs the online dust scheme and the bidirectional dust–climate coupling we sought to avoid.

The additional explanation has been incorporated into the supplementary information of our revised manuscript for clarity. We also cited it here for convenience.

The atmospheric component of CESM, the Community Atmosphere Model version 4.3

(CAM4.3), incorporates several major improvements in its physics parameterizations compared to previous CAM versions. We choose this version instead of the more updated Community Atmosphere Model version 5 (CAM5) or Community Atmosphere Model version 6 (CAM6) because dust aerosols can be prescribed in this version, while in later versions it is computed online by meteorological variables and soil features, which cannot be easily controlled. Furthermore, we employed CESM version 1.2 rather than the updated CESM version 2 because the latter is exclusively coupled with CAM6. In CAM6, dust mixing ratios are computed interactively through a bidirectional coupling with meteorological conditions, which again limits the ability to constrain dust concentrations for our experimental design.

2. Prior work has linked anthropogenic aerosols and greenhouse gases to Indian Ocean warming and IOD-like patterns, and has also shown that Middle East and West Asian dust influences the South Asian monsoon and Arabian Sea SST (see Banerjee and Kumar, 2016; Jin et al., 2014; Zheng and Hoteit, 2025). Also, It has been shown that Indian summer monsoon rainfall responds positively to Middle East dust (Jin and Yang, 2014). These findings from previous studies should be discussed explicitly in the main manuscript.

-Banerjee, Priyanka, and S. Prasanna Kumar. "ENSO modulation of interannual variability of dust aerosols over the northwest Indian Ocean." *Journal of Climate* 29, no. 4 (2016): 1287-1303.

-Jin, Qinqian, Jiangfeng Wei, and Zong - Liang Yang. "Positive response of Indian summer rainfall to Middle East dust." *Geophysical Research Letters* 41, no. 11 (2014): 4068-4074.

-Zheng, Yiling, and Ibrahim Hoteit. "Asymmetric impacts of Indian Ocean Dipole on summer climate over Arabian Peninsula." *Geophysical Research Letters* 52, no. 20 (2025): e2025GL118195.

Reply: Thanks for your helpful suggestions. We have now explicitly discussed the important findings from the cited studies in the revised manuscript. This discussion

provides a crucial context for our work by highlighting the established roles of anthropogenic forcings and regional dust in shaping the Indian Ocean climate system, thereby helping to better position our specific findings on the dust-IOD connection within the broader literature. We also cited the discussion here.

Most studies attribute IOD variability to external forcing^{4,9}, internal air–sea interactions and remote El Niño–Southern Oscillation (ENSO) influences^{1,10,11}, yet the role of aerosols remains largely unexplored. The TIO is located close to the world’s second largest dust source – the Middle East deserts. Previous studies have identified the far-reaching impacts of Middle East dust on the South Asian monsoon, Arabian Sea SST, and Indian summer monsoon rainfall^{12–14}.

3. Please use other satellite dust AOD products to check if the observed dust AOD pattern variability is reliable. In particular, since MODIS DOD has known bias, please cross-validate with IASI-DAOD or other independent datasets (such as CALIPSO).

Reply: Thanks for your insightful and constructive suggestions. Due to its sparse orbital tracks and significant data gaps caused by narrow swath width, CALIPSO lacks the continuous spatial coverage required for robust pattern analysis of dust AOD variability. This sampling inadequacy is particularly problematic for dust studies, where episodic dust events and complex transport patterns require continuous spatial monitoring to reliably characterize variability patterns. Additionally, frequent cloud contamination further reduces data availability, compounding the spatial representation issues. We therefore rely on IASI-DAOD and other independent datasets for cross-validation and checking if the observed dust AOD pattern variability is reliable.

We found that the SST dipole structure is highly robust, as confirmed by multiple independent dust datasets, including MODIS dust optical depth, MERRA-2 dust column mass density, station dust frequency, MISR non-spherical aerosol optical depth, and IASI dust optical depth (Fig. R1 and Fig. R2, the same as Extended Data

Fig. 5 and Fig. 1d in the revised manuscript).

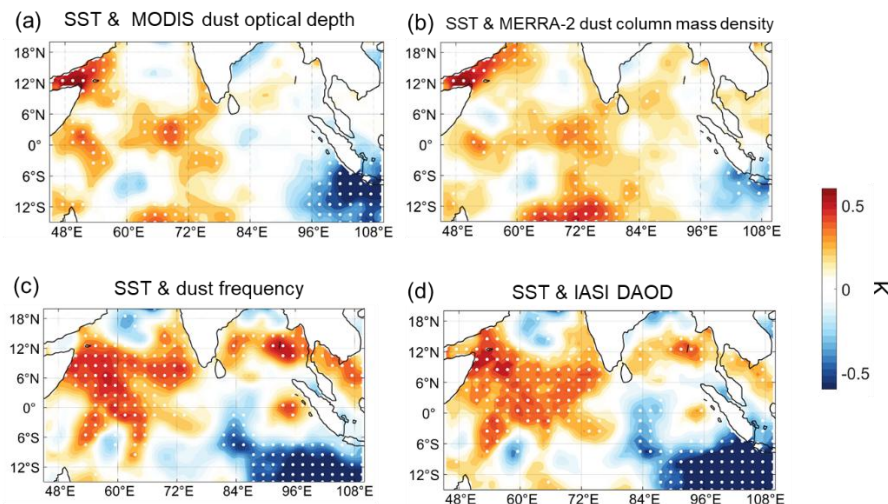


Fig. R1. The regression coefficients of detrended SON SST on the detrended JJA dust activity proxies averaged over the Middle East. These dust proxies include (a) MODIS dust optical depth (2003-2023), (b) MERRA-2 dust column mass density (2003-2023), (c) station dust frequency (1980-2023), and (d) IASI dust optical depth (2008-2021). Note that the regression coefficients in all figures are taken as their negative values corresponding to dust reduction. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

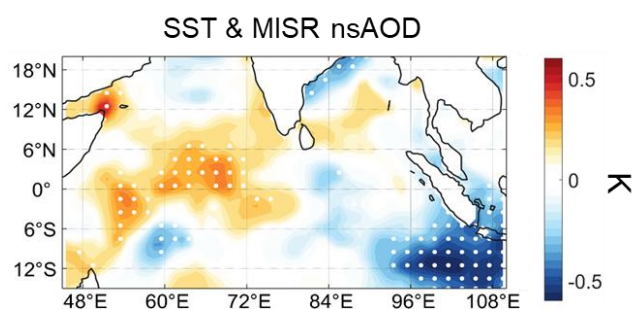


Fig. R2. Similar to Fig. R1, but for the detrended JJA MISR non-spherical aerosol optical depth averaged over the Middle East from 2003 to 2023

We also incorporated additional introduction for the validating dataset and cited it here.

Dust Aerosol Optical Depth (DAOD) retrievals from the Infrared Atmospheric Sounding Interferometer (IASI) onboard the Metop-A satellite was also used to provide an independent validation of dust patterns⁵⁶. IASI derives DAOD from thermal infrared spectral measurements, thereby providing 24-hour observational capability and addressing challenges associated with surface reflectance over bright deserts that affect visible-based sensors (e.g., MODIS)⁵⁷. The analysis utilizes the IASI-A product from 2008 to 2021, a period selected for its consistent data availability to ensure a stable and homogeneous dataset for robust cross-validation.

4. Line #72: MISR only provides aerosol data from approximately year 2000 onward, whereas the caption of Fig. 1 states the MISR non-spherical aerosol optical depth data from 1980 to 2023. This should be corrected. If other datasets are combined for the pre-MISR period, this should be clearly mentioned in the figure caption.

Reply: Thank you for catching this error. You are correct that MISR data are only available from 2000 onward. We have corrected the caption for Figure 1 to reflect the accurate time range (2000–2023), and we apologize for the oversight. We also cited the corrected figure caption here for convenience.

Fig. 1. *Dust proxies, sea surface temperature and meteorological field regressed on dust time series. (a) The regression coefficients of JJA station dust record on the Middle East regional-averaged station dust frequency (averaged over the 10°S–30°N, 35°E–70°E). (b) Similar to a, but for the JJA MISR non-spherical aerosol optical depth (AOD). (c) Time series of standardized JJA station dust frequency (the solid line) from 1980 to 2023, and JJA MISR non-spherical aerosol optical depth (the dashed line) from 2003 to 2023. (d–g) The regression coefficients of SON meteorological fields on the JJA MISR non-spherical aerosol optical depth averaged over the Middle East. These meteorological fields include (d) sea surface temperature. (e) meridional mean (20°S–20°N) vertical cross section of temperature (shaded) and mixed layer depth (the gray dashed line), (f) sea level pressure (shaded) with 850 hPa zonal and*

meridional wind (UV, vectors, m/s), and (g) meridional mean (20°S-20°N) vertical cross section of geopotential height (GPH, shaded) with zonal and vertical wind (UW, vectors, m/s). The y-axes on the right in (e) corresponds to the response of mixed layer depth. The regression is currently done for individual years. The area with white dots passed the significance test of $p \leq 0.05$ by Student's *t*-test.

5. In Fig. 1a, it is not clear whether the regression is performed on climatological means or on individual years. I assume the regression is currently done for individual years, comparing dust during JJA with other meteorological values during SON.

Reply: Sorry for the unclear explanation and you are right. The regression is currently done for individual years, comparing dust during JJA with other meteorological values during SON. We have clarified it in the figure caption and cited it here for convenience.

Fig. 1. Dust proxies, sea surface temperature and meteorological field regressed on dust time series. (a) The regression coefficients of JJA station dust record on the Middle East regional-averaged station dust frequency (averaged over the 10°S~30°N, 35°E~70°E). (b) Similar to a, but for the JJA MISR non-spherical aerosol optical depth (AOD). (c) Time series of standardized JJA station dust frequency (the solid line), and JJA MISR non-spherical aerosol optical depth (the dashed line) from 1980 to 2023. (d-g) The regression coefficients of SON meteorological fields on the JJA MISR non-spherical aerosol optical depth averaged over the Middle East. These meteorological fields include (d) sea surface temperature. (e) meridional mean (20°S-20°N) vertical cross section of temperature (shaded) and mixed layer depth (the gray dashed line), (f) sea level pressure (shaded) with 850 hPa zonal and meridional wind (UV, vectors, m/s), and (g) meridional mean (20°S-20°N) vertical cross section of geopotential height (GPH, shaded) with zonal and vertical wind (UW, vectors, m/s). The y-axes on the right in (e) corresponds to the response of mixed layer depth. The regression is currently done for individual years. The area with white dots passed the

significance test of $p \leq 0.05$ by Student's t-test.

6. The rationale for using different time periods for the datasets is unclear, such as most satellite dust DOD cover 2003–2023, while dust station data spans 1980–2023. The manuscript should clarify the reason and discuss any resulting limitations and uncertainties in the analysis.

Reply: Thanks for pointing it out. We opted for different time periods because the available data lengths vary across datasets. Our primary rationale for utilizing the longer station record (1980-2023) was to maximize the length of the temporal series for more robust results. Satellite data become available only since 2003, whereas station data can extend back to 1980. To minimize errors arising from insufficient sample sizes, we utilized the longest possible time span for each dataset. Moreover, the regression patterns derived from these different time periods exhibit considerable consistency (Extended Data Fig. 7 & 8 in the revised manuscript), further demonstrating that our findings are not sensitive to the specific time frame selected but are robust across different intervals. We also added the supplementary discussion in the revised manuscript and cited it here.

Moreover, the regression patterns derived from these different time periods exhibit considerable consistency (Extended Data Fig. 7 & 8), further demonstrating that our findings are not sensitive to the specific time frame selected but are robust across different intervals.

7. Lines 117-120: “Reduced Middle East dust emissions are statistically linked to atmospheric and oceanic states resembling pIOD events, suggesting that decadal variations in dust loading likely exert an important, previously underappreciated influence on tropical Indian Ocean climate.” It is not clear whether the authors remove ENSO-related variability from SST fields (in Fig. 1 and Extended Figs 1–5) before computing the IOD index. Also, there are several confounding factors that can also influence the IOD, such as the MJO and the PDO. The manuscript should detail

how these confounding factors are accounted for or removed in the dust–IOD statistical analyses. Please cite that previous work here, especially when stated as “previously underappreciated influence on tropical Indian Ocean climate.”

Reply: We thank the reviewer for raising this important point. We have removed ENSO-related variability from the SST fields by linear regression (Fig. 1 and Extended Figs 1–5 in the revised manuscript) prior to computing the IOD index, in order to isolate the influence of ENSO on IOD variability.

Regarding the Madden–Julian Oscillation (MJO), which is a dominant mode of intra-seasonal (30–100 days) variability, we note that its behavior is primarily modulated by the phase of the IOD rather than directly influencing the IOD itself (Benedict et al., 2015; Chen et al., 2022). To minimize interference from intra-seasonal climate signals, we employ a seasonal mean, which smooths out these higher-frequency variations.

Concerning the Pacific Decadal Oscillation (PDO), we acknowledge its potential role in modulating IOD variability. However, in the present analysis, the PDO was not explicitly removed due to its relatively weaker teleconnection with tropical Indian Ocean climate on interannual timescales (Krishnamurthy and Krishnamurthy, 2016). To isolate the independent influence of dust from that of the Pacific Decadal Oscillation (PDO), we performed correlation analysis again but after regressing out the PDO signal, as shown in Fig. R3. The result confirms that dust forcing maintains a persistent and independent impact on the tropical Indian Ocean dipole pattern (Fig. R3).

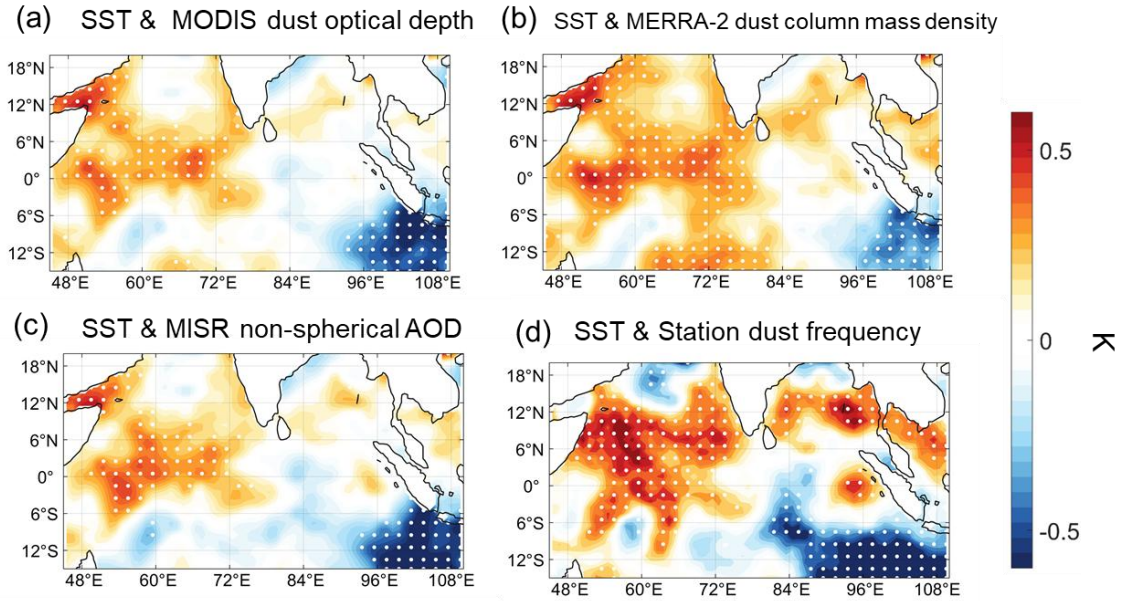


Fig. R3. The regression coefficients of detrended SON SST on the detrended JJA dust activity proxies averaged over the Middle East by regressing out the impacts of PDO. These dust proxies include (a) MODIS dust optical depth (2003-2023), (b) MERRA-2 dust column mass density (2003-2023), (c) MISR non-spherical AOD (2003-2023), and (d) station dust frequency (1980-2023). Note that the correlation coefficients in all figures are taken as their negative values corresponding to dust reduction. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test. SST and dust proxies have been regressed out by PDO considering PDO's considerable global impact.

We have now included a detailed description in the manuscript outlining how these potential confounding factors—including MJO and PDO—were addressed or accounted for in our dust–IOD statistical analyses. We also cited the corresponding explanation in the revised manuscript here for convenience.

The potential signal of other climate variability, such as ENSO, Pacific Decadal Oscillation (PDO) and Madden Julien Oscillation (MJO), were largely removed from our analysis. Specifically, ENSO and PDO were removed by regressing out the Niño3.4 index (https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/)⁷¹ as well as the PDO index (https://psl.noaa.gov/gcos_wgsp/Timeseries/PDO/) from both the DMI

time series and SMED time series. The MJO is primarily modulated by the IOD phase rather than directly influencing the IOD itself^{72,73}, and we have effectively smoothed out its intra-seasonal variability by applying a low-pass filter to seasonal mean data.

8. Lines 131-135: The use of summertime station-based dust-frequency observations to scale annual-mean dust mass density in CESM v1.2 needs further justification. Could you please clarify why the other seasons were not considered? This could potentially underestimate the true annual mean dust mass density. The authors should also clarify this methodological choice and its possible implications.

Reply: We thank the reviewer for this comment concerning our methodological use of summertime observations and for identifying the inadvertent error. We have corrected it to the intended phrasing: "Specifically, the summertime-mean dust mass density in CESM was scaled each year according to the corresponding summertime station-based dust-frequency observations over the Middle East."

The primary reason for focusing on the summer (JJA) season is that dust activity in the Middle East exhibits strong seasonality, with emissions and long-range transport being the most intense and spatially coherent during summer (Extended Data Fig. 1 in the revised manuscript). This makes the summer season the most representative period for capturing the dominant dust patterns and their interannual variability that are central to our study. This seasonal focus is consistent with the approach of several previous regional dust-climate studies (Liu et al., 2023; Xia et al., 2022).

We acknowledge the reviewer's concern that this approach might not fully capture the annual mean. To address this, we conducted a validation exercise by comparing our scaled annual-mean dust mass density against independent annual-mean data from the MERRA-2 reanalysis (Fig. R4). The results showed a reasonable consistency between the two, increasing our confidence that the summertime-based scaling captures the key spatial features of the annual-mean dust distribution effectively.

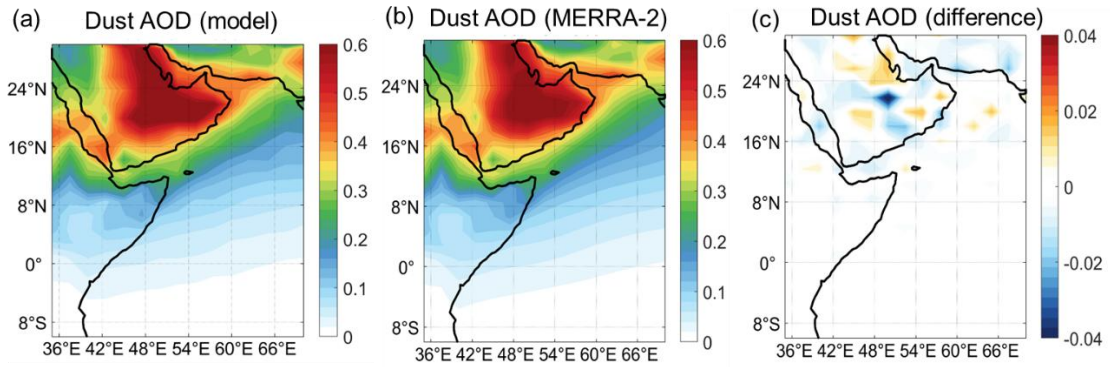


Fig. R4. Distribution of annual-mean dust AOD over the Middle East. (a) the CESM model, (b) MERRA-2 reanalysis, and (c) their difference (a minus b).

9. Line # 142- “Both the spatial configuration and the intensity of these anomalies strongly indicate that SMED acts as an external forcing capable of generating pronounced interannual variability in the TIO”. This conclusion is currently overstated, as the authors are not investigating the impact of other aerosols on IOD changes. How do PDO and MJO manifest in changes in IOD, since they are also affected by dust forcing, which in turn can affect the positive and negative phases of IOD?

Reply: We thank the reviewer for this insightful comment. We agree that stating SMED acts as an external forcing based solely on our current analysis may be too strong, as we have not fully isolated its effect from other potential drivers like PDO and MJO. We acknowledge that these climate variabilities can co-vary with both dust emissions and IOD phases, and that future studies using targeted numerical experiments are needed to fully disentangle their relative contributions and causal pathways.

In response, we have toned down this specific conclusion in the manuscript to state that our results suggest SMED can act as a significant external forcing, rather than definitively indicate it does. We also cited it here for convenience.

Both the spatial configuration and the intensity of these anomalies suggest that SMED could act as a significant external forcing capable of generating pronounced

interannual variability in the TIO.

Furthermore, we have added a new paragraph to the discussion section to explicitly address the potential confounding roles of PDO, MJO, and other aerosols, while also acknowledging the limitations of the current study that warrant further investigation in future work.

While this study demonstrates a robust statistical linkage between SMED and IOD variability, reinforced by sensitivity experiments that seek to isolate the dust influence from other factors (e.g., ENSO and PDO), we acknowledge that conclusively attributing this signal solely to dust remains challenging. Despite our efforts, the potential for complex, non-linear interactions with other aerosols or low-frequency climate modes cannot be entirely ruled out. Therefore, we conclude that SMED likely acts as a significant external forcing on the IOD, but its independent contribution and the precise pathways involved should be further validated through future idealized modeling studies designed to definitively separate these intertwined influences.

10. Lines # 57-60, Supplementary Information (extended Fig. S6). Why, in the extended Fig. 6a, are they not including the SMED versus DMI sim? It would be good to plot the correlation coefficient and also the SVD analysis for this simulation run. As shown in Fig. S6b, the observations are quite off for the SMED and DMI patterns from 2010 onwards. What could be the reason for that?

Reply: We thank the reviewer for these insightful questions regarding Extended Data Fig. 6.

(1) The correlation and SVD for the SMED vs. DMI simulation: We agree with the reviewer that this is a valuable suggestion. In the revised manuscript, we have now included the spatial correlation coefficient between the simulated SMED and DMI patterns in the caption or directly on the panel for Fig. R5a here, same as Extended Data Fig. 9a in the revised manuscript. Furthermore, we have conducted the recommended SVD analysis between the dust emissions and SST fields from this specific simulation. The results of this SVD analysis, which robustly capture the

dominant dust-IOD coupling mode, have been added as a new supplementary figure (Fig. R6 here, same as Extended Data Fig. 6e-f in the revised manuscript) to strengthen our mechanistic interpretation.

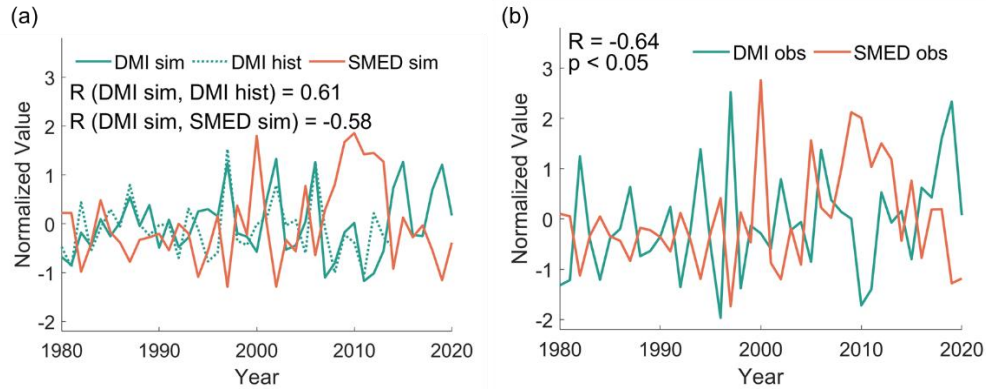


Fig.R5. The standardized DMI and SMED from 1980 to 2020. The time series are (a) simulated DMI forced by dust (solid cyan line), simulated DMI in the historical run with all forcing (dashed cyan line), and simulated SMED (solid red line) and (b) observed DMI and SMED. All the time series are standardized for comparison

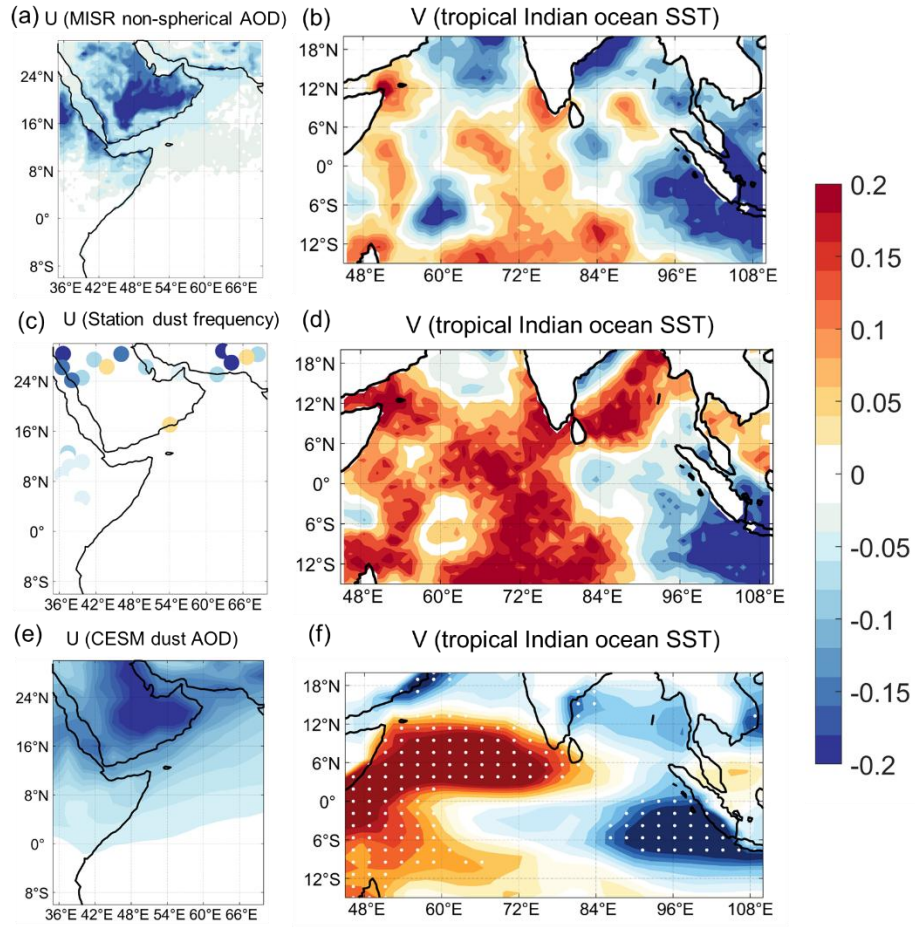


Fig. R6. *The spatial pattern of the first SVD mode between dust proxies and tropical Indian ocean SST. The first mode of SVD between (a) detrended JJA MISR non-spherical AOD in the Middle East, accounting for 64.2% of the covariance and (b) detrended SON tropical Indian Ocean SST from 2003 to 2023. (c-d) Similar to a-b, but for the station dust frequency from 1980 to 2023. This mode account for 65.7% of the covariance. (e-f) Similar to a-b, but for the dust AOD in the CESM simulation. This mode account for 71.2% of the covariance.*

We also supplemented corresponding discussion about this figure and cited it here.

Complementary singular value decomposition (SVD) between SMED and SON SST further supports this relationship, showing that the leading coupled mode corresponds to negative SMED signals and a pIOD-like SST pattern in the TIO (Extended Data Fig. 6). Correlations exceed 0.6 for the modes derived from both MISR AOD, station-based dust frequency observations, and dust AOD in the CESM simulations,

highlighting the consistency of the results.

(2) The model-observation discrepancy post-2010: You are right that there might be a divergence between the observed and simulated SMED-DMI relationship after approximately 2010. The primary factors likely include the increased influence of other climate forcings and limitations in the observed dust record. Specifically, the period post-2010 was characterized by strong and persistent climate anomalies, including a notable prevalence of Central Pacific El Niño events and a strong positive phase of the PDO (Freund et al., 2019; Lin et al., 2018). These modes exert a powerful influence on the IOD, which may have temporarily overshadowed or modulated the dust-IOD linkage in the observations—a nuance not captured by the idealized "SMED-only" forcing simulation. Additionally, the observational dust data itself may contribute to the discrepancy, as this period encompasses the transition between satellite sensors and potential calibration drifts. Such technical factors can introduce inhomogeneities in the long-term dust trend that are unrelated to true climate variability.

We have revised the text to explicitly acknowledge this period of discrepancy and provide the above discussion on its potential causes, thereby presenting a more complete and critical assessment of our results.

Notably, a possible post-2010 divergence between the observed and simulated SMED-DMI relationship may stem from the increasing influence of other climate forcings (e.g., Central Pacific El Niño, PDO) and limitations inherent in the station-based dust record^{28,29}.

11. Line 474: Please cite the methodology and relevant references related to the implementation of Singular Value Decomposition Analysis.

Reply: Thanks for pointing this out. We have cited the methodology and relevant references. We also cited them here for convenience.

The Singular Value Decomposition (SVD) is a multivariate statistical method used to identify coupled spatial-temporal relationships between two covarying fields by

decomposing their cross-covariance matrix^{81,82}. This method has been widely used in the statistical analysis of climate data^{83,84}.

12. Lines #212-215; “Once transported, these aerosols exert a strong radiative forcing by absorbing solar radiation, which heats the upper troposphere, while simultaneously reducing the amount of shortwave radiation reaching the ocean surface”.

It depends on the dust mineralogy as well; without constraining that over SMED, it is perhaps uncertain to quantify that. Authors should also consider providing the heating rate map rather than showing changes in surface radiative flux. That is important for assessing how much the radiative heating rate changes. To correctly determine vertical radiative heating rates, authors could consider the vertical profiles of dust extinction. Authors should also use the CALIPSO data or the CESM-based vertical profile of the dust extinctions to identify changes in heating rates.

Reply: We thank the reviewer for this insightful comment and for the constructive suggestions to strengthen our analysis. We have addressed each point as detailed below.

(1) Regarding dust mineralogy:

We agree with the reviewer that dust mineralogy is a key factor influencing radiative forcing. As our study did not employ a spatially resolved mineralogy scheme for the SMED region, we have now acknowledged this as a source of uncertainty in the revised manuscript. A sentence has been added to the Discussion section in the revised manuscript and cited here for convenience:

It should also be noted that the magnitude of the dust radiative forcing is also dependent on dust mineralogy, which is not specifically constrained for the Middle East region in our simulations, which may introduce some uncertainty in the quantitative estimates.

(2) Regarding the heating rate and vertical profiles:

We fully agree that analyzing the atmospheric heating rate provides a more direct metric for assessing the impact of dust absorption on the atmospheric temperature structure. In response to the reviewer's suggestion, we have added a new figure (Fig. R7b, the same as Extended Data Fig. 13b) showing the vertical heating rate profile in the model. We also analyzed the spatial distribution of the dust-induced atmospheric heating rate (Fig. R7c, the same as Extended Data Fig. 13c).

Furthermore, to correctly interpret the vertical structure of this heating, we have followed the reviewer's advice and analyzed the vertical profile of dust extinction from our CESM simulations (Fig. R7a, the same as Extended Data Fig. 13a). The model results indicate that the majority of the transported dust aerosol is confined within the troposphere. This vertical profile supports the pattern of heating rates shown in our new figure, confirming that the dominant radiative heating occurs within the atmospheric column, consistent with the dust layer's location.

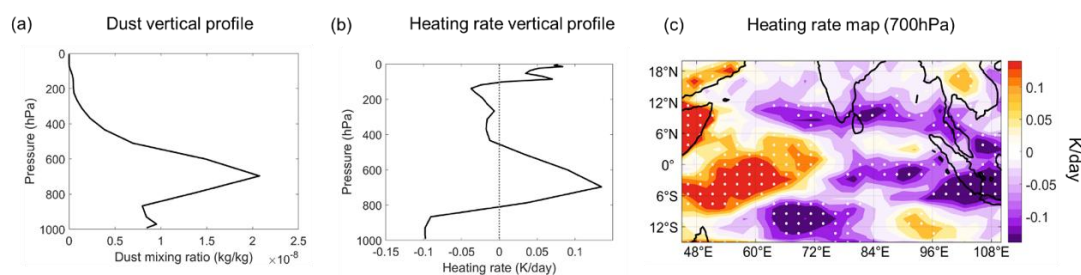


Fig. R7. Dust vertical profile and its corresponding heating rate for reduced dust.

(a) The vertical profile of dust mixing ratio and (b) heating rate over the transported area (10°S~10°N, 35°E~70°E) in the model. (c) The responses of SON 700 hPa heating rate to reduced Middle East dust forcing in the CESM. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

We also added the corresponding text in the revised manuscript to describe the added heating rate map and discusses the relationship between the simulated dust vertical profile and the resulting radiative heating. We cited it here for convenience.

Once transported, these aerosols exert a strong radiative forcing by absorbing solar radiation, which heats the upper troposphere, while simultaneously reducing the

amount of shortwave radiation reaching the ocean surface. The dust-induced heating rate profile aligns with the simulated vertical distribution of dust extinction, which is primarily confined within the troposphere. This vertical coherence confirms that the radiative heating maxima correspond well with the dust layer's location, reinforcing the direct thermodynamic impact of dust radiative absorption on the atmospheric column. (Extended Data Fig. 13).

13. Please explain why the TIO low cloud fraction is decreasing, and the high cloud fraction is increasing in the reduced-dust over SMED scenarios. How are authors constraining the other aerosols in the CESM v1.2 setup? Are authors only changing dust aerosol, or are they also changing other aerosols, such as sea salt aerosol in CESM v1.2 setup?

Reply: We thank the reviewer for raising these important points. The decrease in TIO low-level cloud fraction and increase in high-level cloud fraction under reduced dust can be attributed to dust-induced changes in atmospheric stability induced by changes in vertical temperature profile; this mechanism has been clarified in the revised manuscript. We also cited it here for convenience.

This vertical redistribution of energy alters atmospheric stability: the lower atmosphere warms more strongly, while diminished warming in the upper atmosphere results in a relative cooling there (Extended Data Fig. 15). These changes significantly affect cloud dynamics, driving a decrease in low-level cloud cover and an increase in high-level clouds over the western TIO (Fig. 3c, d).

Regarding the model setup, we confirm that only dust aerosol emissions were modified in our CESM v1.2 experiments. Other aerosols, including sea salt, were prescribed at their default, present-day levels and not altered in the sensitivity simulations. We also added supplementary explanation about the aerosol setup in the revised manuscript and cited it here.

To isolate the impact of Middle Eastern dust (10° S–30° N, 35° E–70° E) on interannual IOD variability, we drove CESM with observed summertime dust mass

density over the Middle East for 1980–2020 and diagnosed the resulting IOD index. Specifically, the annual-mean dust loading in CESM was rescaled each year using the region’s summertime station dust frequency observations, generating a transient dust-mass time series that faithfully captures observed variability. Other aerosols were prescribed at their default, present-day levels and not altered in the sensitivity simulations.

14. Lines #225-227 “These changes significantly affect cloud dynamics, driving a decrease in low-level cloud cover and an increase in high-level clouds over the western TIO (Fig. 3c, d).” Figure S8 and Figure 3 show otherwise. I see an enhanced low cloud fraction from the CSEM runs over the Western TIO. Please explain.

Reply: We thank the reviewer for this thoughtful observation, which has allowed us to improve the clarity of our figure. We acknowledge that the colormap in the original Figures 3 and S8 (now Figure S12) could have been more intuitively designed. To clarify, in these figures, the brown shades indeed indicate a decrease in cloud fraction, while the blue shades indicate an increase. The western TIO region is predominantly brown, supporting our conclusion of a decreased low-cloud fraction there. We thus added additional explanation in the revised manuscript to avoid misunderstanding and cited it here for convenience.

These changes significantly affect cloud dynamics, driving a decrease in low-level cloud cover (blue shades) and an increase in high-level clouds (brown shades) over the western TIO (Fig. 3c, d).

15. Lines #227-230: This needed a detailed investigation of the cloud feedback; the authors should cite past work for this statement here: “The transformation of cloud fields further modifies the radiative budget by increasing both longwave and shortwave radiation, thereby amplifying the warming signal over the western TIO in synergy with the direct radiative effects of reduced dust.”

Reply: We thank the reviewer for this suggestion. We have revised the manuscript to provide a more detailed mechanistic explanation of the cloud feedback, supported by

key literature.

The text now explicitly states that the increase in shortwave radiation results from reduced low-level clouds (e.g., stratocumulus), which decreases planetary albedo. Conversely, the increase in longwave radiation is linked to enhanced high-level cloud cover (e.g., cirrus), which amplifies the greenhouse effect.

This explanation is now grounded in established cloud-radiative feedback theory, supported by previous studies. The revised text presents a logically supported process rather than an assertion.

We also cited the revised text here for convenience.

The transformation of cloud fields—characterized by a reduction in low-level cloud fraction and an increase in high-level cloud fraction—further modifies the radiative budget (Figs. 3a, b). Specifically, the decrease in low clouds reduces the albedo, allowing more shortwave radiation to penetrate and warm the ocean surface^{37,38}. Concurrently, the increase in high clouds enhances the atmospheric greenhouse effect by absorbing and re-emitting longwave radiation, which inhibits radiative cooling at the surface^{37,39}. These two effects act in synergy with the direct radiative effect of reduced dust loading to amplify the warming signal over the western TIO. This cloud feedback process, particularly the low-cloud albedo feedback, is well-established as a key positive feedback mechanism modulating TIO variability.

16. Lines 232-237: Did the authors run the CESM v1.2 simulation from 1980 to 2020, or from 2010 to 2020?

Reply: Sorry for the misunderstanding. We ran the CESM v1.2 simulation from 1980 to 2020. The regression coefficients shown here were scaled by the magnitude of dust decreasing trend from 2010 to 2020 in the CESM.

We also modified the figure caption to clarify this and cited it here for convenience.

Fig. 3. *The underlying mechanism accounting for the SMED-IOD teleconnection. The regression coefficients of SON meteorological fields onto JJA dust aerosol optical*

depth (AOD) from 1980 to 2020. These coefficients were scaled by the magnitude of dust decreasing from 2010 to 2020 in the CESM. These meteorological fields include (a) net shortwave flux at surface, (b) net longwave flux at surface, (c) high cloud fraction, and (d) low cloud fraction. The area with white dots passed the significance test of $p \leq 0.05$ by Student's *t*-test.

17. Line 288 and other places: “Furthermore, analysis of the month-to-month evolution of the IOD signal (figures omitted)”. The figure not shown does not look ideal. Please consider including all referenced figures in the supplementary materials.

Reply: Thanks for your helpful suggestions. We have included all figures in the supplementary materials following your suggestions. We also cited it here for convenience.

Furthermore, analysis of the month-to-month evolution of the IOD signal (Extended Data Fig. 2) shows that anomalies peak in both the amplitude and statistical significance during SON, corroborating the selection of SON as the representative season for IOD-related analysis.

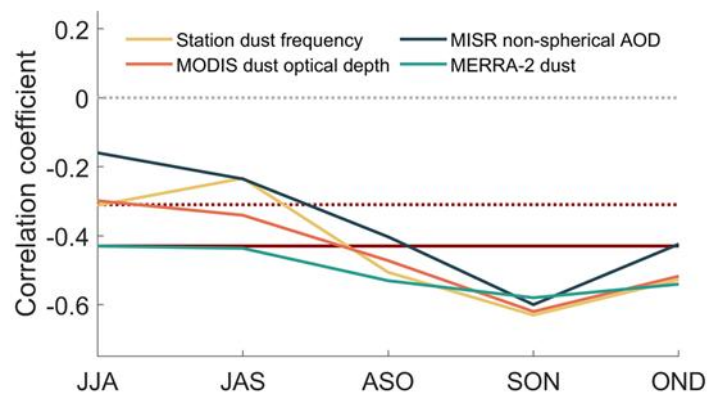


Fig. R8. Correlation coefficients between JJA dust proxies and DMI in different three months. These dust proxies include station dust frequency (the yellow line, 1980-2023), MODIS dust optical depth (the orange line, 2003-2023), MISR non-spherical AOD (the black line, 2003-2023), and MERRA-2 dust column mass density (the green line, 2003-2023). The dashed grey line indicates the position of

zero correlation.

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Response to the review of “Middle East Dust as a Dominant External Driver of the Indian Ocean Dipole” (NCOMMS-25-75253-T).

Responses to Review 02 's comments

Summary:

This study examined how mineral dust aerosols emitted from the Middle East affect the Indian Ocean Dipole (IOD) using both observational data and the CESM model. While previous studies have examined how anthropogenic aerosols effect IOD, how Middle Eastern dust aerosols affect the IOD is largely unclear. The study addresses a very important question in the region, and the topic is very novel and inspiring. The overall analysis is quite comprehensive, however, some details in model setting, the feedback link from subtropical dust loading to tropical SSTs, and the magnitude of the radiative forcing need further clarification. Adding some discussion about the uncertainties in data and methodology also would strengthen the paper.

Reply: We are grateful to the reviewer for his/her insightful and very valuable suggestions, which have significantly contributed to the enhancement of our manuscript. We have carefully addressed the comments and made the necessary revisions, hoping that the updated version meets the journal's standards. Our responses to each of the comments and suggestions are as follows. The referee's original comments are shown in blue. Our replies are shown in black. The corresponding changes in the manuscript are shown in *Italic black*.

Major comments

1. Usually, the lifetime of dust aerosols in the atmosphere, especially in the lower troposphere, is fairly short, from several days to a couple of weeks. The statement “multi-month atmospheric residence time of dust aerosols” (line 60) needs more evidence to support. I think it is important to understand whether the strong connection between JJA Middle Eastern dust and SON IOD is primarily due to an usually long residence time of summertime Middle Eastern dust, or instead a delayed response through ocean-atmosphere feedback. It would also be helpful to clarify whether Middle Eastern dust in SON has any impact on the IOD in SON.

Reply: Thank you for your valuable comments and insightful suggestions.

We agree that the near-surface residence time of dust aerosols is relatively short. The original statement referring to a "multi-month atmospheric residence time" has been revised for greater precision, and supporting references have been added. The revised text now emphasizes that under specific conditions—such as when dust is lifted by strong upward air currents into the stratosphere or when fine-grained particles undergo long-range transport—certain fractions of dust aerosols may exhibit extended residence times (e.g., exceeding one month). We have cited relevant studies on transatlantic transport of Saharan dust and trans-Pacific transport of Asian dust (Kim et al., 2019; Prospero et al., 2021; Yu et al., 2019a; Yu et al., 2019b), illustrating that under favorable atmospheric circulation conditions, fine dust particles can remain in the atmosphere from several weeks to months.

Moreover, your distinction between the two possible mechanisms—long residence time versus delayed ocean–atmosphere feedback—is indeed critical. The ocean–atmosphere interaction is likely the dominant mechanism. Specifically, Middle Eastern dust in summer may influence the radiative balance and thus affect sea surface temperature patterns over the Arabian Sea and western Indian Ocean by the delayed response through ocean-atmosphere feedback. These effects may subsequently trigger an IOD event in the following season through air–sea

interactions.

Additionally, Middle Eastern dust in SON has limited direct influence on the IOD during the same season as validated by various dust proxies (Fig. R1). This may be attributed to the generally weaker dust activity in the Middle East during autumn (Extended Data Fig. 1c in the revised manuscript), as well as the fact that the IOD is already in its mature phase by SON, during which coupled ocean–atmosphere processes dominate its evolution and external forcings such as dust play a relatively minor role.

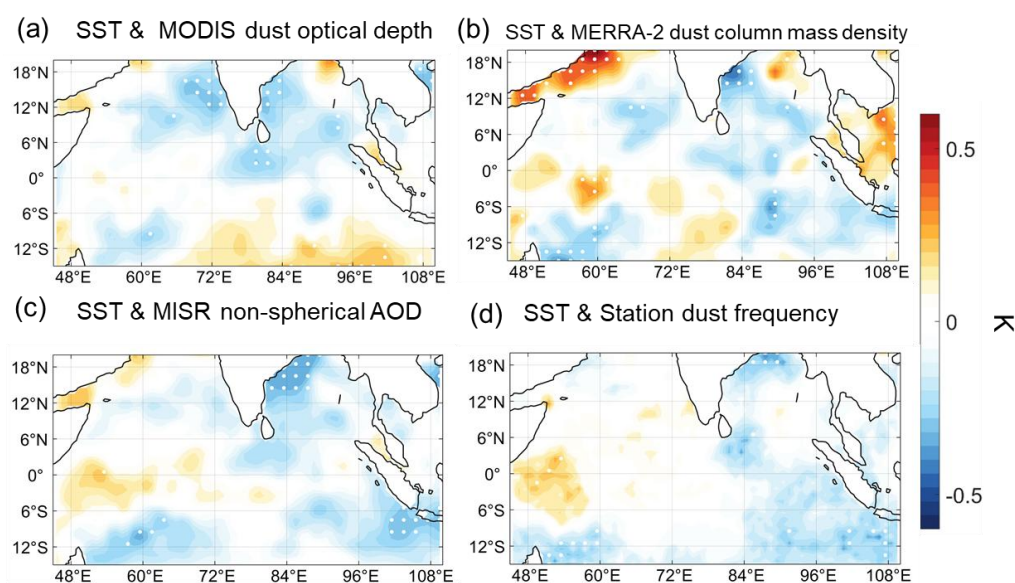


Fig. R1. The regression coefficients of detrended SON SST on the detrended SON dust activity proxies averaged over the Middle East. These dust proxies include (a) MODIS dust optical depth (2003-2023), (b) MERRA-2 dust column mass density (2003-2023), (c) station dust frequency (1980-2023), and (d) IASI dust optical depth (2008-2021). Note that the regression coefficients in all figures are taken as their negative values corresponding to dust reduction. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

We also incorporated these discussions here for convenience.

This seasonal offset is physically plausible given the multi-month atmospheric residence time of dust aerosols under specific conditions (strong upward air currents

and long-range transport for fine-grained particles) and the delayed response through ocean-atmosphere feedback¹⁹⁻²². Additionally, the dust activity over Middle East in SON has limited direct influence on the IOD, as weaker autumn dust activity coincides with the IOD's mature phase (Extended Data Fig. 1c), during which coupled ocean-atmosphere processes dominate and the role of external forcings like dust is diminished.

2. The averaging area for the summertime Middle East Dust (SMED) index was not very clear (e.g., in Fig. 1c). As shown in Figs. 1a and 1b, the domain only covers southern Middle East, and it also includes the Horn of Africa, which is often not geographically considered part the Middle East. In the Methods section, there is a definition of Middle East dust (“10° S–30° N, 35° E–70° E”, line 522). But It’s unclear if this the averaging region used to calculate all the time series of SMED. And also, the domain is a quite large, while most of the Middle East dust are located to the north of 10° N (supplementary Fig. 1). Are the results sensitive to the averaging area of SMED? Would the correlations change much if only averaging over the region with high dust loading, e.g., to the north of 10° N?

Reply: We sincerely thank the reviewer for raising this critical point regarding the spatial definition of our Summertime Middle East Dust (SMED) index. The selected domain (10°S–30°N, 35°E–70°E) was intentionally designed as an "effective influence region" to capture dust aerosol loading over the Indian Ocean that is relevant to long-range transport and ocean-atmosphere interactions, rather than to strictly adhere to geographical boundaries. This domain aims to include dust aerosols over the Arabian Sea and northwestern Indian Ocean—which are positioned to directly influence local sea surface temperatures via radiative effects—while excluding dust from northern source regions that predominantly undergoes short-range transport and may has limited reach over the ocean.

Additionally, we have also performed a sensitivity analysis using a domain north of 10°N (Fig. R2) and found that this domain selection also exhibits a very high correlation with the original (Extended Data Fig. 5 in the revised manuscript), and all

key correlations with the IOD remain nearly identical. We also plot two time series, one derived from the region north of 10°N (10°N–30°N, 35°E–70°E) and the other from the region north of 10°S (10°S–30°N, 35°E–70°E). Both time series exhibit similar temporal variability across the entire study period (Fig. R3). The above-mentioned results further confirm that our results are robust to the specific latitudinal boundary. We have clarified this physical rationale and added a note on robustness in the revised manuscript.

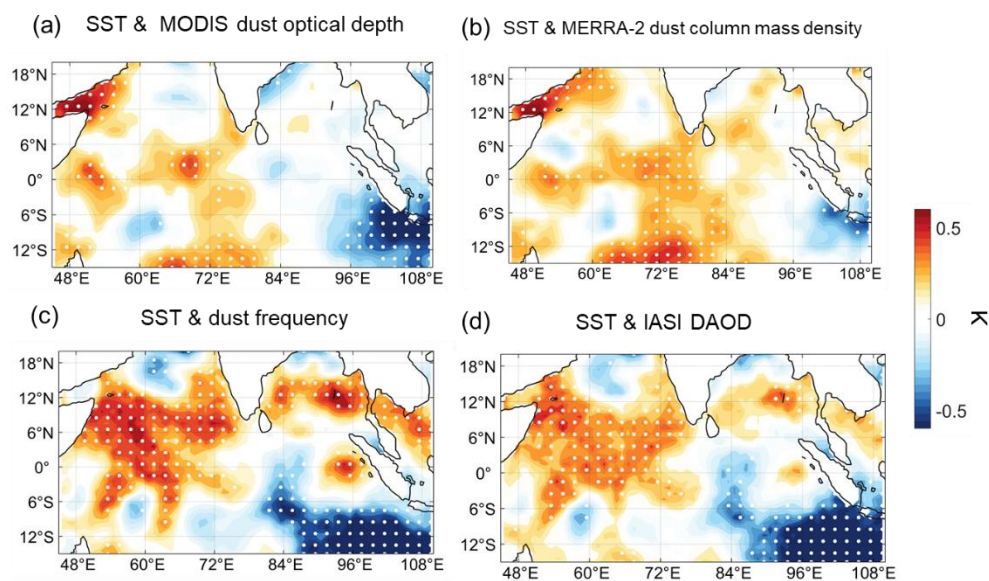


Fig. R2. The regression coefficients of detrended SON SST on the detrended JJA dust activity proxies averaged over the Middle East (averaged over the 10°N~30°N, 35°E~70°E) by regressing out the impacts of ENSO. These dust proxies include (A) MODIS dust optical depth (2003-2023), (B) MERRA-2 dust column mass density (2003-2023), (C) MISR non-spherical AOD (2003-2023), and (D) station dust frequency (1980-2023). Note that the correlation coefficients in all figures are taken as their negative values corresponding to dust reduction. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test. SST and dust proxies have been regressed out by ENSO considering ENSO's considerate global impact.

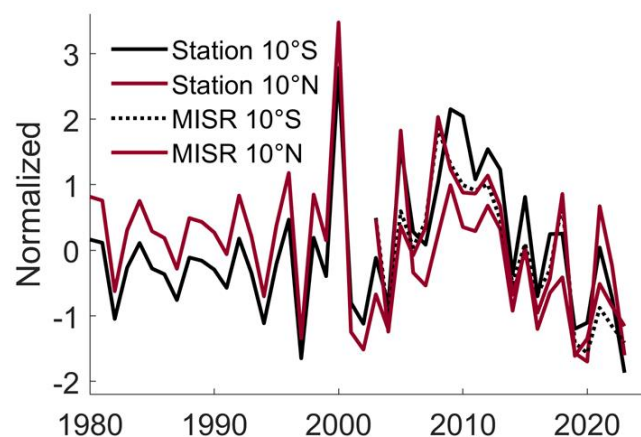


Fig. R3. Time series of dust proxies analyzed in this study. Solid lines denote the standardized June–July–August (JJA) station dust frequency from 1980–2023, with black and dark red lines representing the regions (10°S–30°N, 35°E–70°E) and (10°N–30°N, 35°E–70°E), respectively. Dashed lines indicate the JJA MISR non-spherical aerosol optical depth from 2003–2023, corresponding to the same two geographic domains.

3. The radiative forcing of the dust aerosols are shown in both the coupled CESM simulations and atmosphere-only model (CAM) runs. However, the location of radiative forcing directly from the dust aerosols. With reduced Middle Eastern dust aerosols, one would expect to see enhanced shortwave (SW) fluxes (i.e., warming) at the surface extending from the Arabian Peninsula southward toward the Arabian Sea. However, this pattern is not clearly shown in the coupled simulation (Fig. S8c)--there is a cooling around 12 °N, while the warming single is located further south, round 6 °N-6 °S, where the climatological dust loading is low. Is this due to a teleconnection?

Reply: Thank you for this insightful observation regarding the spatial pattern of surface shortwave radiation response in our coupled model experiments. You have correctly identified a key nuance in how dust aerosol impacts manifest in coupled versus atmosphere-only simulations.

You rightly noted that reduced Middle Eastern dust should directly enhance surface

shortwave fluxes over dust-laden regions from the Arabian Peninsula to the Arabian Sea. This expected response is clearly present in our atmosphere-only (CAM) experiments, as shown in Extended Data Fig. 14a. The different pattern in the coupled (CESM) simulation—with cooling near 12°N and warming displaced farther south—is indeed attributable to ocean-atmosphere coupling and the associated teleconnections as you suggested. The initial radiative perturbation triggers a specific chain of adjustments:

(1) Circulation Adjustment: The surface warming over the western Tropical Indian Ocean (TIO) enhances convection and establishes a low-pressure anomaly (Fig. 2c). This sets up a basin-scale pressure gradient, driving an anomalous clockwise vertical circulation and generating prevailing anomalous easterly winds at the surface over the central TIO, opposite to the climatological westerlies (Fig. 2c-d).

(2) Mechanism for the Displaced Warming: These easterly anomalies suppress the eastward advection of warm water and, through Bjerknes and wind-evaporation-SST (WES) feedbacks, help sustain and confine the core of the warming signal further south, near 6°N–6°S.

(3) Mechanism for the Cooling near 12°N: Crucially, in the region near 12°N (Arabian Sea), the circulation adjustment leads to a strengthening of the prevailing climatological winds (Fig. 2c, vectors). This increase in surface wind speed enhances local evaporation, which produces a net surface cooling via the WES feedback. This wind-driven cooling effectively counteracts and overshadows the direct radiative warming from dust reduction, resulting in the net cooling anomaly observed in Extended Data Fig. 14c.

In summary, the coupling-induced atmospheric circulation adjustment—particularly the wind speed changes and the subsequent WES feedback—redistributes the thermal response, explaining both the southward shift of the warming and the localized cooling around 12°N.

Therefore, we have expanded the discussion in the revised manuscript to explicitly address this mechanism. We also cited the discussion here for convenience.

Moreover, the atmospheric-only simulation exhibits a radiative response that is spatially coherent with the dust aerosol distribution (Extended Data Fig. 14), while the coupled simulation displays additional spatial heterogeneity due to oceanic adjustments (Extended Data Fig. 11). This redistribution likely stems from ocean-atmosphere coupling, wherein the initial radiative perturbation triggers atmospheric circulation adjustments and subsequent wind-evaporation-SST feedbacks, creating secondary radiative perturbations that partially obscure the direct dust–radiation signal, which is ultimately manifested as a teleconnected response. Nevertheless, both experiments consistently support the proposed physical framework linking Middle Eastern dust forcing to IOD variability.

4. In the CAM simulations, enhanced SW fluxes do appear from southern Arabian Peninsula towards the Arabian Sea (Figs. S13a, S10a), but mainly over the northern and eastern Arabian Sea. And the changes in SW flux over the western tropical Indian Ocean are relatively weak. Does this imply a teleconnection that allow the local radiative impact of dust aerosols over the Arabian Peninsula and northern Arabian Sea to propagate to the tropical Indian Ocean?

Reply: Thank you for this perceptive question, which gets to the heart of the dynamical mechanisms at play. You are correct in observing that the enhanced SW fluxes in the CAM simulations are concentrated over the northern and eastern Arabian Sea, with a weaker direct signal over the western tropical Indian Ocean. This spatial structure indeed implies that the local radiative forcing from reduced dust does not remain confined, but rather initiates an atmospheric teleconnection that propagates its influence downstream.

The mechanism is a three-step process:

(1) Local Radiative Forcing & Atmospheric Adjustment: Reduced dust over the

Arabian Peninsula/northern Arabian Sea increases surface SW absorption, creating a strong vertical heating gradient (surface warming, relative upper-level cooling; Extended Data Figs. 11, 13a). This modifies local stability and circulation.

(2) Atmospheric Teleconnection & Downstream Cloud Response: The adjusted circulation and zonal cell (Fig. 2d) act as a teleconnection bridge, transporting the perturbation's influence to the western TIO. This alters the vertical thermodynamic profile, driving a characteristic cloud reorganization there: decreased low-level and increased high-level cloud cover (Fig. 3c, d). In the atmosphere-only (CAM) run, this teleconnected response is constrained by fixed SSTs, explaining the weaker direct maritime signal.

(3) Amplification via Ocean-Atmosphere Coupling: This step explains the stronger oceanic signal in the coupled model. The teleconnected cloud changes (Step 2) now interact with the ocean. Reduced low cloud cover increases surface shortwave radiation, leading to SST warming. This warming then activates powerful positive feedback loops: the cloud–SST feedback further suppressing low clouds (Lin et al., 2025; Wu et al., 2025; Wyant et al., 1997), the Bjerknes feedback and the wind-evaporation-SST (WES) feedback. These coupled feedbacks dramatically amplify and extend the initial atmospheric perturbation.

Therefore, the CAM pattern confirms the dust reduction initiates an atmospheric teleconnection. The coupling with the ocean is essential to transform this initial adjustment into the stronger, basin-scale ocean-atmosphere feedbacks that effectively drive the IOD development, as detailed in our manuscript. We have expanded the discussion in the revised manuscript to explicitly address this mechanism. We also cited the discussion here for convenience.

Notably, the spatial pattern of the SW flux response in the CAM simulations, with its maximum over the northern and eastern Arabian Sea rather than uniformly across the basin (Extended Data Fig. 17a &c), suggests that the radiative impact of dust

reduction initiates an atmospheric teleconnection. The initial perturbation mainly over the land likely alters regional atmospheric heating and circulation patterns⁴⁶⁻⁴⁸, which in turn redistributes the energy downstream, setting the stage for the more extensive and evident ocean-atmosphere signals and feedbacks that propagating to the TIO in the coupled model.

5. Regarding the mechanisms of dust radiative forcing, it would be more convincing to include figures to show radiative fluxes at the TOA and also vertical heating profiles in the regions with high dust loading.

Reply: We appreciate the reviewer's insightful comment regarding the mechanisms of dust radiative forcing. In response, we have added the new figure (Fig. R4 and Fig. R5 here) in the revised manuscript (Extended Data Fig. 13 and 17) as suggested.

These new results clearly illustrate the radiative forcing of reduced dust at the top of atmosphere and its heating rate, which aligns well with the temperature response in the revised manuscript (Extended Data Fig. 15).

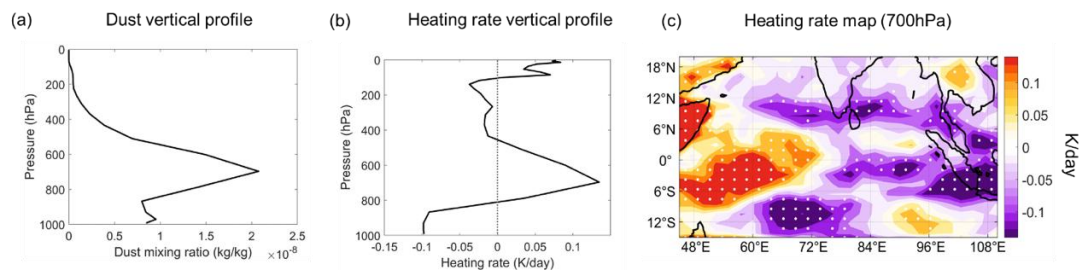


Fig. R4. Dust vertical profile and its corresponding heating rate for reduced dust.

(a) The vertical profile of dust mixing ratio and (b) heating rate over the transported area (10°S~10°N, 35°E~70°E) in the model. (c) The responses of SON 700 hPa heating rate to reduced Middle East dust forcing in the CESM. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

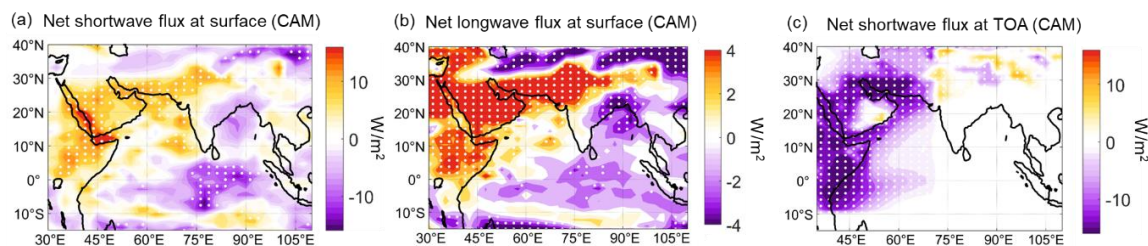


Fig. R5. The responses of SON radiation fluxes to reduced Middle East dust forcing in the CAM. The radiation fluxes include (a) net shortwave flux at surface, (b) net longwave flux at surface, and the net shortwave flux at the top of atmosphere (TOA). The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

We also added the corresponding discussion and cited it here.

Once transported, these aerosols exert a strong radiative forcing by absorbing solar radiation, which heats the upper troposphere, while simultaneously reducing the amount of shortwave radiation reaching the ocean surface. The dust-induced heating rate profile aligns with the simulated vertical distribution of dust extinction, which is primarily confined within the troposphere. This vertical coherence confirms that the radiative heating maxima correspond well with the dust layer's location, reinforcing the direct thermodynamic impact of dust radiative absorption on the atmospheric column. (Extended Data Fig. 13).

6. Some aspects of the model simulation setup are not very clear. In the CESM coupled simulation from 1980 to 2020, besides SMED, what other forcings are included? Are anthropogenic aerosols and greenhouse gases included in the model? Do they vary over time? What's the spin-up time for the coupled run?

Reply: We thank you for raising these important questions regarding our model configuration, which we are pleased to clarify. In our CESM1.2 coupled simulations, only the emissions of dust aerosols were modified between the control and sensitivity experiments. All other external forcings, including anthropogenic aerosols (e.g., sulfate, black carbon, organic carbon) and greenhouse gases, were included in the model and prescribed at their default, present-day levels. These non-dust forcings

were held constant throughout the 1980–2020 simulation period and did not vary interannually.

The coupled model was initialized from a pre-industrial control run and subsequently spun up for five years prior to the beginning of our formal experimental period (1980) (Xie et al., 2018). This spin-up duration ensured that the model's ocean and atmosphere components reached a stable equilibrium under the prescribed forcing.

We have added a detailed description of the experimental design, including the aerosol and greenhouse gas forcing specifications and the spin-up procedure to the revised manuscript for greater clarity.

To isolate the impact of Middle Eastern dust (10° S–30° N, 35° E–70° E) on interannual IOD variability, we drove CESM with observed summertime dust mixing ratio over the Middle East for 1980–2020 and diagnosed the resulting IOD index. Specifically, the summertime-mean dust loading in CESM was rescaled each year using the region's summertime station dust frequency observations, generating a transient dust-mass time series that faithfully captures observed variability. Other aerosols were prescribed at their default, present-day levels and not altered in the sensitivity simulations. Five ensemble members—generated by perturbing initial temperature fields over land and ocean—were averaged to suppress internal climate noise. The magnitude of the temperature perturbation is 1×10^{-14} K⁹³. The coupled model was also initialized from a pre-industrial control run and subsequently spun up for five years under present-day forcing conditions prior to the beginning of our formal experimental period (1980). This spin-up duration ensured the model's ocean and atmosphere components reached a stable equilibrium under the prescribed forcing⁹⁴. All atmospheric variables and the IOD index were then regressed onto regional dust loading to quantify the dust-driven changes from 1980 to 2020.

Minor comments

7. It is mentioned that dust aerosols are prescribed in the model, however, it is not

clear which dust variable was perturbed. Was it dust AOD, dust mass concentration at each pressure level, or emission fluxes? And is dust prescribed only the Middle East (leaving the rest of the world dust-free) or globally? It states that “we drove CESM with observed summertime dust mass density “(line 523), but it is unclear which observational dataset was used, and whether the forcing is applied only during the summer months or throughout the year. Are both dry and wet deposition included in the model?

Reply: We sincerely thank the reviewer for raising these important points regarding the dust aerosol prescription in our model. We have carefully revised the manuscript to clarify the following aspects, as suggested.

(1) Which dust variable was perturbed?

In our simulations, the dust aerosol forcing was implemented by perturbing the dust mixing ratio—that is, the three-dimensional field of dust mass concentration across atmospheric pressure levels. This approach allows us to consistently represent the spatial and vertical distribution of dust aerosols. We have now explicitly stated this in the revised text and cited it here for convenience.

In our simulations, the dust aerosol forcing was applied by perturbing the dust mixing ratio—the 3D mass concentration field.

(2) Spatial and temporal scope of dust prescription

The dust perturbation was applied only over the Middle East region (10°S~30°N, 35°E~70°E), as defined in the study, and only during the summer months (June–August). Outside this region and season, dust concentrations remain at their model climatological levels. The model is not dust-free elsewhere; rather, it uses the default climatological dust fields in other regions and seasons. We have clarified this in the revised manuscript and cited it here.

Notably, the dust perturbation was applied exclusively over the Middle East during

JJA. Beyond this spatiotemporal domain, the model uses its default climatological dust fields.

(3) Observational dataset and scaling method

The dust mixing ratio used to constrain the model is based on the MERRA-2 reanalysis dataset. To ensure consistency with observed dust aerosol optical depth (AOD), we scaled the default dust fields so that the simulated dust AOD matches the MERRA-2 dust AOD distribution over the study region. This scaling is applied only in summer and only over the Middle East. We have emphasized this in the revised text.

In our simulations, the dust aerosol forcing was applied by perturbing the dust mixing ratio—the 3D mass concentration field. However, the default dust mixing ratio of CESM is not sufficiently accurate to reproduce the spatiotemporal distribution of dust in the Middle East because of its inaccurate dust emission^{50,89-91}. To address this issue, we first conduct a control run using the default dust concentration file. Then, we divide the monthly dust AOD result of MERRA-2 by the monthly dust AOD in the control run to obtain monthly proportionality coefficients. By multiplying these monthly coefficients with the original dust mixing ratio, we can better reproduce the spatiotemporal distribution of Middle Eastern dust in the model. Results indicate that the model successfully reproduces the spatial pattern and intensity of the dust in the Middle East (Extended Data Fig. 10a). Notably, the dust perturbation was applied exclusively over the Middle East during JJA. Beyond this spatiotemporal domain, the model uses its default climatological dust fields.

(4) Inclusion of deposition processes

Both dry and wet deposition processes are fully represented in the model, as part of the standard aerosol module in CESM. We have added a statement in the manuscript to explicitly confirm this and cited it here.

Both dry and wet deposition processes are fully represented in the model, as part of the standard aerosol module in CESM⁸⁹.

We hope these clarifications adequately address the reviewer's concerns. Thank you once again for the constructive feedback.

8. For the sensitivity test with reduced dust loading, was the forcing applied only in summertime or all year round? It would be helpful to include a table summarizing key features of each simulation.

Reply: We thank you for this pertinent question regarding the experimental design. In the dust reduction sensitivity experiment, the forcing (i.e., the reduction in dust aerosol emissions) was applied exclusively during the summer (JJA) season. During the rest of the year, dust emissions, along with all other model forcings, were identical to those in the control run. This setup was intentionally chosen to isolate the specific climatic impact of summertime Middle Eastern dust variability. We also cited the added explanation in the revised manuscript and cited it here.

The final summertime forcing field is derived by subtracting this scaled perturbation field from the 1980-2020 climatological mean, ensuring compatibility with CAM4's input requirements. Additionally, during the rest of the year, dust emissions, along with all other model forcings, were identical to those in the control run.

Furthermore, we fully agree with your suggestion that a summary table would enhance the clarity of our experimental setup. In response, we have included a new table (Table R1, namely Extended Data Table 1) in the revised manuscript. This table systematically summarizes the key features of all simulations conducted in this study, including the specific forcing modifications, their temporal application, and the integration periods for both the CESM and CAM experiments.

Table S1 Key features of each simulation.

Component	Dust Forcing	Simulation Period
	The observed summertime dust mixing ratio over the Middle East for 1980–2020	1980-2020
CESM	1980-2020 climatological mean dust mixing ratio reduced dust mixing ratio by ~20% change increased dust mixing ratio by ~20% change	Five years
CAM	1980-2020 climatological mean dust mixing ratio reduced dust mixing ratio by ~20% change	

9. It is recommended to include some discussion about the uncertainties of the study. For instance, in model simulations, dust content is prescribed, so any feedback from atmospheric circulation to the dust loading is not considered. In terms of station data, what's the uncertainty in measurements? Do the station location and numbers change from 1980 to 2020? Does the uneven spatial distribution of the stations affect the results?

Reply: We thank the reviewer for this valuable suggestion. We have added a discussion on the uncertainties in the revised manuscript. A key model uncertainty is that prescribing dust aerosols neglects feedbacks from atmospheric circulation onto dust emissions and transport. For the station data, we only selected stations with long-term records, so the location and number do not change from 1980 to 2020.

While we used stations with long-term records to mitigate temporal inconsistencies, the uneven coverage remains a limitation, which we acknowledge may influence the representativeness of the observed regional trends. This discussion provides a more balanced interpretation of our results.

We also cited the discussion about the uncertainties regarding the model and station data here.

This study has limitations regarding the model and station dust observations. Specifically, the model experiments prescribe dust and thus neglect feedbacks of atmospheric circulation on dust emissions. Additionally, the observational trends could be influenced by the uneven spatial distribution of meteorological stations over the analysis period.

10. Line 64, it may be helpful to show the response the strongest in SON.

Reply: We thank the reviewer for this valuable suggestion. We agree that explicitly demonstrating the peak season of the SST response strengthens our argument. Following the reviewer's advice, we have conducted the additional analysis and created a figure that clearly shows the seasonal evolution of the SST response, confirming that it is indeed strongest in the September-October-November (SON) season.

This new figure has been included in the Supplementary Information as Fig. R6 (or Extended Data Fig. 3 in the revised manuscript), and we have added a citation to it in the revised manuscript. We also cited it here for convenience.

Model simulations also confirm that SON is the season when the IOD responds most strongly to reductions in dust forcing, thereby identifying SON as the optimal season for analysis (Extended Data Fig. 3).

We believe this addition significantly improves the clarity of our manuscript and are grateful to the reviewer for the constructive input.

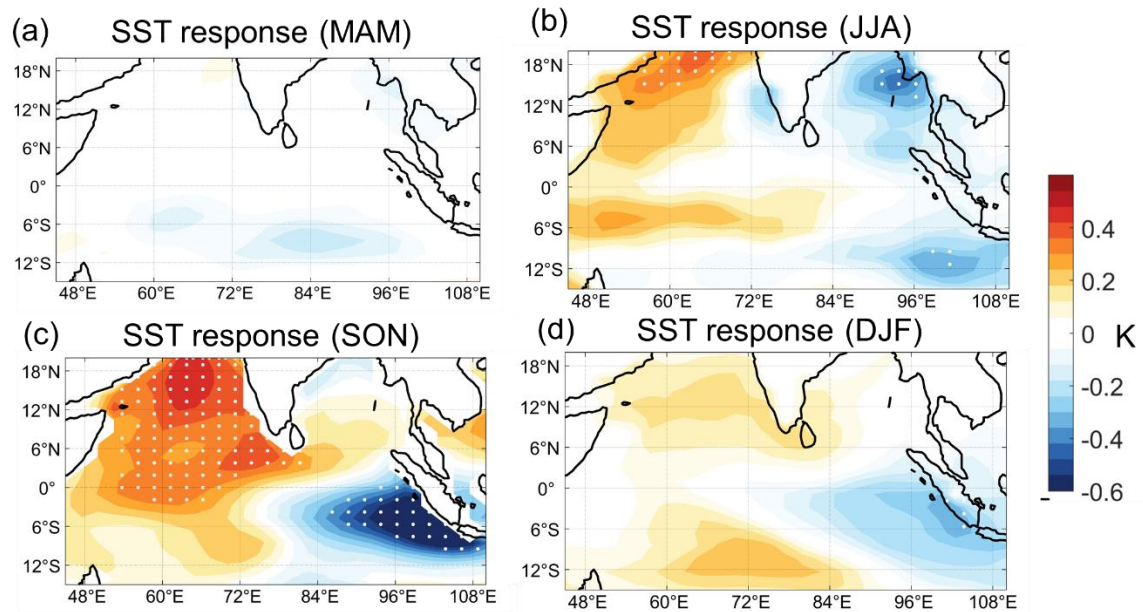


Fig. R6. The SST responses in different seasons including (a) MAM, (b) JJA, (c) SON, and (d) DJF. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

11. Lines 78-79, it is not clear what averaging area is used for the MISR non-spherical AOD.

Reply: Thanks for pointing it out. The averaging area for the MISR non-spherical AOD is the same as station dust record (averaged over the 10°S~30°N, 35°E~70°E). We have added this supplementary explanation in the figure caption.

12. Line 158, this seems to contradict the statement in lines 134-135. Could you please clarify what the systematic biases are?

Reply: We sincerely thank the reviewer for this insightful comment, which highlights a need for greater clarity in our discussion. The two statements address complementary rather than contradictory aspects of the model's performance, and we have revised the text to eliminate any potential for misunderstanding.

The statement in Lines 134-135 emphasizes the model's success in reproducing the spatial pattern of the dust-IOD relationship—namely, the large-scale dipole structure

over the tropical Indian Ocean. This demonstrates that the fundamental physical linkage is captured by the model.

In contrast, the statement in Line 158 pertains to the attenuation of the temporal correlation coefficient (i.e., the simulated correlation is systematically lower than observed). One key reason for this attenuation is the model's inherent systematic biases in its representation of IOD dynamics. These include well-documented biases in climate models, such as an overly strong thermocline feedback in the eastern Indian Ocean, an exaggerated seasonal cycle, or an inaccurate mean state (Yao et al., 2016; Xiao et al., 2022). Such biases do not necessarily prevent the model from simulating the correct spatial pattern of the IOD's SST anomalies, but they can distort the amplitude and precise timing of its evolution. This distortion in the dynamics introduces "noise" into the simulated year-to-year relationship between dust (SMED) and the Dipole Mode Index (DMI), thereby collectively amplifying the deviation from observations in the strength of the temporal correlation.

To clarify this, we have revised the relevant sentence in the manuscript and cited it here.

Nevertheless, the simulated correlation coefficient remains systematically lower than that estimated by observation. This attenuation is attributable to (i) the reliance of the model on station-based dust frequency to scale column-integrated dust-mass density, which introduces additional sampling uncertainty, and (ii) systematic biases in the model's representation of IOD dynamics (e.g., in the thermocline feedback and seasonal phase locking), which distort the precise evolution of the mode and collectively amplify the attenuation of the simulated correlation relative to observations.

13. Line 175, there is also a weak increase in the mixed layer depth over the eastern tropical Indian Ocean from 100°E to 108 °E (Fig. 2b). What could be the cause of this?

Reply: We thank the reviewer for this observation. The weak increase in mixed layer depth over the eastern tropical Indian Ocean is likely a result of internal climate variability or model uncertainty in responding to the prescribed forcing. We have acknowledged this point in the revised manuscript as part of the broader discussion on the regional nuances of the model response. We also cited it here for convenience.

It is noteworthy that a weak increase in MLD is also simulated over the eastern tropical Indian Ocean (Fig. 2b), which may be attributed to internal climate variability rather than a direct response to dust forcing.

14. Line 219, regression analysis is less straightforward than performing another simulation without the variability of Middle Eastern dust and comparing the differences. Conducting a linear regression assumes that the relationships are linear, which may not necessarily be true.

Reply: Thank you for this important methodological point. We agree with the reviewer that a carefully designed sensitivity experiment provides a more direct and robust demonstration of causality than regression analysis alone. In fact, we have conducted two additional sensitivity experiments as detailed in Extended Data Table 1: one with increased Middle Eastern dust and another with decreased dust over this region.

In our analysis, the regression analysis is mainly applied to the observational and reanalysis data to identify statistical relationships. In contrast, the changes shown in the model experiments (with increased and decreased dust; Extended Data Figs. 9 & 10) represent the direct model response to the prescribed dust forcing.

The coherent alignment—in both pattern and sign—between this direct model response and the statistical relationships identified from observations strengthens the robustness of the dust-IOD link, moving the evidence beyond the potential constraints of a purely linear statistical framework.

15. Line 220, “Increased solar radiation penetrates to the surface...” , this is not clearly shown in Fig. S8c, especially over the region with reduced dust. Please clarify.

Reply: Thanks for pointing it out. You are correct that the region of increased net shortwave radiation at the surface in the fully coupled model experiment (Fig. S8c) does not perfectly align with the primary dust reduction area. This occurs precisely because the CESM is a fully coupled climate model. The initial radiative perturbation from dust reduction triggers a chain of ocean-atmosphere interactions, including adjustments in atmospheric circulation and wind-evaporation-SST feedbacks. These processes redistribute the energy downstream, generating secondary radiative anomalies that can partially mask the direct local signal. This energy redistribution is a fundamental feature of the coupled climate system and is the key mechanism that establishes the remote teleconnection pattern we describe.

In contrast, as the reviewer might anticipate, a parallel experiment conducted with an atmosphere-only model (CAM, Extended Data Fig. 14c) does show a clear and localized increase in net shortwave radiation confined to the dust source region, as it lacks these ocean-mediated feedbacks. The comparison between these two experiments robustly demonstrates how the direct radiative forcing from dust evolves into a broader teleconnection within a coupled framework.

We have clarified this crucial point in the revised manuscript to better guide the reader's interpretation of Extended Data Fig. 11c. We also cited the clarification here.

Moreover, the atmospheric-only simulation exhibits a radiative response that is spatially coherent with the dust aerosol distribution (Extended Data Fig. 14), while the coupled simulation displays additional spatial heterogeneity due to oceanic adjustments (Extended Data Fig. 11). This redistribution likely stems from ocean-atmosphere coupling, wherein the initial radiative perturbation triggers atmospheric circulation adjustments and subsequent wind-evaporation-SST feedbacks, creating secondary radiative perturbations that partially obscure the direct dust–radiation signal, which is ultimately manifested as a teleconnected response. Nevertheless, both experiments consistently support the proposed physical framework linking Middle Eastern dust forcing to IOD variability.

16. Lines 221-225, it's not clear why the coupled results are already available (line 192) but then the analysis switches to an atmosphere-only model, and then returns to the coupled simulation.

Reply: We thank the reviewer for raising this point regarding our experimental workflow, which we agree requires clear justification. The sequential use of the coupled model (CESM) and the atmosphere-only model (CAM) was a deliberate design to dissect the underlying mechanisms.

The fully coupled simulation reveals the net effect of dust forcing, including all subsequent ocean-atmosphere feedbacks and teleconnections. We then introduced the atmosphere-only (CAM) experiments specifically to isolate the direct atmospheric response to the dust aerosol radiative forcing, devoid of any ocean feedbacks due to its use of prescribed SSTs. This approach allows us to cleanly attribute the initial atmospheric perturbation to the dust forcing itself.

Finally, returning to the coupled model results allows us to interpret the full, evolved climate response—including the teleconnection patterns—as a consequence of the initial forcing identified in CAM, now amplified and modulated by coupled processes.

We have clarified this rationale in the revised manuscript to guide the reader through our analytical strategy. We also cited it here for convenience.

By employing prescribed SSTs, this atmosphere-only simulation inherently excludes ocean feedbacks, thus allowing a clear attribution of the atmospheric response to the dust forcing.

17. Line 229-230 “the direct radiative effects of reduced dust”, is it possible to clarify the location of this effect in the figure?

Reply: Thanks for your suggestion. We have clarified the location of this effect, which is over the western TIO and cited it here.

The transformation of cloud fields further modifies the radiative budget by increasing both longwave and shortwave radiation, thereby amplifying the warming signal over

the western TIO in synergy with the direct radiative effects of reduced dust (Figs. 3a, b).

18. Line 267, the response of shortwave fluxes is mainly over the land. How does the signal propagate to the TIO?

Reply: Thank you for raising this question. The signal propagates from the land to the Tropical Indian Ocean (TIO) primarily through an atmospheric teleconnection. The mechanism is a three-step process:

(1) Local Radiative Forcing & Atmospheric Adjustment: Reduced dust over the Arabian Peninsula/northern Arabian Sea increases surface SW absorption, creating a strong vertical heating gradient (surface warming, relative upper-level cooling; Extended Data Figs. 11, 13a). This modifies local stability and circulation.

(2) Atmospheric Teleconnection & Downstream Cloud Response: The adjusted circulation and zonal cell (Fig. 2d) act as a teleconnection bridge, transporting the perturbation's influence to the western TIO. This alters the vertical thermodynamic profile, driving a characteristic cloud reorganization there: decreased low-level and increased high-level cloud cover (Fig. 3c, d). In the atmosphere-only (CAM) run, this teleconnected response is limited by fixed SSTs, explaining the weaker direct maritime signal.

(3) Amplification via Ocean-Atmosphere Coupling: This step explains the stronger oceanic signal in the coupled model. The teleconnected cloud changes (Step 2) now interact with the ocean. Reduced low clouds enhance surface SW, warming the SST. This warming then triggers powerful positive feedbacks: the cloud–SST feedback further suppressing low clouds (Lin et al., 2025; Wu et al., 2025; Wyant et al., 1997), the Bjerknes feedbacks and wind-evaporation-SST (WES) feedbacks. These coupled feedbacks dramatically amplify and extend the initial atmospheric perturbation.

Therefore, the CAM pattern confirms the dust reduction initiates an atmospheric teleconnection. The coupling with the ocean is essential to transform this initial adjustment into the stronger, basin-scale ocean-atmosphere feedbacks that effectively

drive the IOD development, as detailed in our manuscript.

In summary, the dust-induced radiative heating over the Middle East perturbs the regional atmospheric circulation, which in turn triggers a remote response that influences the TIO.

We have systematically elaborated this dynamical pathway in the revised manuscript within the " Mechanism: how dust shapes the IOD" section, detailing the key processes of (1) local radiative adjustment, (2) atmospheric bridge via zonal cell circulation, and (3) amplification through air-sea feedbacks, and we refer the reader to that discussion here.

We have also clarified this dynamical pathway in the revised manuscript and cited it here.

The initial perturbation mainly over the land likely alters regional atmospheric heating and circulation patterns ⁴⁶⁻⁴⁸, which in turn redistributes the energy downstream, setting the stage for the more extensive and evident ocean-atmosphere signals and feedbacks that propagating to the TIO in the coupled model.

19. Lines 275-276, "(Extended Data fig. 10)", isn't the figure from the atmosphere-only model run (as mentioned in line 221)?

Reply: Thanks for pointing it out and you are right. We have modified the statement and cited it here.

Atmosphere-only model and observation comparisons further reinforce these findings.

20. Line 304, cooler western part?

Reply: Thanks for pointing it out and sorry for the typo. We have revised as suggested.

21. Line 355, do you mean "reduced dust anomalies"

Reply: Thanks for pointing it out and you are right. We have incorporated this suggestion into the revised manuscript.

22. Line 360, dust forcing in JJA or SON?

Reply: Sorry for the misunderstanding. It is indeed the dust forcing in JJA. We have clarified this in the revised manuscript and cited it here.

23. Lines 252-257, how is this done? Are you using the ratio of JJA MERRA-2 dust AOD to modeled dust AOD to scale dust loading in each month?

Reply: Thanks for your suggestion and you are right. We are using the ratio of JJA MERRA-2 dust AOD to modeled dust AOD to scale dust loading in each month. We also clarified this procedure in the revised manuscript and cited it here.

To address this issue, we used the ratio of JJA MERRA-2 dust AOD to modeled dust AOD to scale dust loading in each month. Specifically, we first conduct a control run using the default dust concentration file. Then, we divide the monthly dust AOD result of MERRA-2 by the monthly dust AOD in the control run to obtain monthly proportionality coefficients. By multiplying these monthly coefficients with the original dust mixing ratio, we can better reproduce the spatiotemporal distribution of JJA Middle Eastern dust in the model.

24. Line 258, “by perturbing initial temperature fields”, is it land or ocean surface temperature? How large are the perturbation?

Reply: We thank the reviewer for this question. The small, machine-level perturbation (1×10^{-14} K) was applied to the initial temperature fields of both the land and ocean components to initiate the ensemble spread (Yeager et al., 2018). This detail has been clarified in the revised manuscript and cited here for convenience.

Five ensemble members—generated by perturbing initial temperature fields over land and ocean—were averaged to suppress internal climate noise. The magnitude of the temperature perturbation is 1×10^{-14} K.

25. Line 540, one standard deviation over what time period?

Reply: We thank the reviewer for pointing out the need for clarification. The one standard deviation (1σ) is calculated from the summertime (June-July-August) data

spanning the entire study period of 1980 to 2020, based on the regional mean time series. This scaling is used to define the characteristic magnitude of the perturbations. We have amended the manuscript to explicitly state this timeframe.

Subsequently, the coefficient field is scaled by one standard deviation (1σ) over summertime from 1980 to 2020 of the regional mean time series to define characteristic perturbation magnitudes.

26. Fig. 1c, consider adding all the dust time series as a reference (e.g., including MODIS DOD and MERRA-2 dust column mass density). Is it possible to include DMI

time series as well and show the correlations between DMI and different Middle Eastern dust indices from 1980 to 2023 and 2003 to 2023? Fig. 1d-g, can you please clarify in the figure caption the time period over which the regressions were calculated? Was it 2003 to 2023? Were the data detrended before calculating the regressions?

Reply: Thank you for this helpful suggestion. We have included time series of additional Middle Eastern dust indices and DMI time series in Extended Data Fig. 4 in the revised manuscript (Fig. R7 here). This avoids overcrowding the figure while ensuring all relevant data and statistical evidence are fully available to the reader in the supplement. We also show the correlations between DMI and different Middle Eastern dust indices from 1980 to 2023 and 2003 to 2023 in corresponding figures (Fig. 1 and Extended Data Fig. 4 in the revised manuscript). We cited this figure here for convenience.

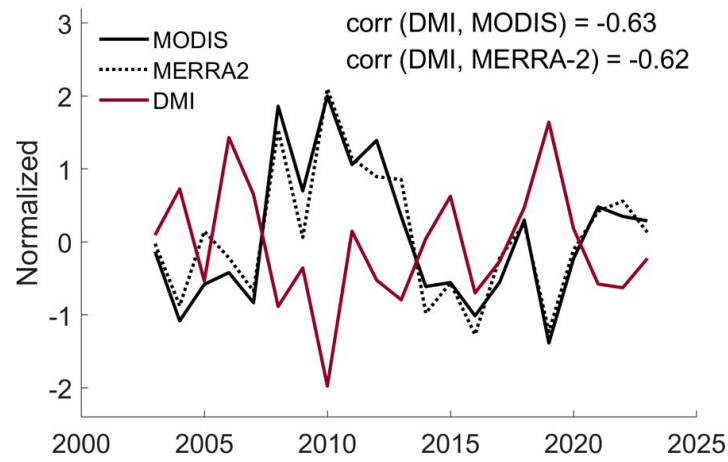


Fig. R7. Time series of standardized JJA MODIS dust optical depth (the black solid line), JJA MERRA-2 dust column mass density (the black dashed line), and SON DMI index (the red solid line) from 2003 to 2023.

Moreover, we have clarified the figure caption the time period over which the regressions were calculated. The data has been detrended before calculating the regressions. We have modified the figure caption (Fig. 1 in the revised manuscript and Fig. R8 here) as suggested and cited it here.

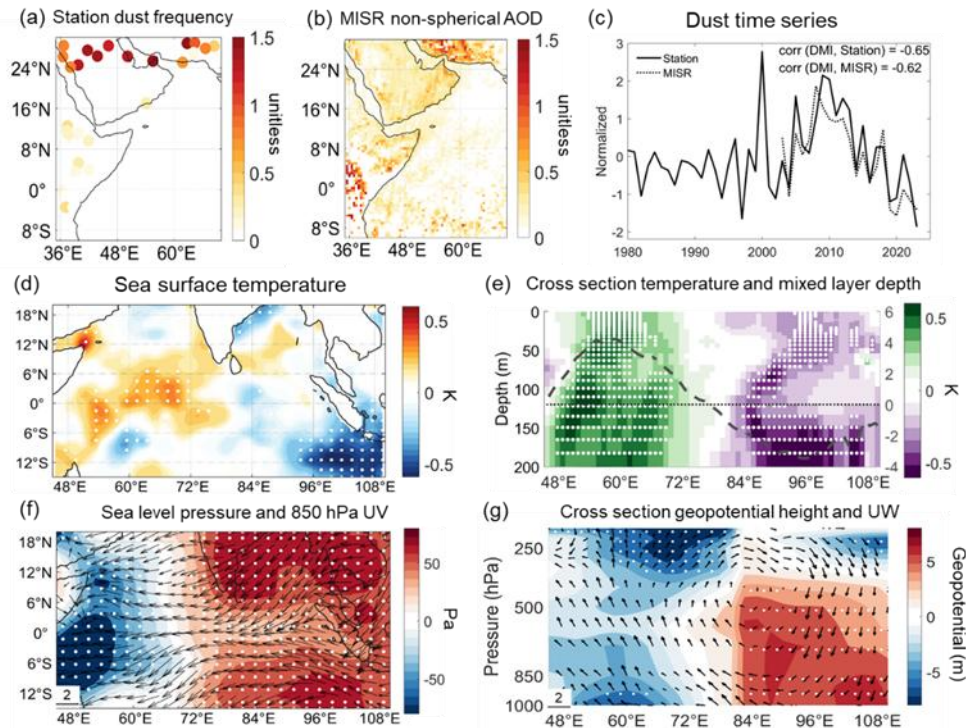


Fig. R8. Dust proxies, sea surface temperature and meteorological field regressed on dust time series. (a) The regression coefficients of JJA station dust record on the Middle East regional-averaged station dust frequency (averaged over the 10°S~30°N, 35°E~70°E). (b) Similar to a, but for the JJA MISR non-spherical aerosol optical depth (AOD, also averaged over the 10°S~30°N, 35°E~70°E). (c) Time series of standardized JJA station dust frequency (the solid line) from 1980 to 2023, and JJA MISR non-spherical aerosol optical depth (the dashed line) from 2003 to 2023. (d-g) The detrended regression coefficients of SON meteorological fields on the detrended JJA MISR non-spherical aerosol optical depth averaged over the Middle East from 2003 to 2023. These meteorological fields include (d) sea surface temperature. (e) meridional mean (20°S-20°N) vertical cross section of temperature (shaded) and mixed layer depth (the gray dashed line), (f) sea level pressure (shaded) with 850 hPa zonal and meridional wind (UV, vectors, m/s), and (g) meridional mean (20°S-20°N) vertical cross section of geopotential height (GPH, shaded) with zonal and vertical wind (UW, vectors, m/s). The y-axes on the right in (e) corresponds to the response of mixed layer depth. The regression is currently done for individual years. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

27. Fig. 2, are the fields derived from time averages or from regression? Fig. 2b, the location of the temperature anomalies appears at a higher altitude than in the observation (Fig. 1). Is this due to model bias? Could you please comment on this?

Reply: We thank the reviewer for these insightful questions.

Firstly, the fields in Fig. 2 are derived from regression analysis, not simple time averaging. We have clarified this in the figure caption of the revised manuscript.

Fig. 2. The regression coefficients of SON meteorological fields onto JJA dust aerosol optical depth (AOD) from 1980 to 2020 in the CESM coupled model simulations. These coefficients were scaled by the magnitude of dust decreasing from 2010 to 2020 in the CESM. These meteorological fields include (a) sea surface temperature. (b) meridional mean (20°S-20°N) vertical cross section of temperature (shaded) and

mixed layer depth (the gray dashed line), (c) sea level pressure (shaded) with 850 hPa zonal and meridional wind (UV, vectors, m/s), and (d) meridional mean (20°S-20°N) vertical cross section of geopotential height (GPH, shaded) with zonal and vertical wind (UW, vectors, m/s). The y-axes on the right in (b) corresponds to the response of mixed layer depth. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.

Secondly, we agree that the displacement of temperature displacement is likely attributable to model bias. However, despite this bias in the exact altitude, the model successfully captures the key physical process crucial for our proposed pathway. We have added the additional discussion regarding the inconsistency of temperature response in the manuscript and cited it here.

The CESM experiments reveal a robust dipole SST anomaly pattern across the TIO in response to reduced dust forcing (see Method), closely mirroring the observed regression between dust and SST (Fig. 2a) despite some latitudinal displacements that are partly attributed to model biases.

28. Fig. S2, please mark whether the correlations are statistically significant.

Reply: Thanks for your suggestions. We have the marked critical correlation coefficients for statistical significance in Extended Data Fig. 2 in the revised manuscript and cited it here (Fig. R9).

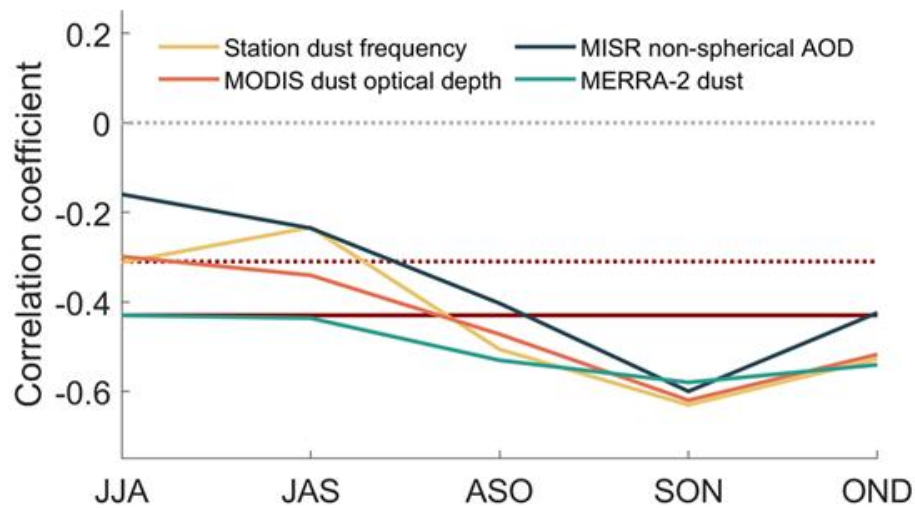


Fig. R9. Correlation coefficients between JJA dust proxies and DMI in different three months. These dust proxies include station dust frequency (the yellow line, 1980-2023), MODIS dust optical depth (the orange line, 2003-2023), MISR non-spherical AOD (the black line, 2003-2023), and MERRA-2 dust column mass density (the green line, 2003-2023). The dashed grey line indicates the position of zero correlation. The dashed and solid red lines indicate the critical correlation coefficients for statistical significance of station dust frequency and the other three dust proxies, respectively.

29. Fig. S6a, could you please add the stimulated dust AOD to it?

Reply: Thanks for your helpful suggestions and we have added the simulated dust AOD as suggested (Fig. R10 here, the same as the Extended Data Fig. 9 in the revised manuscript). We also cited it here for convenience.

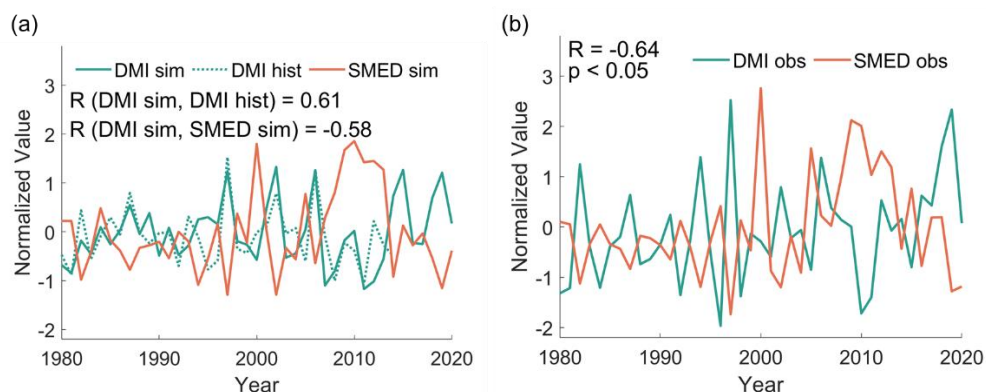


Fig. R10. *The standardized DMI and SMED from 1980 to 2020. The time series are (a) simulated DMI forced by dust (solid cyan line), simulated DMI in the historical run with all forcing (dashed cyan line), and simulated SMED (solid red line) and (b) observed DMI and SMED. All the time series are standardized for comparison*

We also added the explanation for this figure and also cited it here.

The simulated SMED also has high correlation with DMI series (Extended Data Fig. 9a, $R = -0.58$, $p \leq 0.05$), further validating their relationship.

30. Fig. S8a, is the obtained through regression?

Reply: Yes, you are right. We have clarified this in the figure caption.

31. Figs. S10b, d, are the flux date from MERRA-2? And what is the averaging area used for MISR AOD in the regression analysis?

Reply: Indeed, you are correct. The flux data are sourced from MERRA-2. Regarding the averaging area for MISR AOD, we confirm that it is identical to that specified in the manuscript (10°S~30°N, 35°E~70°E) for consistency.

32. Fig. S11, which simulation does this refer to? Is it from the sensitivity simulation or the coupled run from 1980 to 2020?

Reply: This simulation refers to the CESM coupled model simulations from 1980 to 2020. We have clarified this in the figure caption and cited it here.

Fig. S11. *The responses of SON meridional mean (20 °S-20 °N) vertical cross section of temperature to reduced Middle East dust forcing from 1980 to 2020 in the CESM coupled model simulations. The area with white dots passed the significance test of $p \leq 0.05$ by Student's t-test.*

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Response to the review of “Middle East Dust as a Dominant External Driver of the Indian Ocean Dipole” (NCOMMS-25-75253-T).

Responses to Review 03 ’s comments

Summary:

The manuscript investigates the role of mineral dust aerosols from the Middle East in modulating interannual variability of the Indian Ocean Dipole (IOD). Using a combination of satellite observations, reanalysis datasets, and climate model experiments, the authors demonstrate that variations in summer dust emissions between 1980 and 2020 explain approximately 36% of the observed interannual IOD variance—exceeding the influence of the El Niño–Southern Oscillation (ENSO) during boreal autumn. Overall, the paper identifies a previously underappreciated dust–IOD teleconnection, emphasizing the importance of aerosol forcing in seasonal prediction and long-term climate projections. Overall, the work is novel, and supported by comprehensive analysis. However, the manuscript is not always easy to follow, as several figure captions and axis labels lack clarity and may cause confusion for readers. I recommend publication after revision to address the points detailed below.

Reply: We are grateful to the reviewer for his/her insightful and very valuable suggestions, which have significantly contributed to the enhancement of our manuscript. We have carefully addressed the comments and made the necessary revisions, hoping that the updated version meets the journal's standards. Our responses to each of the comments and suggestions are as follows. The referee's original comments are shown in blue. Our replies are shown in black. The corresponding changes in the manuscript are shown in *Italic black*.

1. The paper explains how dust emission reduction over Middle East causes a positive anomaly in solar radiation reaching to the western Indian ocean surface. However, it does not clearly discuss how this enhanced radiative energy translates into a positive SST anomaly, considering the ocean's large heat capacity. Please expand on this physical mechanism. Is the ~2-month lag used in the analysis related to the ocean mixed-layer adjustment timescale?

Reply: We thank the reviewer for raising this crucial point regarding the mechanism linking enhanced solar radiation to the positive SST anomaly. We agree that a clearer discussion of this process is essential and have expanded upon it in the revised manuscript.

The translation of increased net surface shortwave radiation into a positive SST anomaly occurs through the gradual heat accumulation within the ocean's mixed layer. The **~2-month lag** used in our analysis is indeed closely related to the mixed-layer adjustment timescale for the western Indian Ocean. Case studies in the tropical Indian Ocean have shown that the thermodynamic response of the mixed layer to sustained atmospheric forcing (such as radiative anomalies) can manifest over a period of approximately 2 to 2.5 months (Azaneu, 2022).

In our case, the persistent positive anomaly in net surface heat flux (dominated by shortwave radiation) progressively heats the relatively shallow mixed layer typical of the western tropical Indian Ocean. The observed lag represents the integrated time required for this accumulated heat to become a robust SST signal, consistent with the established mixed-layer response timescale for this region. We have incorporated this explanation with supporting references into the revised discussion section.

The translation of increased shortwave radiation into the initial SST anomaly involves the gradual heat accumulation within the ocean's mixed layer. The observed ~2-month lag reflects the mixed-layer adjustment timescale, which is approximately 2 to 2.5 months for sustained thermal forcing in the TIO³⁴. Given the relatively shallow mixed layer in the western Indian Ocean³⁵⁻³⁷, this persistent radiative forcing can efficiently

warm the upper ocean within this timeframe, overcoming the damping from mixing and latent heat loss.

2. Please explain why there is a positive net LW flux at surface over the western Indian ocean in the case of dust deduction? Moreover, for both SW and LW, why the flux anomaly over eastern Indian ocean is always opposite to the western part?

Reply: We thank the reviewer for these insightful questions regarding the surface energy balance.

(1) Positive net LW flux anomaly over the western Indian Ocean: The positive anomaly in net surface longwave (LW) radiation is a result of coupled atmospheric adjustments. We propose two complementary mechanisms: First, as previously noted, the initial warming and enhanced evaporation increase atmospheric water vapor, which strengthens downward LW radiation. Second, and importantly, the dust reduction triggers an atmospheric teleconnection that perturbs cloud fields. As elaborated below, this leads to increased high-level cloudiness over the western IO basin. These high clouds are highly effective at emitting LW radiation downward, thereby significantly contributing to the observed positive net LW flux anomaly at the surface. We have also incorporated the explanation in the revised manuscript and cited it here.

The transformation of cloud fields further modifies the radiative budget by increasing both longwave and shortwave radiation, thereby amplifying the warming signal over the western TIO in synergy with increased SW and LW radiative fluxes over this region of reduced dust (Figs. 3a, b). Moreover, the initial warming and enhanced evaporation might increase atmospheric water vapor over the western TIO, which strengthens downward LW radiation (Fig. 3b).

(2) Dipole pattern of flux anomalies: The opposing flux anomalies are a direct manifestation of the zonal atmospheric circulation cell excited by the Middle East dust forcing. Over the western basin, the large-scale ascendance leads to reduced low-level cloudiness, allowing more shortwave radiation to penetrate to the surface

(positive SW anomaly). Concurrently, the circulation fosters increased high-level cloudiness, which traps longwave radiation (positive LW anomaly). Over the eastern basin, the opposite vertical motion and cloud adjustments occur (increased low-cloud and decreased high-cloud) because of the anomalous zonal circulation, resulting in negative SW and LW flux anomalies. We have incorporated this physical interpretation into the revised manuscript to provide a more mechanistic explanation of the surface flux changes and cited it here.

Moreover, the dipole pattern of radiative flux anomalies over the TIO arises from the anomalous zonal circulation (Fig. 2d) and zonal asymmetry in cloud vertical structure (Fig. 3c, d). Over the western basin, diminished low-level clouds enhance incoming shortwave radiation, while increased high-level clouds trap outgoing longwave radiation, leading to positive anomalies in both SW and LW fluxes. Conversely, the eastern basin exhibits opposite cloud adjustments—more low-level and fewer high-level clouds—resulting in reduced surface radiative fluxes.

3. Line 88, ‘reversing the regression coefficients to represent dust reduction’ is very confusing, I figured out its meaning when I looked at the figure caption of Fig. S3, it means you take the negative values of the regression coefficient. Please modify the sentence, and also clarify it in the caption of Fig.1.

Reply: We thank the reviewer for pointing out this lack of clarity. We have modified the sentence and clarified the caption of Fig. 1 to explicitly state that the patterns for dust reduction were obtained by taking the negative values of the regression coefficients. We also cited them here for convenience.

To quantify the dust-IOD connection, we regressed SON SST anomalies over the tropical Indian Ocean against SMED and took the negative values of the regression coefficients to indicate dust reduction.

4. Fig S3, you mentioned ‘regression coefficient’ and ‘correlation coefficient’ in the figure caption, are they the same? Please clarify what you used and keep them consistent.

Reply: We thank the reviewer for highlighting this inconsistency. Indeed, the two terms are different and the analysis presented is based on the regression coefficient. We have corrected the caption of Fig. S3 (and any other relevant figures) to consistently use the term "regression coefficient" throughout the manuscript to avoid any confusion.

5. In Fig1 (e), please clarify that the grey dashed line is the mixed layer depth anomaly, right? It is not just mixed layer depth. Also, please clarify the grey dashed line is corresponding to the y-axis on the right. Otherwise, it's too confusing.

Reply: We thank the reviewer for this suggestion. The reviewer is correct. The grey dashed line in Fig. 1e represents the mixed layer depth anomaly. We have revised the figure caption to explicitly state this and to clarify that it corresponds to the right y-axis, in order to eliminate any potential confusion.

We also cited it here for convenience.

Fig. 1. Dust proxies, sea surface temperature and meteorological field regressed on dust time series. (a) The regression coefficients of JJA station dust record on its regional mean (averaged over the $10^{\circ}\text{S}\sim 30^{\circ}\text{N}$, $35^{\circ}\text{E}\sim 70^{\circ}\text{E}$). (b) Similar to a, but for the JJA MISR non-spherical aerosol optical depth (AOD, also averaged over the $10^{\circ}\text{S}\sim 30^{\circ}\text{N}$, $35^{\circ}\text{E}\sim 70^{\circ}\text{E}$). (c) Time series of standardized JJA station dust frequency (the solid line) from 1980 to 2023, and JJA MISR non-spherical aerosol optical depth (the dashed line) from 2003 to 2023. (d-g) The detrended regression coefficients of SON meteorological fields on the detrended JJA MISR non-spherical aerosol optical depth averaged over the Middle East from 2003 to 2023. These meteorological fields include (d) sea surface temperature. (e) meridional mean ($20^{\circ}\text{S}\sim 20^{\circ}\text{N}$) vertical cross section of temperature (shaded) and mixed layer depth anomaly (the gray dashed line), (f) sea level pressure (shaded) with 850 hPa zonal and meridional wind (UV, vectors, m/s), and (g) meridional mean ($20^{\circ}\text{S}\sim 20^{\circ}\text{N}$) vertical cross section of geopotential height (GPH, shaded) with zonal and vertical wind (UW, vectors, m/s).

*These coefficients were scaled by the magnitude of dust decreasing from 2010 to 2020 in the JJA MISR non-spherical aerosol optical depth dataset. The right y-axis in (e) corresponds to the mixed layer depth; the grey dashed line represents its zero value. The regression is currently done for individual years. The area with white dots passed the significance test of $p \leq 0.05$ by Student's *t*-test.*

6. Line 93, ‘0.5K per standard deviation of dust variability’, please clarify the meaning of this term. Authors use different dust proxies, e.g., dust AOD, column mass density, and dust frequency, what are their standard deviation of dust variability, respectively.

Reply: We thank the reviewer for this important clarification. The statement “~0.5 K per standard deviation of dust variability” should be interpreted as a statistical estimate derived from the composite of multiple dust proxies—not as a precise one-to-one relationship for each individual proxy. In our analysis, a one-standard-deviation decrease in different dust indicators (station dust frequency, MISR non-spherical AOD, MERRA-2 dust column mass density) is associated with a western Indian Ocean warming of roughly 0.5 K. Because each proxy has its own magnitude of variability, the exact warming per standard deviation slightly differs across indicators; the value of ~0.5 K represents a central estimate from the multi-proxy analysis. We have revised the relevant text in the manuscript to clarify this point and to avoid any potential misinterpretation.

The regression coefficients from the multi-proxy analysis collectively suggest that a decrease in Middle Eastern dust loading is associated with a western Indian Ocean warming of approximately 0.5 K per standard deviation, a magnitude comparable to SST anomalies observed during moderate IOD events.

7. Line 336, ‘suppress eastern upwelling’, should that be suppress eastern downwelling?

Reply: Thank you. We have revised as suggested.

References

- Azaneu, M., Matthews, A., and Baranowski, D.: Eddy advection and the evolution of Mixed layer properties: a case study at Southeast Tropical Indian Ocean, EGU General Assembly 2022, Vienna, Austria2022.
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- Prasad, T. G. and Bahulayan, N.: Mixed layer depth and thermocline climatology of the Arabian Sea and western equatorial Indian Ocean, Indian Journal of Marine Sciences, 25, 189-194, 1996.
- Sharma, R., Agarwal, N., Momin, I. M., and Agarwal, V. K.: Mixed Layer Depth and its Variability in the Eastern Equatorial Indian Ocean as Revealed by Observations and Model Simulations, Marine Geodesy, 33, 154-163, 10.1080/01490419.2010.492281, 2010.

Response to the review of “Middle East Dust as a Dominant External Driver of the Indian Ocean Dipole” (NCOMMS-25-75253A).

Responses to Review 01 ’s comments

Summary:

The authors have addressed my major concerns, and the revised manuscript is substantially improved. I thank the authors for their careful and thorough revisions. I have one remaining minor point, concerning consistency between the limitations now stated in the manuscript and the stronger framing used in the title and abstract. The newly added limitations paragraph (Lines 465–481, beginning “While this study demonstrates a robust statistical linkage between SMED and IOD variability...”) is a valuable and welcome addition.

In light of these acknowledged uncertainties, the wording “dominant external driver” in the title appears stronger than what can be conclusively supported. I recommend softening this language to better align with the paper’s own caveats, for instance, removing “dominant” from the title, abstract, and conclusion and replacing it with wording such as “important.” One possible revision to the title is “Middle East Dust as an Important External Driver of the Indian Ocean Dipole.” Related phrasing in the abstract and conclusion should be adjusted accordingly (e.g., Line 416: “exerts a dominant control”). With this minor wording adjustment, I recommend the manuscript for publication.

Reply: Thank you for your positive assessment of our revisions and for your final recommendation for publication. We are very pleased to hear that you find the manuscript substantially improved.

We fully agree with your point regarding the need for consistency between the title/abstract framing and the nuanced limitations discussed in the text. Accordingly, we have implemented your recommendation as follows:

1. Title: Changed from “Middle East Dust as the Dominant External Driver of the

Indian Ocean Dipole” to “Middle East Dust as an Important External Driver of the Indian Ocean Dipole.”

2. Conclusion: Modified the phrase “exerts a dominant control” to “exerts an important control” (Line 407). Modified the phrase “the dominant driver” to “the important driver” (Line 435).

We believe these careful adjustments ensure that the manuscript’s claims are now fully consistent with its own caveats, strengthening the overall balance and precision of the paper.

Reviewer #1 (Remarks on code availability):

<https://zenodo.org/records/15684742>

Regarding the post-processing Matlab code posted on Zenodo (<https://zenodo.org/records/15684742>): for accessibility and ease of use by international readers, I recommend that the in-code comments be provided in English (or at least include English translations alongside any non-English comments). This would make the scripts much easier to follow and reproduce for the broader community. Thank you.

Reply: Thank you for this helpful suggestion. We agree that English comments are essential for accessibility and have now updated all in-code comments in the Zenodo repository accordingly.

Responses to Review 02 's comments

Summary: The authors did a great job in addressing my comments and questions. I have no further suggestions.

Reply: Thank you for your positive feedback and for confirming that all your comments have been addressed. We greatly appreciate your time and valuable suggestions.

Responses to Review 03 's comments

Summary: The authors have addressed the reviewers' comments well. The responses are clear, and the revisions have improved the manuscript. I do not have any remaining major concerns, and I believe the paper is now suitable for publication in Nature Communications. I recommend acceptance in its current form.

Reply: Thank you for your positive and constructive feedback. We are very pleased that you find the revised manuscript suitable for publication. We sincerely appreciate your time and valuable contributions throughout the review process.

Review of “Middle East Dust as a Dominant External Driver of the Indian Ocean Dipole” by Liu et al.

This study examined how mineral dust aerosols emitted from the Middle East affect the Indian Ocean Dipole (IOD) using both observational data and the CESM model. While previous studies have examined how anthropogenic aerosols effect IOD, how Middle Eastern dust aerosols affect the IOD is largely unclear. The study addresses a very important question in the region, and the topic is very novel and inspiring. The overall analysis is quite comprehensive, however, some details in model setting, the feedback link from subtropical dust loading to tropical SSTs, and the magnitude of the radiative forcing need further clarification. Adding some discussion about the uncertainties in data and methodology also would strengthen the paper.

Major concerns:

1. Usually, the lifetime of dust aerosols in the atmosphere, especially in the lower troposphere, is fairly short, from several days to a couple of weeks. The statement “multi-month atmospheric residence time of dust aerosols” (line 60) needs more evidence to support. I think it is important to understand whether the strong connection between JJA Middle Eastern dust and SON IOD is primarily due to an usually long residence time of summertime Middle Eastern dust, or instead a delayed response through ocean-atmosphere feedback. It would also be helpful to clarify whether Middle Eastern dust in SON has any impact on the IOD in SON.
2. The averaging area for the summertime Middle East Dust (SMED) index was not very clear (e.g., in Fig. 1c). As shown in Figs. 1a and 1b, the domain only covers southern Middle East, and it also includes the Horn of Africa, which is often not geographically considered part the Middle East. In the Methods section, there is a definition of Middle East dust (“10° S–30° N, 35° E–70° E”, line 522). But It’s unclear if this the averaging region used to calculate all the time series of SMED. And also, the domain is a quite large, while most of the Middle East dust are located to the north of 10° N (supplementary Fig. 1). Are the results sensitive to the averaging area of SMED? Would the correlations change much if only averaging over the region with high dust loading, e.g., to the north of 10° N?
3. The radiative forcing of the dust aerosols are shown in both the coupled CESM simulations and atmosphere-only model (CAM) runs. However, the location of radiative forcing directly from the dust aerosols. With reduced Middle Eastern dust aerosols , one would expect to see enhanced shortwave (SW) fluxes (i.e., warming) at the surface extending from the Arabian Peninsula southward toward the Arabian Sea. However, this pattern is not clearly shown in the coupled simulation (Fig. S8c)-- there is a cooling around 12 °N, while the warming single is located further south, round 6 °N-6 °S, where the climatological dust loading is low. Is this due to a teleconnection?

In the CAM simulations, enhanced SW fluxes do appear from southern Arabian Peninsula towards the Arabian Sea (Figs. S13a, S10a), but mainly over the northern and eastern Arabian Sea. And the changes in SW flux over the western tropical Indian Ocean are relatively weak. Does this imply a teleconnection that allow the local radiative impact of dust aerosols over the Arabian Peninsula and northern Arabian Sea to propagate to the tropical Indian Ocean?

4. Regarding the mechanisms of dust radiative forcing, it would be more convincing to include figures to show radiative fluxes at the TOA and also vertical heating profiles in the regions with high dust loading.
5. Some aspects of the model simulation setup are not very clear. In the CESM coupled simulation from 1980 to 2020, besides SMED, what other forcings are included? Are anthropogenic aerosols and greenhouse gases included in the model? Do they vary over time? What's the spin-up time for the coupled run?

It is mentioned that dust aerosols are prescribed in the model, however, it is not clear which dust variable was perturbed. Was it dust AOD, dust mass concentration at each pressure level, or emission fluxes? And is dust prescribed only the Middle East (leaving the rest of the world dust-free) or globally? It states that “we drove CESM with observed summertime dust mass density” (line 523), but it is unclear which observational dataset was used, and whether the forcing is applied only during the summer months or throughout the year. Are both dry and wet deposition included in the model?

6. For the sensitivity test with reduced dust loading, was the forcing applied only in summertime or all year round? It would be helpful to include a table summarizing key features of each simulation.
7. It is recommended to include some discussion about the uncertainties of the study. For instance, in model simulations, dust content is prescribed, so any feedback from atmospheric circulation to the dust loading is not considered. In terms of station data, what's the uncertainty in measurements? Do the station location and numbers change from 1980 to 2020? Does the uneven spatial distribution of the stations affect the results?

Minor comments:

1. Line 64, it may be helpful to show the response the strongest in SON.
2. Lines 78-79, it is not clear what averaging area is used for the MISR non-spherical AOD.
3. Line 158, this seems to contradict the statement in lines 134-135. Could you please clarify what the systematic biases are?

4. Line 175, there is also a weak increase in the mixed layer depth over the eastern tropical Indian Ocean from 100°E to 108 °E (Fig. 2b). What could be the cause of this?
5. Line 219, regression analysis is less straightforward than performing another simulation without the variability of Middle Eastern dust and comparing the differences. Conducting a linear regression assumes that the relationships are linear, which may not necessarily be true.
6. Line 220, “Increased solar radiation penetrates to the surface...” , this is not clearly shown in Fig. S8c, especially over the region with reduced dust. Please clarify.
7. Lines 221-225, it's not clear why the coupled results are already available (line 192) but then the analysis switches to an atmosphere-only model, and then returns to the coupled simulation.
8. Line 229-230 “the direct radiative effects of reduced dust”, is it possible to clarify the location of this effect in the figure?
9. Line 267, the response of shortwave fluxes is mainly over the land. How does the signal propagate to the TIO?
10. Lines 275-276, “(Extended Data fig. 10)”, isn't the figure from the atmosphere-only model run (as mentioned in line 221)?
11. Line 304, cooler western part?
12. Line 355, do you mean “reduced dust anomalies”
13. Line 360, dust forcing in JJA or SON?
14. Lines 252-257, how is this done? Are you using the ratio of JJA MERRA-2 dust AOD to modeled dust AOD to scale dust loading in each month?
15. Line 258, “by perturbing initial temperature fields”, is it land or ocean surface temperature? How large are the perturbation?s
16. Line 540, one standard deviation over what time period?
17. Fig. 1c, consider adding all the dust time series as a reference (e.g., including MODIS DOD and MERRA-2 dust column mass density). Is it possible to include DMI time series as well and show the correlations between DMI and different Middle Eastern dust indices from 1980 to 2023 and 2003 to 2023? Fig. 1d-g, can you please

clarify in the figure caption the time period over which the regressions were calculated? Was it 2003 to 2023? Were the data detrended before calculating the regressions?

18. Fig. 2, are the fields derived from time averages or from regression? Fig. 2b, the location of the temperature anomalies appears at a higher altitude than in the observation (Fig. 1). Is this due to model bias? Could you please comment on this?
19. Fig. 3, is it possible to include the corresponding figure of reduced dust loading here? The location of the peak positive shortwave fluxes seems mismatch the location with high dust loading.
20. Fig. S2, please mark whether the correlations are statistically significant.
21. Fig. S6a, could you please add the stimulated dust AOD to it?
22. Fig. S8a, is the obtained through regression?
23. Figs. S10b, d, are the flux date from MERRA-2? Is it possible to add the MISR AOD reduction pattern? And what is the averaging area used for MISR AOD in the regression analysis?
24. Fig. S11, which simulation does this refer to? Is it from the sensitivity simulation or the coupled run from 1980 to 2020?