Indian Institute of Technology Delhi

CLIMATE DATA ANALYSIS

ASL 736 ASSIGNMENT 2

SESSION - 2024-25
SEM - II

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INTRODUCTION

Climate variability and change are critical topics in atmospheric and oceanic sciences, especially given their profound impacts on global weather patterns, ecosystems, and human societies. Analyzing large-scale climate datasets allows researchers to understand the underlying mechanisms driving climate phenomena such as the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO).

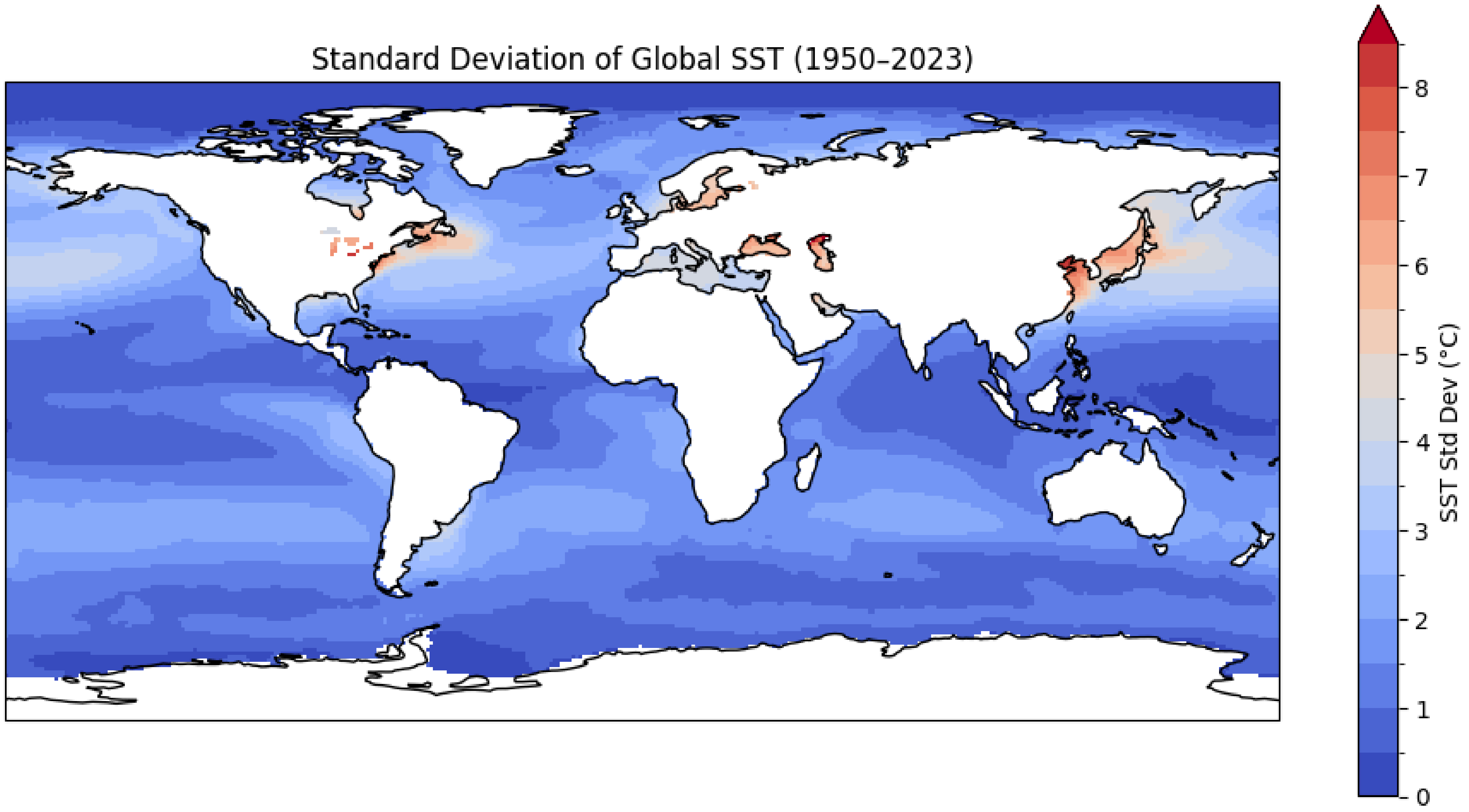
This assignment focuses on applying data analytics techniques to long-term climate datasets, primarily from 1950 to 2023, using reanalysis products and observational records. The objective is to explore and quantify variability in sea surface temperatures (SST), surface air temperatures (SAT), and wind fields across global and regional scales. Key methodologies include Empirical Orthogonal Function (EOF) analysis, correlation and regression mapping, and time series filtering to isolate interannual and decadal signals.

In addition to reproducing results from established scientific literature, this assignment involves generating custom climate indices, comparing them with standardized datasets, and interpreting the physical significance of observed patterns. Through these tasks, we aim to develop a deeper understanding of the interplay between ocean-atmosphere dynamics and the statistical tools used to analyze them.

DATA COLLECTION & SOURCES

S. No.	**Dataset**	**Source**	**Variables**	**Period**	**Website**
1	NCEP/NCAR Reanalysis 2	NOAA PSL	Air Temp, U & V Winds @1000 hPa	1950–2023	https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html
2	Sea Surface Temperature (SST)	APDRC, Univ. of Hawaii	Monthly SST	1950–2023	https://apdrc.soest.hawaii.edu/las/v6/dataset?catitem=2802
3	ENSO (Niño 3.4) Index	NOAA PSL	Niño 3.4 Index (Monthly Anomalies)	1950–2023	https://psl.noaa.gov/data/timeseries/month/data/nino34.long.anom.data
4	Indian Ocean Dipole (DMI) Index	NOAA PSL	Dipole Mode Index (DMI)	1950–2023	https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data
5	Pacific Decadal Oscillation (PDO)	NOAA PSL	PDO Index	Jan 1900–Dec 2023	https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/pdo.long.data
6	Interdecadal Pacific Oscillation (IPO / TPI)	NOAA PSL	Tripole Index (TPI)	Jan 1900–Dec 2023	https://psl.noaa.gov/data/timeseries/IPOTPI/tpi.timeseries.hadisst11.data
7	Atlantic Multidecadal Oscillation (AMO)	NOAA PSL	AMO Index (Smoothed)	Jan 1900–Dec 2023	https://psl.noaa.gov/data/correlation/amon.sm.long.data

STANDARD DEVIATION MAP OF GLOBAL SST (1950–2023)



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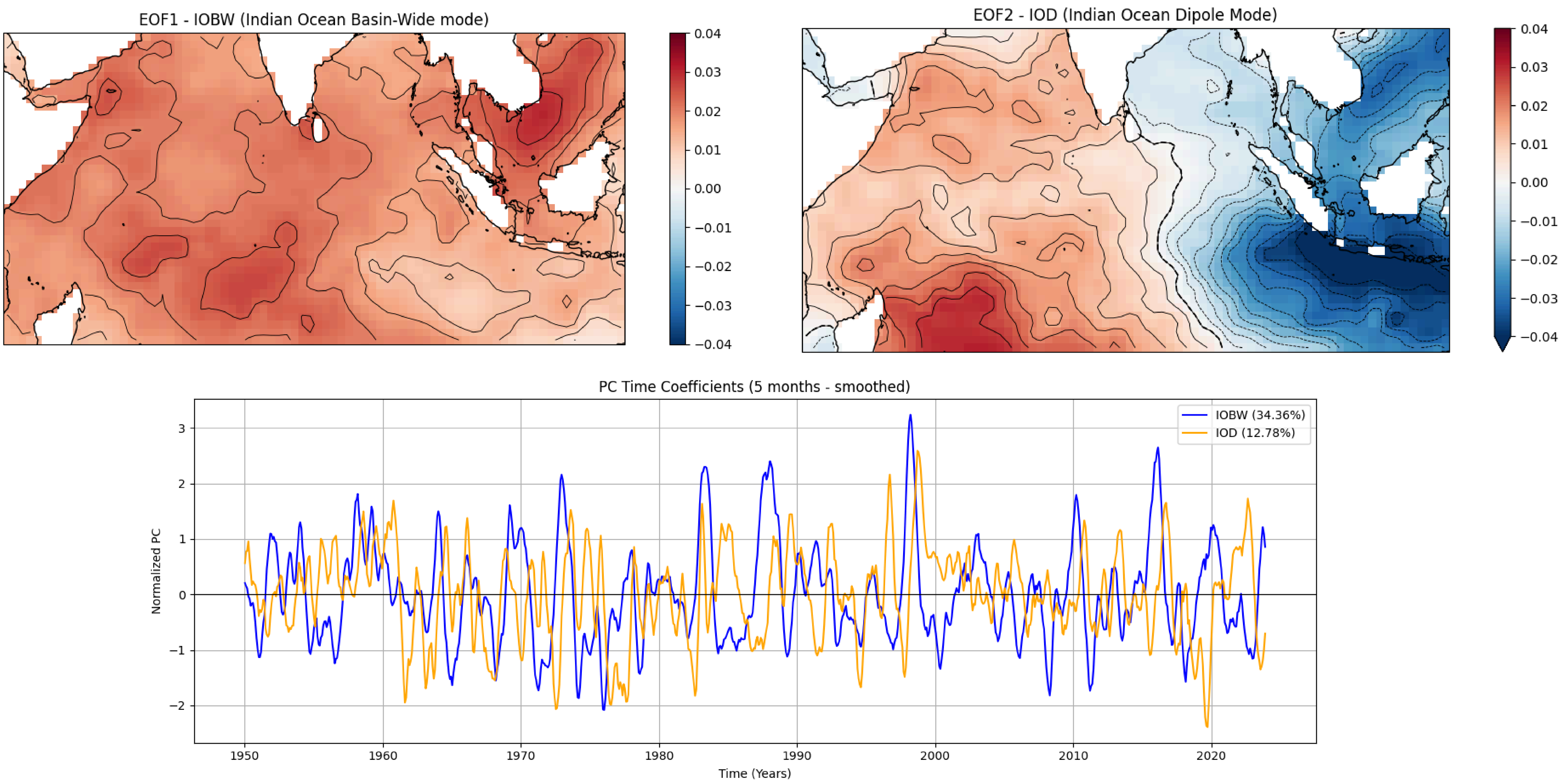
EOF ANALYSIS (INDIAN OCEAN)



RESULT • EOF1 explains 34.36% of variance and EOF2 explains 12.78% of variance

METHODOLOGY FOR STEP 3

We analyzed sea surface temperature (SST) variability over the tropical Indian Ocean (20°S–20°N, 40°E–120°E) for the period 1950–2023.

1 **Data Preparation:**
- Monthly SST data were extracted from the provided dataset and subset to the Indian Ocean region for the period of interest.

2 **Anomaly Calculation:**
- SST anomalies were computed by removing the long-term monthly climatology, thus isolating interannual variability.

3 **Data Cleaning and Detrending:**
- The spatial grid was flattened, and points with missing data were excluded. Each time series was linearly detrended to eliminate long-term warming trends.

4 **Empirical Orthogonal Function (EOF) Analysis:**
- Principal Component Analysis (PCA) was performed on the detrended anomalies to extract dominant modes of variability. The first two EOFs, representing the Indian Ocean Basin-wide (IOBW) mode and the Indian Ocean Dipole (IOD), were retained.

5 **Spatial and Temporal Reconstruction:**
- The leading EOF patterns were reshaped back to the spatial grid to visualize the SST anomaly structures. Corresponding principal component (PC) time series were normalized and plotted to study their temporal evolution.

6 **Variance Assessment:**
- The proportion of total variance explained by each EOF was calculated to confirm the significance of the modes.

4 INTERPRETATION AND OBSERVATIONS

1. Spatial Patterns (EOF Maps):

- EOF1 (Indian Ocean Basin-Wide Mode, IOBW): The first mode shows a nearly uniform warming/cooling across the Indian Ocean, with slightly stronger anomalies in the eastern Indian Ocean. This reflects the basin-wide warming or cooling associated with phenomena like ENSO (El Niño–Southern Oscillation) influences.
- EOF2 (Indian Ocean Dipole, IOD Mode): The second mode displays a clear east-west dipole: negative SST anomalies over the eastern Indian Ocean and positive anomalies over the western part (and vice versa during opposite phases). This spatial pattern is characteristic of the Indian Ocean Dipole (IOD) events.

Aspect	EOF1 (IOBW Mode)	EOF2 (IOD Mode)
Spatial Pattern	Basin-wide warming or cooling across the Indian Ocean	East-west dipole (cooling in east, warming in west, or vice versa)
Variance Explained	34.36%	12.78%
Key Features	Uniform SST anomalies, linked to large-scale modes like ENSO	Strong zonal SST gradients, characteristic of IOD events
Temporal Behavior	Interannual to decadal variability	Intermittent peaks during major IOD years (e.g., 1961, 1994, 1997)
Impact	Influences entire Indian Ocean SST variability	Affects regional monsoon patterns and ocean circulation

2. Temporal Evolution (PC Time Series):

- The blue curve represents the IOBW (EOF1) time series, which explains 34.36% of the total variance.
- It shows strong interannual to decadal fluctuations, with notable peaks during major ENSO events (e.g., late 1997-98 El Niño).
- The orange curve represents the IOD (EOF2) time series, explaining 12.78% of the variance.
- Peaks in this curve correspond to major positive or negative IOD events, e.g., strong positive IOD events around 1961, 1994, and 1997.

3. Variance Explained:

- The first two modes together explain nearly 47% of the total SST variability over the Indian Ocean.
- IOBW dominates the variability, but IOD remains a significant secondary mode.

CORRELATION ANALYSIS BETWEEN PC1 AND PC2

The correlation coefficient between the principal component time series corresponding to EOF1 (PC1) and EOF2 (PC2) is 0.00, with a p-value of 1.0000.

- This indicates that PC1 and PC2 are completely uncorrelated, meaning that the two modes of variability are statistically independent of each other.
- This is expected because Principal Component Analysis (PCA) inherently produces orthogonal (i.e., uncorrelated) components.

PHYSICAL INTERPRETATION:

- EOF1 (PC1) represents the Indian Ocean Basin-Wide (IOBW) mode, characterized by coherent warming or cooling across the entire Indian Ocean, often influenced by ENSO events.
- EOF2 (PC2) represents the Indian Ocean Dipole (IOD) mode, characterized by opposing SST anomalies between the western and eastern parts of the Indian Ocean.

Thus, the IOBW and IOD modes capture distinct physical phenomena affecting Indian Ocean SST variability on different spatial and temporal scales, and their independence is physically meaningful.

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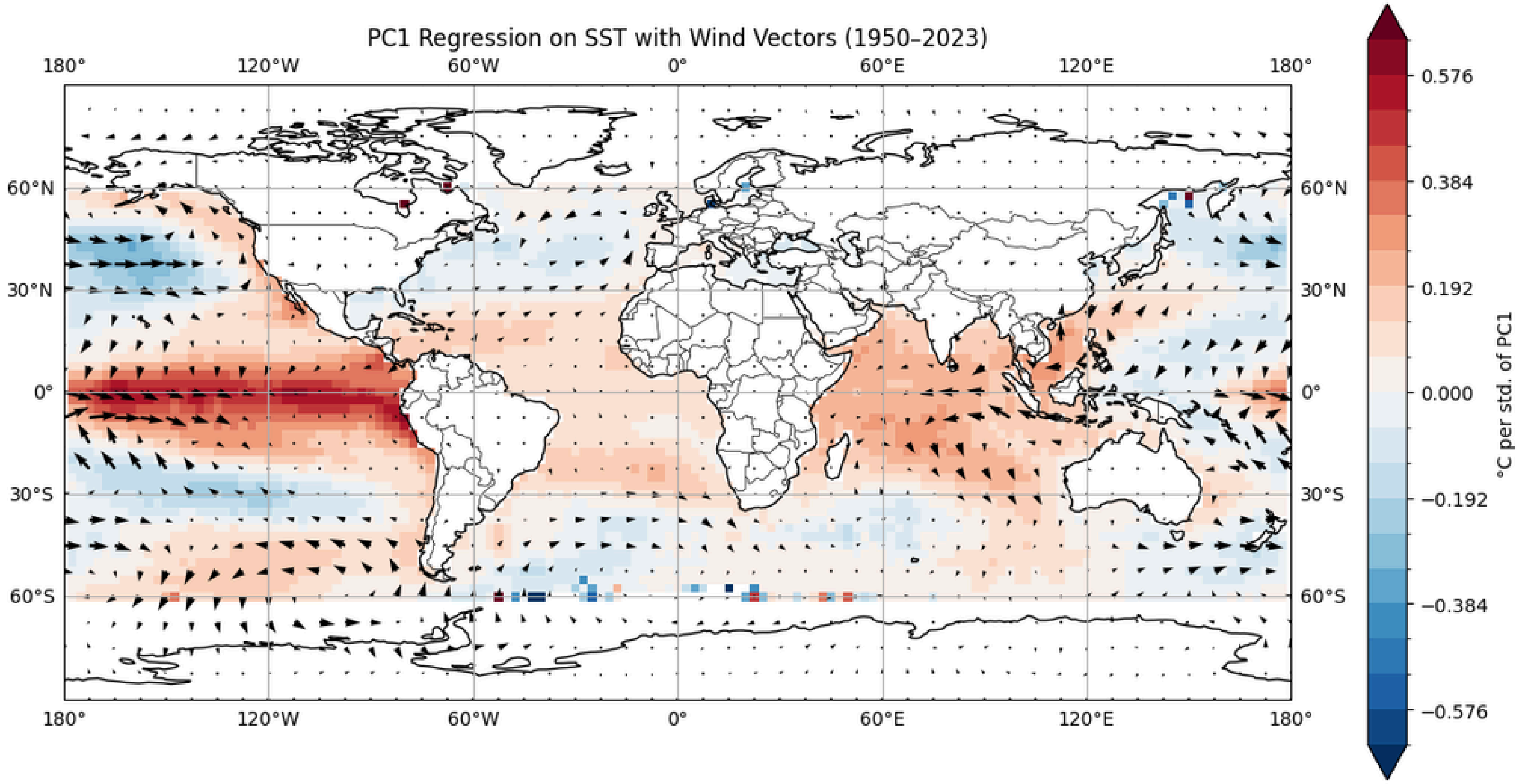
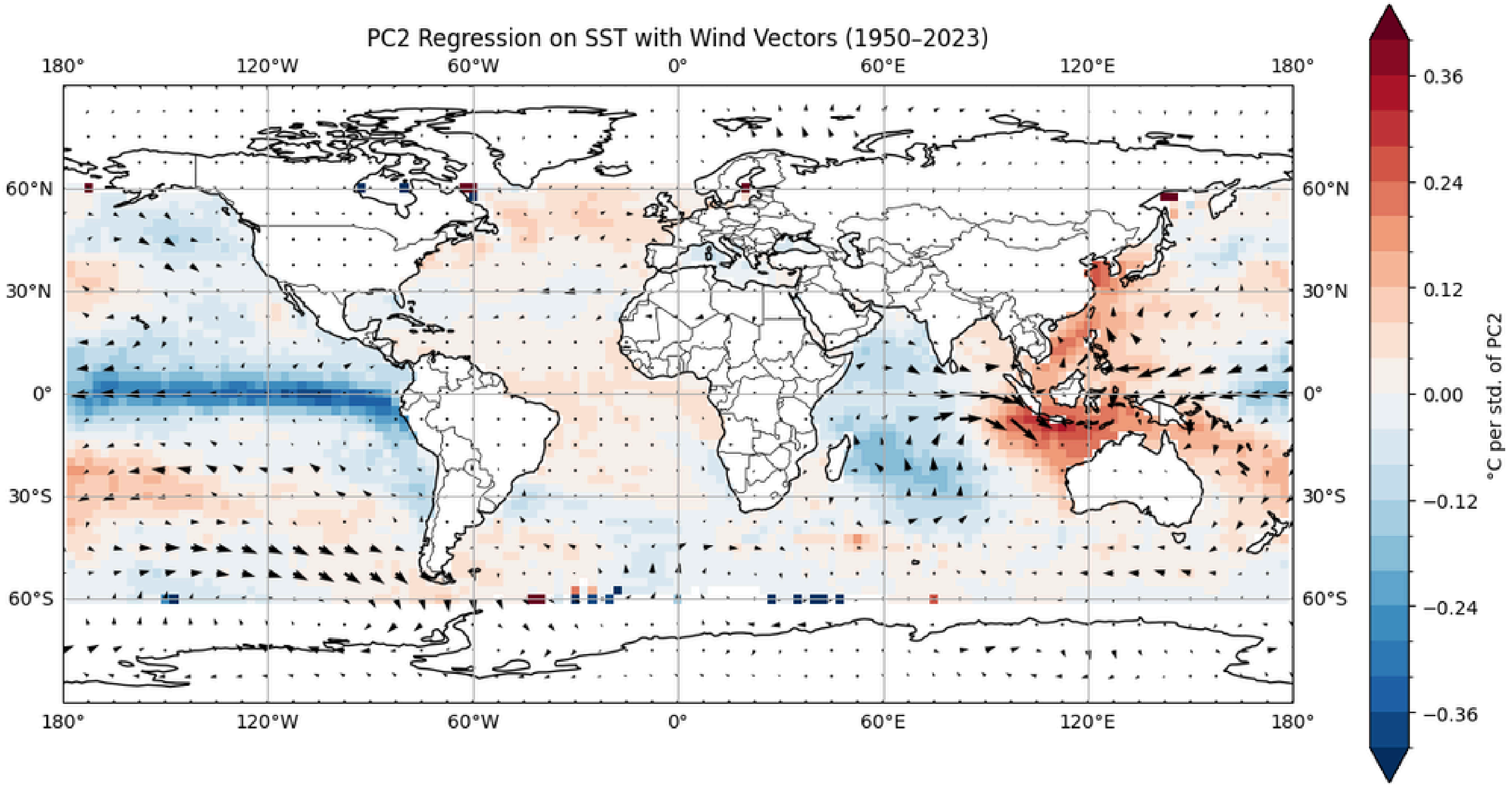
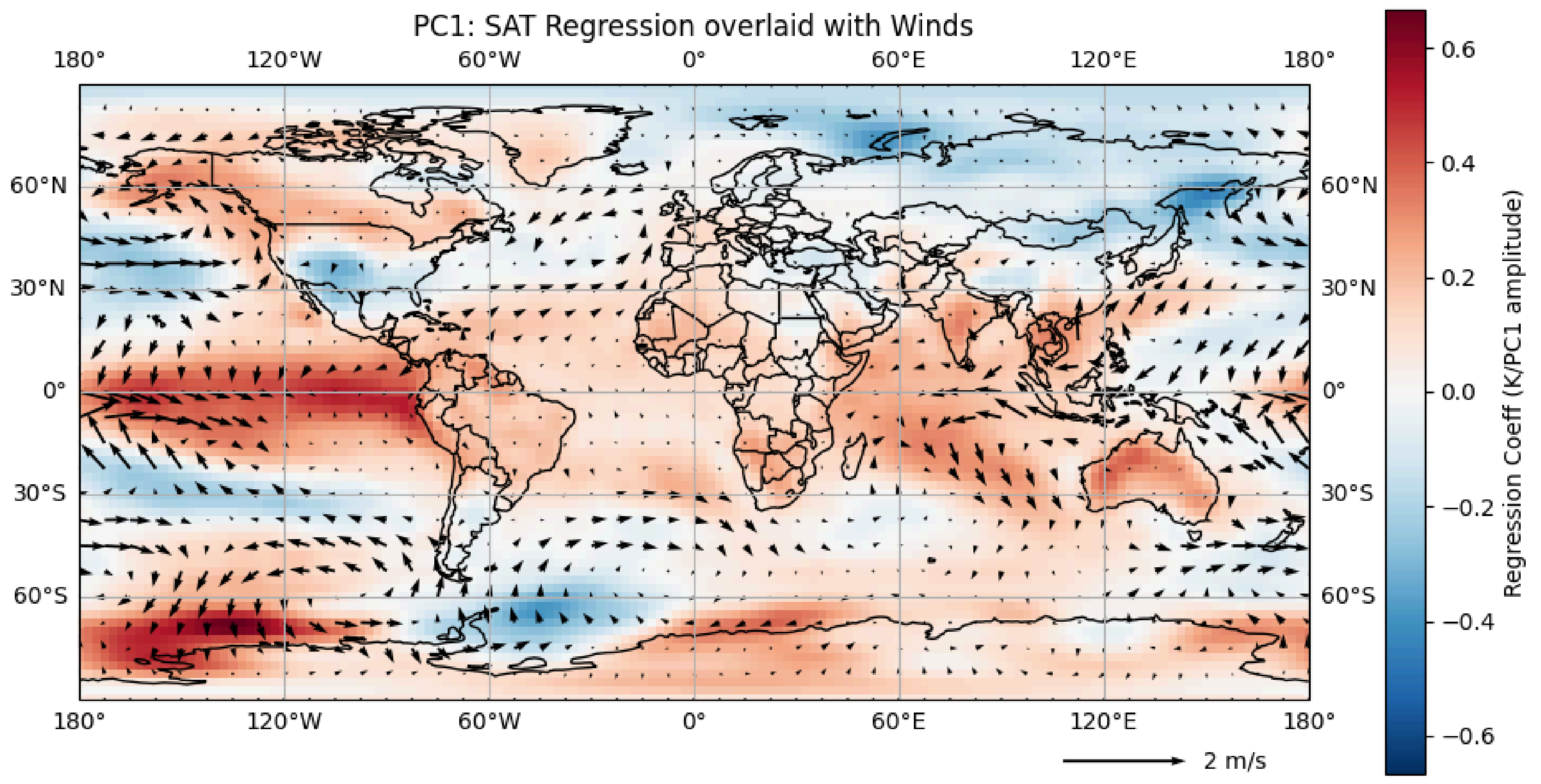
REGRESSION OF EOF TIME SERIES ON GLOBAL SST WITH WINDS

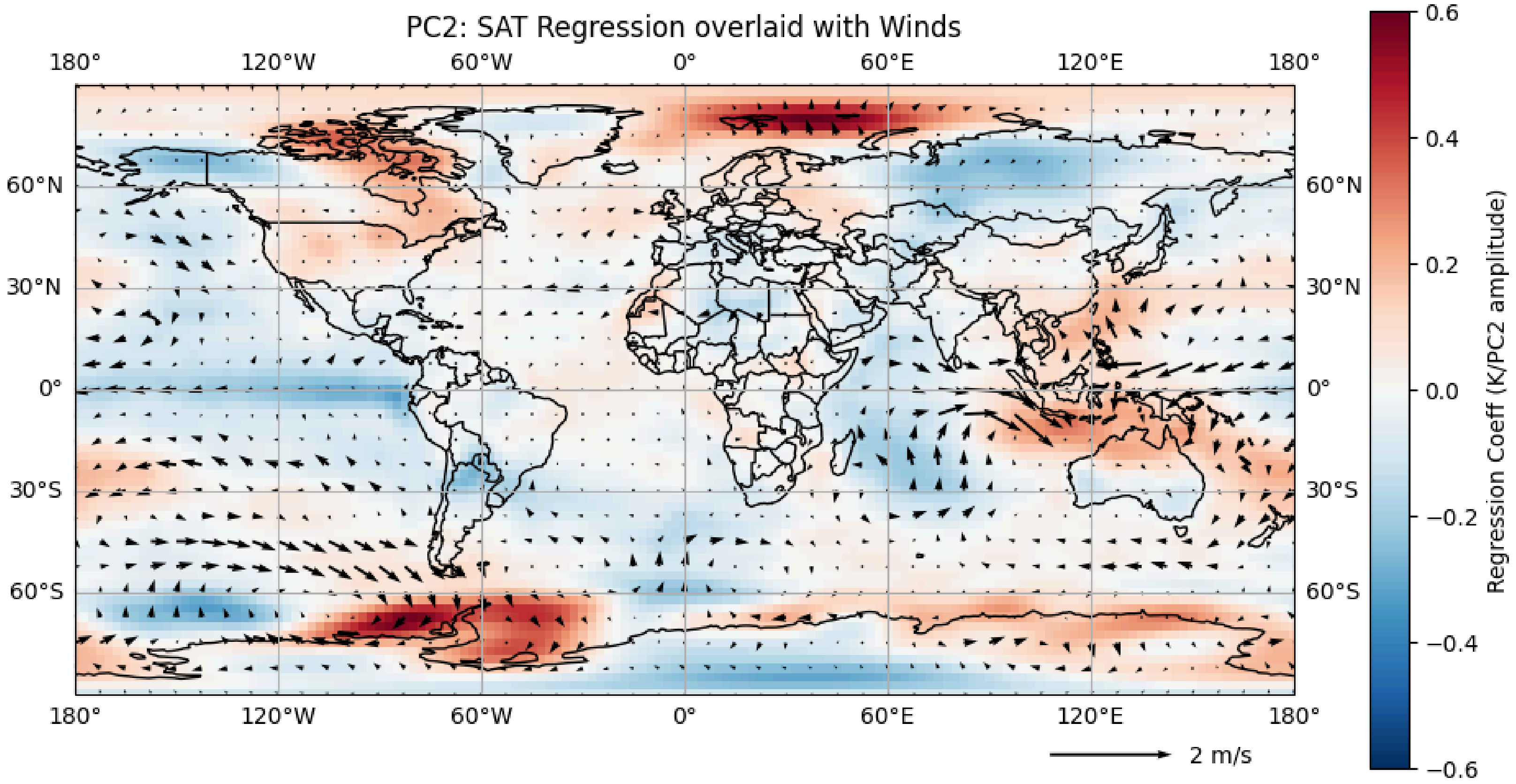




Feature	PC1 - SST Regression	PC2 - SST Regression
Dominant region	Equatorial Pacific (strong El Niño–like pattern)	Maritime Continent / Western Pacific + Eastern Pacific dipole
Structure	Strong **zonal** (east-west) gradient	More **localized** and **asymmetric** structure in Indo-Pacific
Tropical Pacific	Warming in central & eastern Pacific; cooling in western Pacific	Cooling in central-eastern Pacific; warming in Maritime Continent
Associated wind anomaly	**Weakened trade winds** near equator (typical of El Niño)	Strengthened trade winds in central-eastern Pacific (La Niña-like)
Physical interpretation	Canonical **ENSO (El Niño Southern Oscillation)** mode	Likely **ENSO Modoki / IOD (Indian Ocean Dipole) influence**
Teleconnection	Global—affects rainfall, monsoons, jet streams	More regional—stronger Indo-Pacific impact

REGRESSION OF EOF TIME SERIES ON GLOBAL SAT WITH WINDS





Feature	PC1 - SAT Regression	PC2 - SAT Regression
Dominant region	Tropics—especially equatorial Pacific	Extratropics—Arctic, subpolar Atlantic, Southern Ocean
Structure	Global warming pattern + tropical Pacific control	**Dipole** structures in both hemispheres (zonal annular modes)
Tropical pattern	Strong warming in eastern Pacific (El Niño-like)	Weak signal—no major tropical dominance
Mid/high-latitudes	Warming in South America, southern Africa, cooling in North Pacific	Warming in **Alaska, Siberia**, cooling in **Europe, North Atlantic**
Wind anomaly	Walker/Hadley cell adjustments, zonal flows	Strong **zonal wind shifts**, polar jet movement
Physical interpretation	Likely response to **ENSO** + global warming trends	Represents **AO/NAM/SAM-like** annular variability
Climatic role	Affects global temperature and precipitation patterns	Affects **storm tracks**, **cold surges**, **polar heat transport**

NINO3.4 AND DMI INDICES

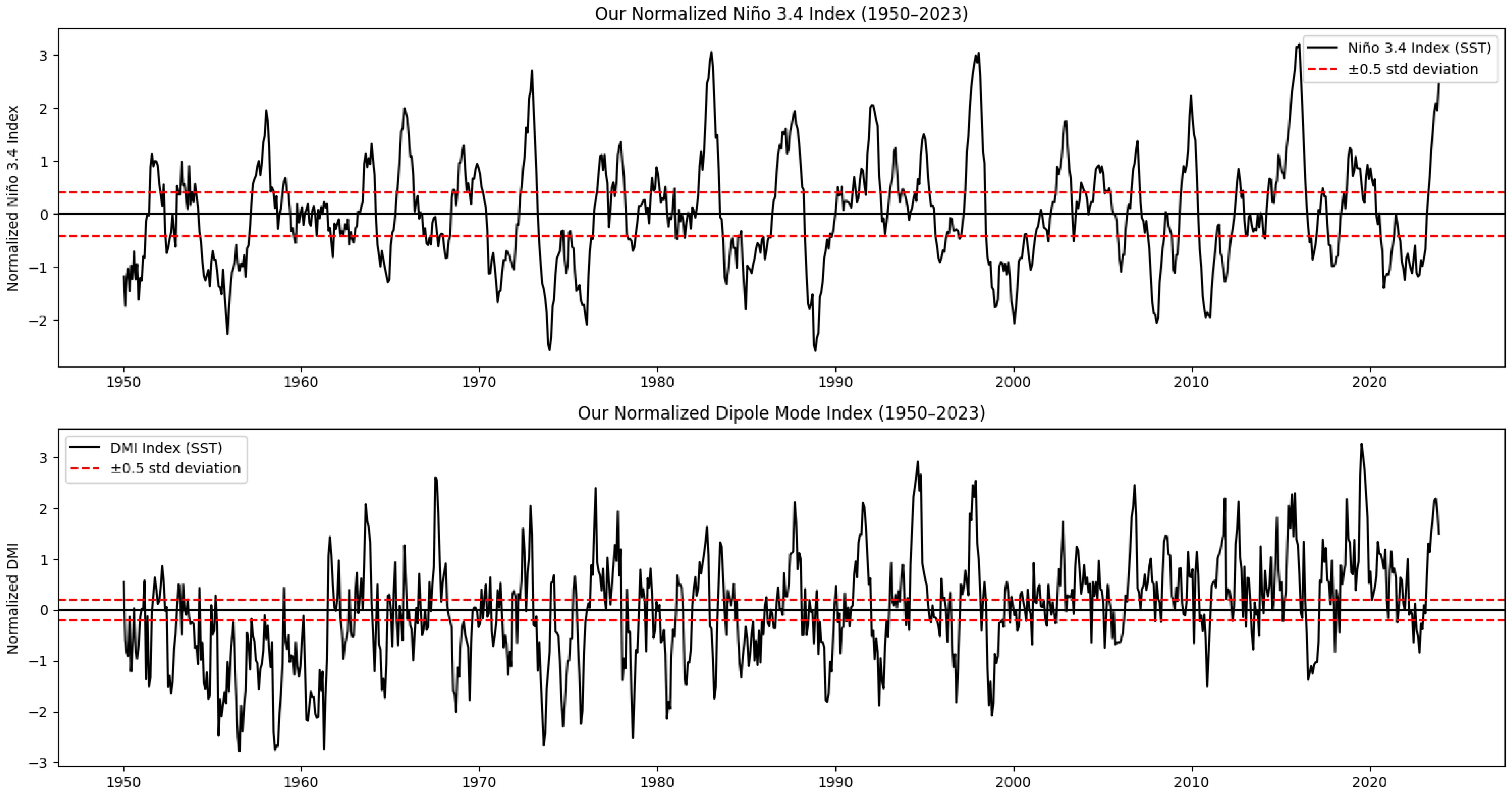
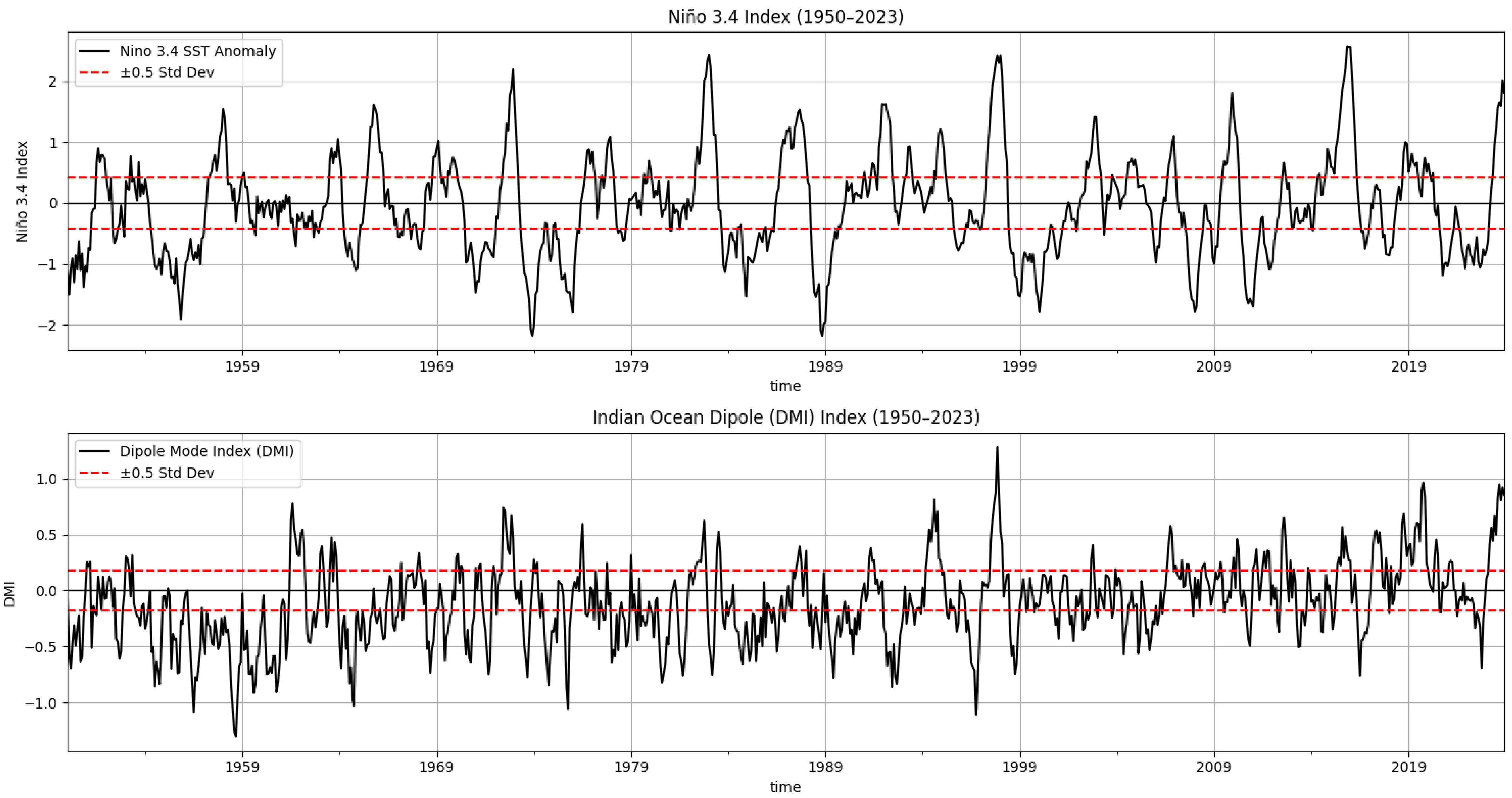


Figure: Normalized Niño 3.4 and DMI indices (1950–2023), based on SST anomalies. Niño 3.4 covers 5°S–5°N, 170°W–120°W; DMI is the SST difference between western (70°E–90°E, 5°S–5°N) and southeastern (100°E–110°E, 10°S–0°) Indian Ocean.

NOAA NINO3.4 AND DMI INDICES



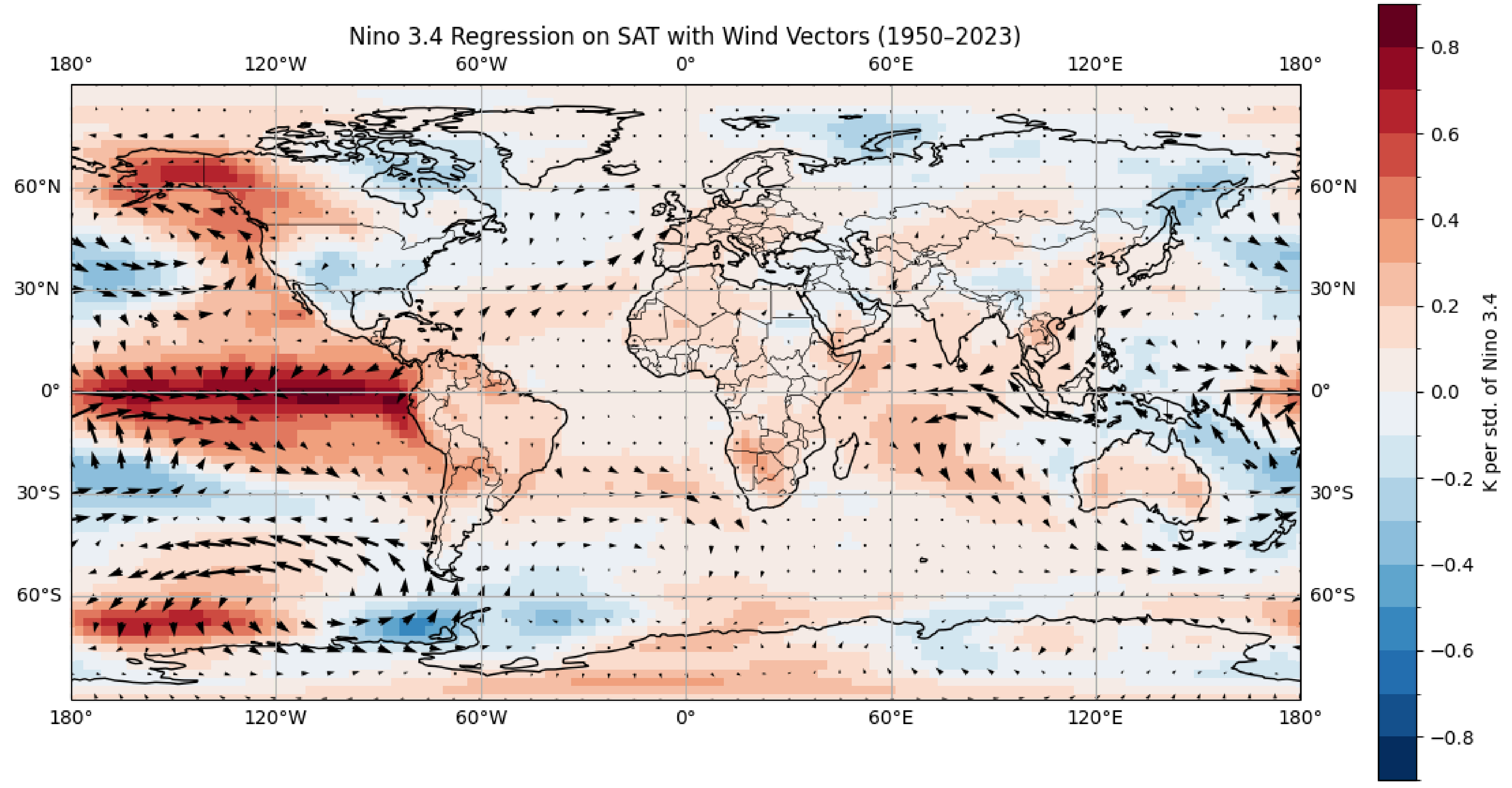
Correlation Coefficient

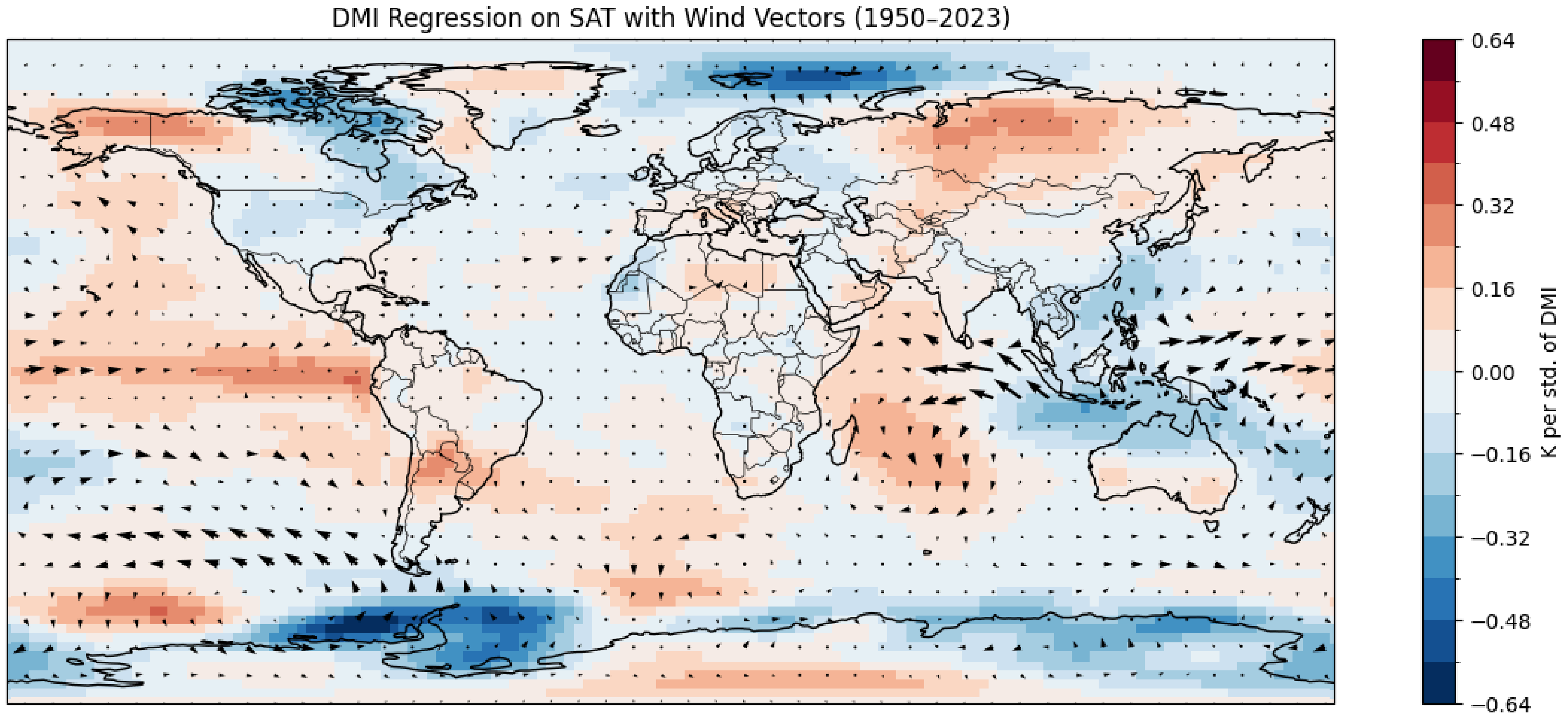
1. Correlation between OUR Niño 3.4 and NOAA Niño 3.4: <u>0.9996</u>
2. Correlation between OUR DMI and NOAA DMI: <u>0.8409</u>

CORRELATION ANALYSIS BETWEEN ENSO AND IOD INDICES AND EOFS

Serial Number	Comparison	Correlation Coefficient	Physical Interpretation
1	OUR Niño 3.4 vs NOAA Niño 3.4	0.9996	Our Niño 3.4 index matches NOAA almost perfectly, validating our calculation method for ENSO variability.
2	OUR DMI vs NOAA DMI	0.8409	Our DMI index shows good agreement with NOAA, meaning we capture Indian Ocean Dipole behavior well.
3	PC1 vs Niño 3.4	0.5797	PC1 moderately reflects ENSO signals (warming/cooling in central Pacific).
4	PC2 vs Niño 3.4	0.292	PC2 is weakly correlated with ENSO, suggesting it captures non-ENSO variability.
5	PC1 vs DMI	0.148	PC1 has very little sensitivity to Indian Ocean Dipole (IOD) events.
6	PC2 vs DMI	0.745	PC2 strongly represents IOD activity.
7	Niño 3.4 vs DMI	0.322	Niño 3.4 and DMI are weakly positively correlated, meaning ENSO and IOD events sometimes but not always co-occur.

NINO3.4 AND DMI REGRESSION ON SAT WITH WIND VECTORS (1950–2023)

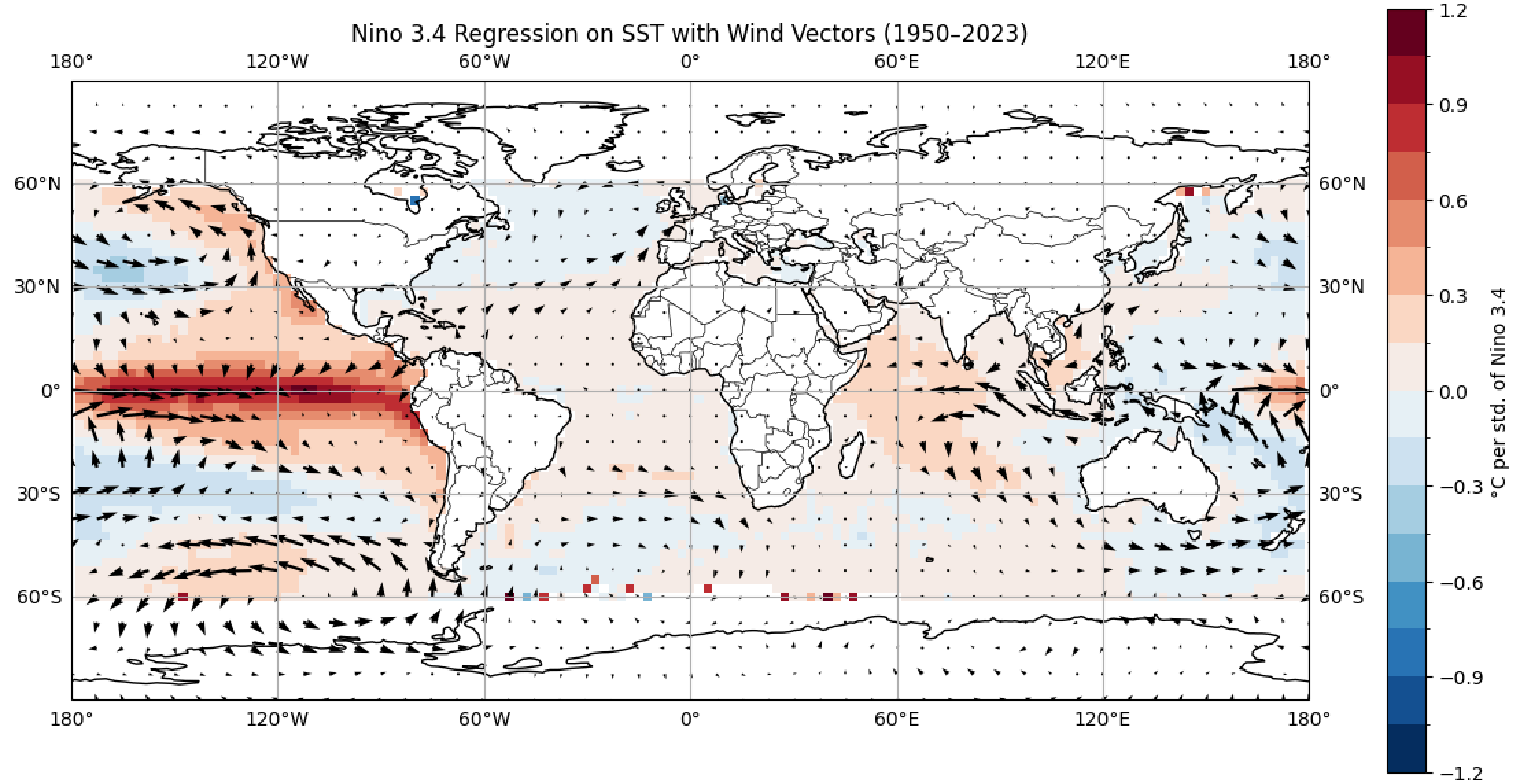


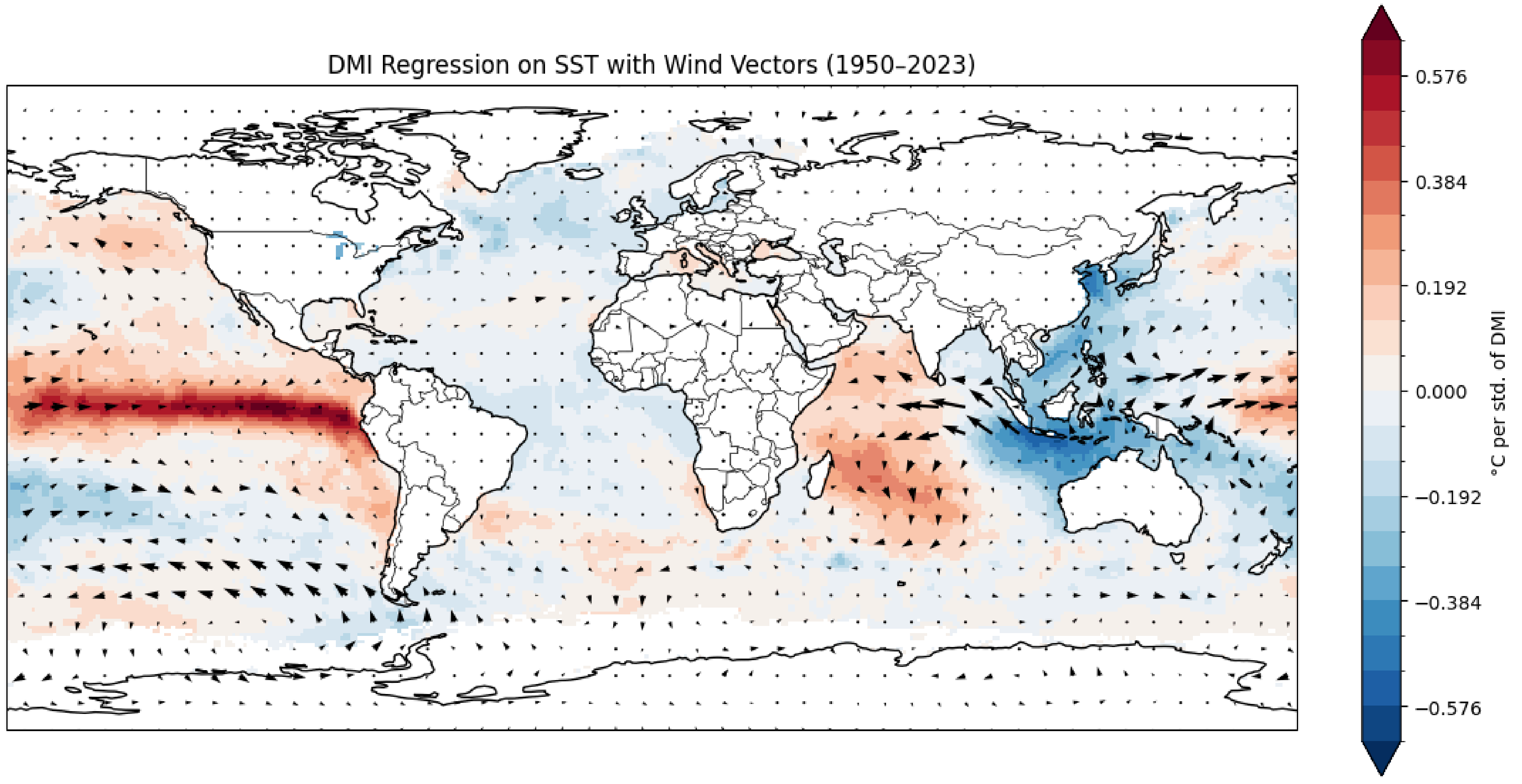


PHYSICAL INTERPRETATION

Feature	Niño 3.4 (ENSO)	DMI (IOD)
Region	Equatorial Pacific	Equatorial Indian Ocean
Global impact strength	Very strong, global reach	Stronger regionally, some remote effects
Tropics response	Strong, widespread (both ocean basins)	Strong but mostly within Indian Ocean
Wind anomalies	Trade wind reversal (eastward in Pacific)	Westward wind anomalies in Indian Ocean
Indonesia	Cools (subsidence from both El Niño and IOD)	Cools during positive IOD
East Africa	Warms (sometimes via both IOD and El Niño)	Warms during positive IOD

NINO3.4 AND DMI REGRESSION ON SST WITH WIND VECTORS (1950–2023)

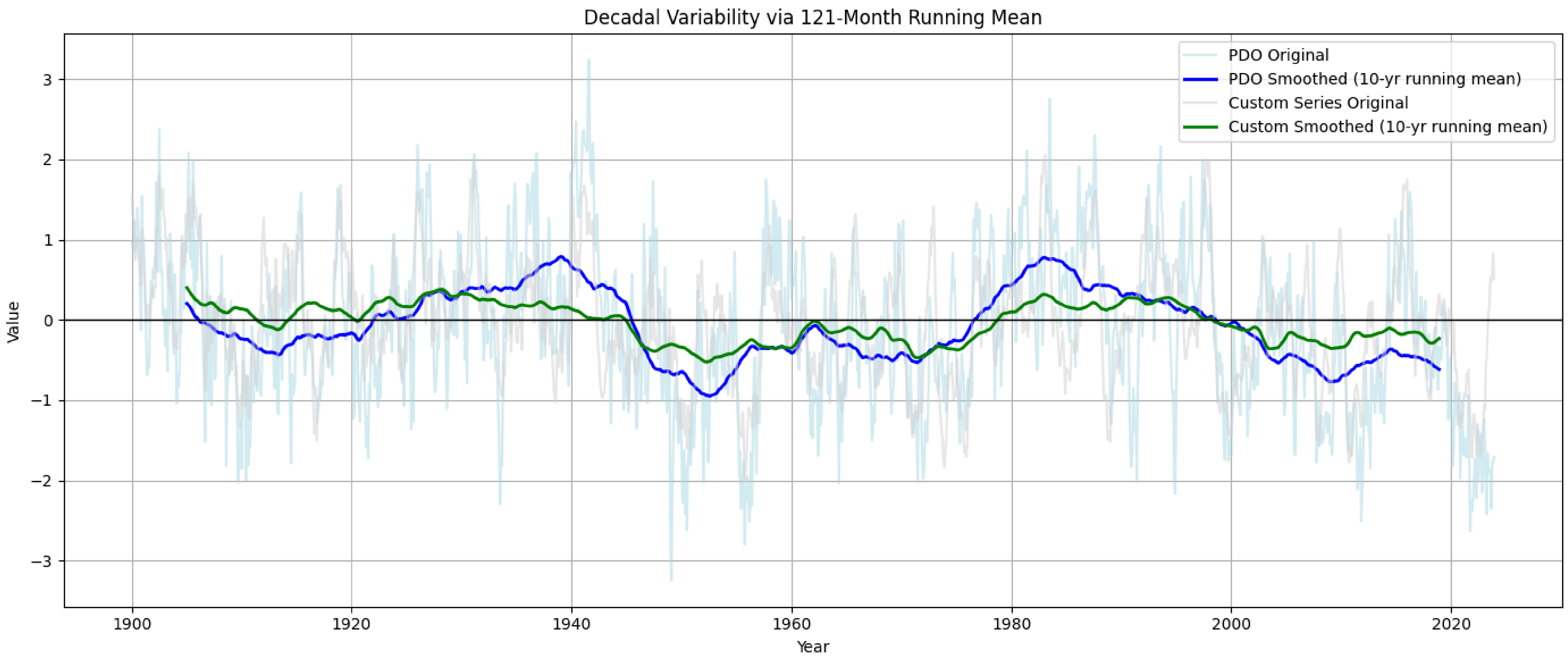




PHYSICAL INTERPRETATION

Feature	Niño 3.4 Regression Map	DMI Regression Map
Region of Focus	Tropical Pacific (Central-East)	Tropical Indian Ocean (West vs East)
Main SST Pattern	Strong warming in central/eastern Pacific	Warm west Indian Ocean / Cool east Indian Ocean
Key Wind Anomalies	Weakening/reversal of equatorial Pacific trade winds (eastward)	Westward surface winds across equatorial Indian Ocean
Teleconnections	Global: impacts seen in Atlantic, Indian Ocean, and extratropics	Regional: strong in Indian Ocean, limited in Pacific & Atlantic
Circulation Impact	Disruption of **Walker circulation** across Pacific	Disruption of Walker circulation **within Indian Ocean**
Monsoon Influence	Can weaken South Asian monsoon (El Niño)	Positive IOD can enhance East African rains, reduce rainfall over Indonesia
Strength of Remote Impact	Very strong – global climatic influence	Moderate – mostly regional with some Pacific interaction

Pacific Decadal Oscillation (PDO) and Inter-decadal Pacific Ocean (IPO)

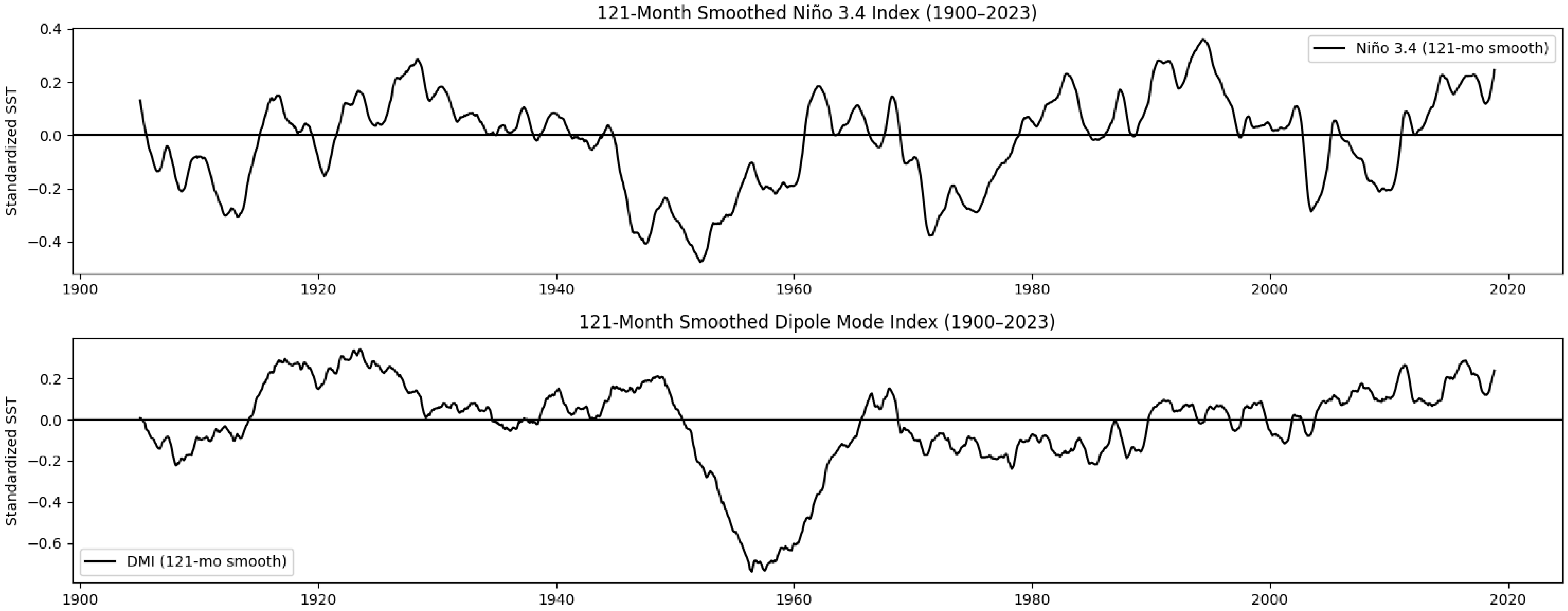


Pearson correlation between PDO and IPO time series: 0.815

Physical Interpretation

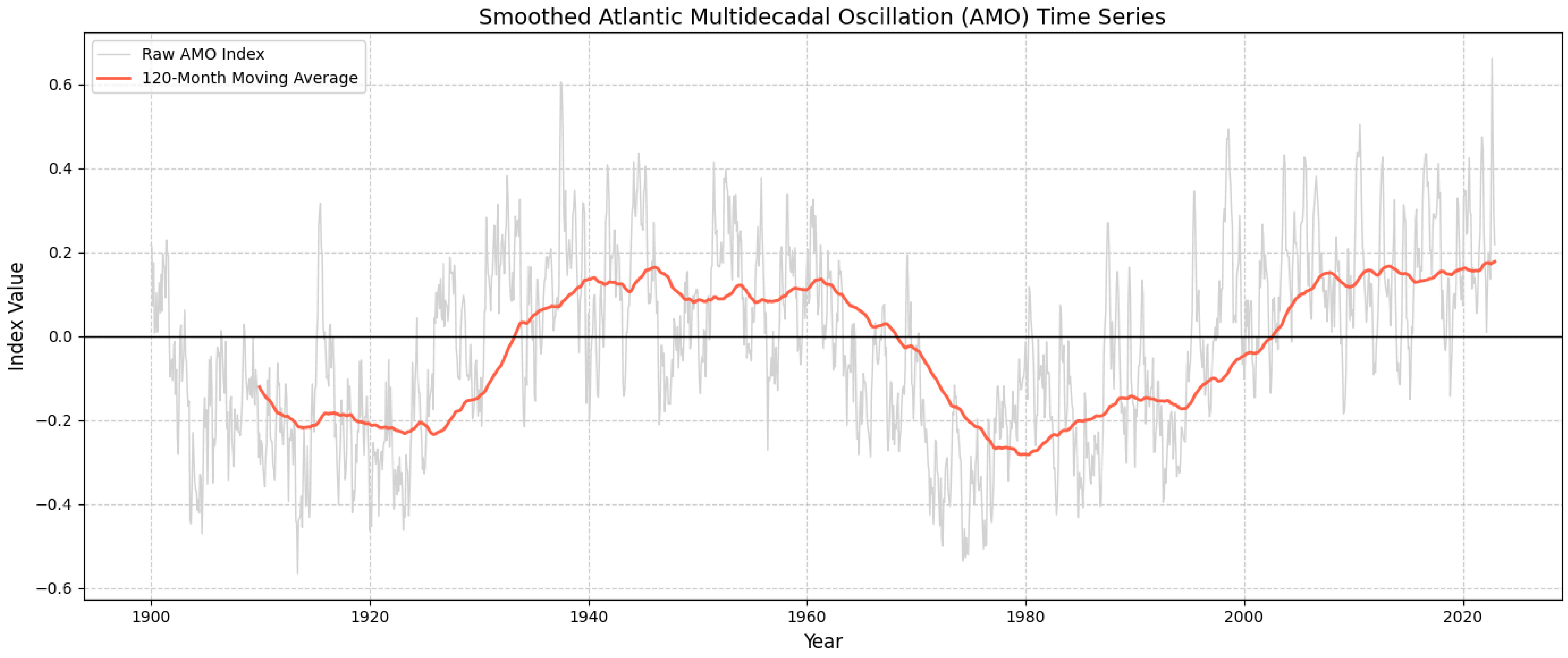
- The strong positive correlation (0.815) between PDO and IPO indicates that both indices often vary together on decadal timescales.
- Both reflect Pacific Ocean SST variability—PDO in the North Pacific and IPO across the broader Pacific, including the tropics.
- This suggests shared physical drivers like ocean circulation, thermocline shifts, and atmosphere-ocean interactions.
- Despite not being perfectly correlated, the high value reflects a coherent decadal climate signal across the Pacific.
- Such alignment can influence global patterns—e.g., droughts, monsoons, marine ecosystems, and climate variability.

CORRELATION BETWEEN FILTERED NINO3.4 AND PDO, IPO (1900–2023)



Serial No.	Index Pair	Correlation	Physical Interpretation
1	**PDO – Niño 3.4**	0.578	Moderate positive link; PDO often reflects tropical ENSO signals but also has extra-tropical influences.
2	**IPO – Niño 3.4**	0.775	Strong correlation; IPO includes ENSO-like variability and shares Pacific SST patterns.
3	**DMI – IPO**	0.351	Weak–moderate correlation; possible indirect atmospheric connections across basins.
4	**DMI – PDO**	0.061	Very weak correlation; indicates largely independent behavior between Indian and North Pacific Oceans.

Atlantic Multi-decadal Oscillation index (AMO)



Interpretation of AMO Correlations with ENSO and IPO

The observed near-zero correlations between AMO and Niño 3.4 (0.023), and between AMO and IPO (-0.089), can be attributed to fundamental differences in the ocean basins, driving mechanisms, and timescales of these climate phenomena.

Different Ocean Basins and Mechanisms:

- The AMO is a multidecadal oscillation in the North Atlantic Ocean, primarily influenced by the Atlantic Meridional Overturning Circulation (AMOC) and variations in oceanic heat transport and salinity. In contrast, Niño 3.4 and IPO are Pacific-based indices, governed largely by tropical ocean-atmosphere interactions, such as trade winds, thermocline depth, and surface pressure anomalies. These distinct mechanisms operate independently in physically separated ocean basins.

Mismatch in Timescales:

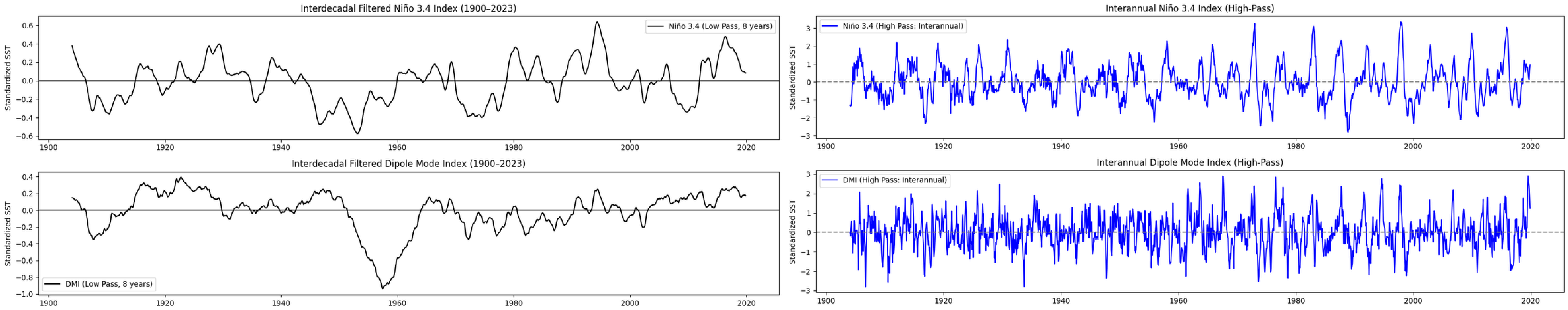
- The AMO operates on multidecadal timescales (~60–80 years), whereas ENSO (as captured by Niño 3.4) shows variability on interannual timescales (2–7 years), and the IPO fluctuates on decadal scales (15–30 years). This disparity means that even if long-term influences exist, they are unlikely to be captured through direct linear correlation.

Weak or Nonlinear Teleconnections:

- While some studies suggest that atmospheric circulation patterns (e.g., the Walker or Hadley circulations) may facilitate teleconnections between the Atlantic and Pacific basins, these links are generally weak, nonlinear, or lagged, and thus not reflected in simple Pearson correlation values.

In summary, the physical decoupling of ocean dynamics, temporal scale differences, and complex indirect interactions explain why the AMO exhibits little to no linear relationship with both Niño 3.4 and IPO.

Filtering of Nino3.4 and DMI Indices (1900–2023)



Index	Correlation (High-Pass vs Low-Pass)	Interpretation
Niño 3.4	-0.0723	Very weak negative correlation, indicating effective separation of frequencies
DMI	0.02	Near-zero correlation, confirming minimal overlap between signal components

Conclusion

- In this study, we systematically analyzed key climate variables — including Sea Surface Temperature (SST), Surface Air Temperature (SAT), and wind components (U and V winds) — from 1950 to 2023 using global reanalysis datasets. By applying statistical and empirical methods such as Empirical Orthogonal Function (EOF) analysis, regression mapping, and correlation analysis, we reproduced and extended important climatological patterns over the Indian Ocean and the Pacific.

- We successfully reconstructed and interpreted major climate indices such as the Niño 3.4 Index, the Indian Ocean Dipole (IOD/DMI), the Pacific Decadal Oscillation (PDO), the Interdecadal Pacific Oscillation (IPO), and the Atlantic Multidecadal Oscillation (AMO). Through EOF analysis, we identified the dominant modes of variability and associated them with known climate phenomena like ENSO and the Indian Ocean Dipole. Regressing the principal components onto SST, SAT, and wind fields further revealed the large-scale teleconnection patterns linked to these modes.

- Applying filtering techniques allowed us to separate interannual and interdecadal variability, thereby deepening our understanding of how different climate oscillations interact over different timescales. The correlation analyses between different indices provided valuable insights into the interconnected nature of ocean-atmosphere variability across the globe.

- Overall, this assignment provided a great learning opportunity. It emphasized the importance of advanced statistical tools in analyzing climate data and offered valuable insights into the temporal and spatial patterns of variability that influence global and regional climate systems. The methods and results explored through this work form a strong foundation for further research in climate dynamics, climate prediction, and understanding the broader impacts of climate change.

THANK YOU