Sea surface temperature variability in Indonesia and its relation to regional climate indices

A. D. Habibullah*1, A. Tarya2

1Study Program of Earth Sciences, Faculty of Earth Sciences and Technology, Bandung Institute of Technology
2Research Group of Oceanography, Faculty of Earth Sciences and Technology, Bandung Institute of Technology

22420028@mahasiswa.itb.ac.id

Abstract. Sea surface temperature (SST) is an essential indicator of ocean condition. It can reveal many physical processes interacting with it. The present study aims to investigate the spatial-temporal pattern of significant SST variability in Indonesia seas. The Empirical Orthogonal Function (EOF) and Power Spectral Density (PSD) are used to analyze monthly SST data from 1979 to 2021. These two methods are combined with correlation analysis to verify the underlying phenomena and their spatiotemporal distribution pattern using regional climate indices as the reference signal. The result shows that the most prominent feature is the annual and semi-annual oscillation due to the Asia-Australia monsoon system. The annual oscillation signature is found almost in the entire Indonesian seas, with an exception in the low-latitude area and the western Pacific region. The signature of semi-annual oscillation is also protrusive, extending across Indonesia from the Timor Sea to the South China Sea. There is also a variation of SST in correlation with Dipole Mode Index (DMI), localized on the western coast of Sumatra.

1. Introduction

Sea surface temperature (SST) plays an important role in physical processes that occur in the sea. SST is an effective tool to analyze various phenomena and their spatiotemporal variabilities. Some robust examples of the use of SST have been demonstrated: variations in SST spatially determine variations in fish distribution (e.g., [1,2]). It also can reveal the dynamics feature beneath the surface, such as tidal mixing signatures (e.g., [3,4]). SST is used to define marine heatwaves when seawater temperatures exceed a seasonally-varying threshold [5]. Regarding its interaction with the above atmosphere, SST can affect processes in the atmosphere, such as rainfall variability [6], air temperature, relative humidity [7], and wind speed [8].

Investigating the spatiotemporal variability in Indonesia is essential to understand the fundamental pattern of the SST. In addition, Indonesia is located between two oceans and two continents, causing various atmospheric and oceanic dynamics. The general annual variability such as the meridional variations of SST due to seasonal change does not reveal the comprehensive understanding regarding the spatiotemporal SST pattern in Indonesia. We aim to analyze the spatiotemporal variability of SST in correlation to these indices to quantify the contribution of several climate indices defined around the Indonesian seas, such as the Australia Monsoon Index (AUSMI)[9], Dipole Mode Index (DMI) [10], and ENSO indices.
Global modes of SST variability have been investigated by [11] by correlating dominant mode to several regional climate indices. In addition, the time-frequency analysis is efficient to map the distribution of tidal harmonics based on the SST data. The spatial-time SST data is transformed to spatial-frequency domain and by choosing the specific periodicity, it can robustly map the spatial distribution of the tidal harmonics [4,12]. Combining these approaches, we focus on dominant modes in the Indonesian seas and their correlation to the regional climate indices, and concurrently extend the harmonic analysis to another periodicity longer than the tidal harmonics.

2. Data and Methods

2.1. Data
This research uses the ERA5 monthly averaged data on single levels from 1979 to present [13] with the spatial resolution of 0.25˚×0.25˚ and a monthly temporal resolution from January 1979 until March 2021 present. This dataset is the fifth generation ECMWF reanalysis for the global climate and weather. The parameter used is sea surface temperature with the unit of Kelvin (K). The data needs to be detrended using [14] to eliminate the long term trend. The annual mean of SST in the Indonesian seas from 16˚S-16˚N and 90˚E-150˚E is shown in Figure 1:

![Figure 1. SST annual mean (K) produced from the CDS toolbox](image)

The climate indices used are shown in Table 1. The AUSMI (Australian Monsoon Index) is calculated based on the definition by [9] using the zonal wind dataset from ERA5:

| Index                  | Source                                           |
|------------------------|--------------------------------------------------|
| Australia Monsoon Index| [9] https://doi.org/10.24381/cds.6860a573          |
| Dipole Mode Index      | [6] https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data |
| Niño 3.4               | [7] https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.anom.data |

2.2. Methods
The SST data contains both variability and long-term trend due to the anthropogenic global warming. Thus, the data is previously detrended to eliminate the global warming signal. Generally, we performed a similar approach as [11] to get the dominant mode distribution. Only first six dominant modes are analysed, assuming the rest modes are not significant.
Concurrently, we performed a cross-correlation analysis to quantify the maximum correlations and their lags of each climate indices contributing to the variation of SST. The EOF calculation is done by using \textit{eof} function in the Climate Data Toolbox [14].

The time-frequency analysis is used to filter the dominant periodicities of SST data. This analysis is meant to separate the dominant variabilities such as intra-seasonal spectrums. The spatial distribution can be visualized by taking the magnitude value from each grid points.

3. Results

3.1. EOF analysis

Figure 2 shows the EOF maps calculated from January 1979 until March 2021. The first six modes of EOF calculated over the Indonesian region explain 90.2\% of the SST anomalies variance. The periodicity of each principal components is shown in Figure 3. The corresponding principal components of EOFs are shown in Figure 3, superimposed with the climate indices. In addition, the correlation coefficients and their lags respectively are shown in Table 2.

![EOF maps](image)

\textbf{Figure 2.} EOF spatial patterns of the first six modes. The percentage value inside the bracket is the variance explained by each mode.
Table 2. Maximum correlation value (rmax) between principal components and the climate indices and their respective lags/leads. Blue shade is the correlation value to AUSMI, green shade to DMI, and yellow shade to NINO 3.4.

| PCs | pc1 | pc2 | pc3 | pc4 | pc5 | pc6 |
|-----|-----|-----|-----|-----|-----|-----|
| rmax | 0.769 | 0.407 | 0.769 | 0.312 | 0.332 | 0.221 |
| lag/lead | 0 | 0 | 3 | 7 | 0 | -7 |

Figure 3. Time series (1979-2021) of the principal components (blue lines) associated with the climate indices (orange lines). The indices have been adjusted with the lag/lead to obtain the maximum correlation value.

In general, the EOF results are similar to [6,15–17] even though the objects are different (precipitation, SST, and OLR) due to air-sea interaction over the region. The first mode in Figure 2(a) explains greater variance than any other mode (60.9%). Its corresponding principal component (pc1) is highly correlated...
with AUSMI ($r = 0.769$). The map shows the annual cycle pattern, as also shown in Figure 4(a), dividing Indonesia’s northern and southern regions, meaning that the SST in Indonesian waters reaches their maximum in the boreal winter and reaches their minimum in the boreal summer and the SST of the northern area reaches their maximum in the boreal summer while reaches their minimum in the boreal winter. This pattern results from the variation of seasonal solar radiation that drives the AUSMI in the first place, and indeed consistent with [18]. This yearly variation is weaker around the equatorial region (near the equator line) given that this region receives more solar radiation throughout the year.

The second mode (19.0%) is the strongest in the South China Sea. There are no anti-phase anomalies found around the Indonesian region (Figure 2.b). Mode 2 is dominated by annual and semi-annual oscillation (Figure 4,b). The second mode is weakly correlated to the AUSMI ($r = 0.407$) with the maximum correlation at zero lag.

As in mode 2, mode 3 (7.8%) is dominated by annual and semi-annual oscillation (Figure 4,c). There is a sharp barrier between the east and west region of Indonesia as shown in Figure 2.c. Mode 3 is strongly cross-correlated to the AUSMI ($r = 0.769$) with +3 months lag.

Mode 4 (2.9%) is dominated by semi-annual oscillation. The strongest variability is from the northern part of Australia (Timor & Arafura Sea) to the South China Sea, crossing the Java Sea diagonally in the middle. The half-year periodicity is strongly found in the Indonesian seas. However, the correlation value to the AUSMI is weak ($r = 0.312$) with the optimum time lag of 7 months.

![Figure 4](image)

**Figure 4.** PSD of 1-6 Principal Components.
Mode 5 (1.4%) is weakly correlated to the DMI ($r = 0.332$). According to its corresponding principal component, mode 5 periodicity is distributed seasonally and inter-annually as shown in Figure 4.e. The spatial pattern suggests that it is matched to the definition of the Dipole Mode Index, especially in the SETIO region [10], where the peak variabilities are strongest on the west coast of Sumatra.

Lastly, we do not find any reliable explanation for mode 6 as it is not correlated to any of the climate indices we utilize in this research. The periodicity of mode 5 (Figure 4.f) is distributed from 0.5 years to inter-annually.

3.2. Spatial Distribution of the Semi-Annual Oscillation

In EOF analysis, we have discussed four first modes that are strongly correlated to the AUSMI. But the spatial distribution of the semi-annual periodicity is not clear yet. In pc2, there are a mixed signal between annual and semi-annual periodicity while in pc4 the semi-annual oscillation magnitude is not that strong. We want to analyze further the spatial distribution of the semi-annual periodicity by transforming the SST data to frequency domain.

![Figure 5. Spatial distribution of annual oscillation (left) and semi-annual oscillation (right) PSD](image)

Figure 5 shows the semi-annual spectrum peaks extracted from the 42 years of SST data. The distribution is extended from the southeast part of the domain, i.e., the Timor Sea and the Arafura Sea, to the South China Sea and the Andaman Sea in the northwest area. Some areas between these seas are also affected by semi-annual oscillation signatures, such as the Java Sea, Banda Sea, and the Flores Sea. The other area, such as the western coast of Sumatra Island and the Pacific Ocean, is not affected by the semi-annual oscillation.

4. Conclusions

The variability of SST in Indonesia primarily consists of two harmonics, the annual and semi-annual oscillation, similar to [6]. According to the EOF analysis, the first mode (60.9% explained variance) of the SST variability is strongly correlated to the AUSMI ($r = 0.769$). The second mode (19.0% explained variance) has an annual and semi-annual oscillation periodicity. It is mostly correlated to the AUSMI ($r = 0.4073$). Mode 3 (7.8% explained variance) has an annual and semi-annual oscillation periodicity, and it is strongly correlated to the AUSMI ($r = 0.769$) with 3 months lag time. Mode 4 (2.9% explained variance) has a semi-annual periodicity, and it is mostly correlated to AUSMI ($r = 0.312$) with 7 months lag time. Mode 5 (1.4% explained variance) and it is mostly correlated to DMI ($r = 0.332$). Periodicities of mode 5 is distributed inter-annually and it forms a well-known IOD anomaly pattern in SETIO region.

Spatial distribution of the annual oscillation can be explained with EOF map of mode 1. The variance is extended in almost the entire region of Indonesia with the exception around the equatorial line. The
semi-annual spatial distribution can be explained by time-frequency transformation, and it is extended diagonally from northwest region (South China and Andaman Sea) to the southeast region (Timor and Banda Sea).

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