The impact of El Niño and the positive Indian Ocean Dipole on rainfall variability in the Indo-Pacific region

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Abstract

In the tropics including the Indonesian maritime continent, the atmosphere is highly sensitive to sea surface temperature variations, especially on interannual time scales, which significantly affect precipitation and atmospheric circulation at these latitudes. Here we study the relative influence of the El Niño (EN) and positive Indian Ocean Dipole (pIOD) events on the Indonesian rainfall variability using long-term observational datasets (1948-2008) based on satellite as well as ground-based observations. The empirical orthogonal function (EOF) analysis of Indonesian rainfall anomaly is employed to extract the modes of variability relevant to the regional rainfall index, defined for three separate regions representing typical rainfall patterns. Since an ordinary correlation between IOD and Indonesian rainfall might be contaminated by the concurrent EN signal, partial correlation technique and composite analysis methods are used on the monthly rainfall anomalies in the three separate regions to extract the apparent teleconnection patterns. The analysis reveals that the pIOD impact on the rainfall is generally overwhelmed by that of EN when the two are in co-occurence. Nevertheless, it is found that the IOD influence remains high (most negative correlation) with a significance of above 95% confidence level after proper removal of the EN influence. Strong EN events influence all regions in Indonesia, whereas the effect of strong pIOD events is most remarkable in western and central regions. The relationship between pIOD and Indonesian rainfall seems to be sustained through pIOD (not negative IOD) occurring in the presence of El Niño events.

Keywords: El Niño, positive IOD, EOF analysis, partial correlation technique.

1. Introduction

The Pacific Ocean exhibits prominent sea surface temperature (SST) variations on timescales that range from interannual to interdecadal. The interannual fluctuations are primarily associated with the El Niño-Southern Oscillation (ENSO), which results from the interactions between the tropical Pacific Ocean and the overlying atmosphere$^{1)}$. The SST of the world's oceans plays a fundamental role in the exchange of energy, momentum, and moisture between the ocean and atmosphere$^{2)}$. The SST variability is crucial for understanding such interactions, in relation to the regional as well as global climate. Since Indonesia is located between the Pacific and Indian Oceans and between the Asian and Australian Continents, the influence of global climate phenomena vary across the region due to the island topography and/or the regional behavior of ocean–atmosphere fluxes. The Indonesian region, also known as the "Maritime Continent", has been identified as an area of major climatic importance both locally and globally$^{3)}$.

Recently, there has been more interest in the climate of the Indian Ocean basin as a whole, yielding the description of the Indian Ocean dipole (IOD)$^{4,5)}$. Saji et al. (1999) identified an interannual mode of variability in Indian Ocean SSTs that has an east-west structure and is distinct from the basin-wide warming attributed to the remote response to El Niño (EN). They argued that the zonal mode identified in their analysis was independent of EN because the years when the zonal mode was most active were not always EN years. Most research on the climate of the Indian Ocean basin and of the countries around the rim of the Indian Ocean has focused on the evolution of the Asian-Australian monsoon. Furthermore, it has usually been assumed that the influence of the Indian Ocean is secondary to ENSO in controlling the climate of India, Africa, and Indonesia.

On the planetary scale, it is expected that Indonesian rainfall is strongly affected by both the EN and the IOD phenomena. Relationships between ENSO/IOD and rainfall in various regions have been investigated$^{4,6,7,8,9,10)}$. Briefly, the results indicated that generally the regional SST anomaly and rainfall anomaly data show strong correlation during the EN and positive IOD (pIOD) periods. As an extension of these previous works, here we extract strong EN and pIOD events from a time span of 60-years (1948-2008), highlighting the essential aspects of their influence on the regional rainfall in Indonesia.

2. Data and method

The basic SST dataset used in this study are the 2°×2° extended NOAA reconstructed SST version 3 (ERSST v3) dataset. This was constructed by using the recently available International Comprehensive Ocean Atmosphere Dataset (ICOADS) SST data and improved statistical methods that allow stable

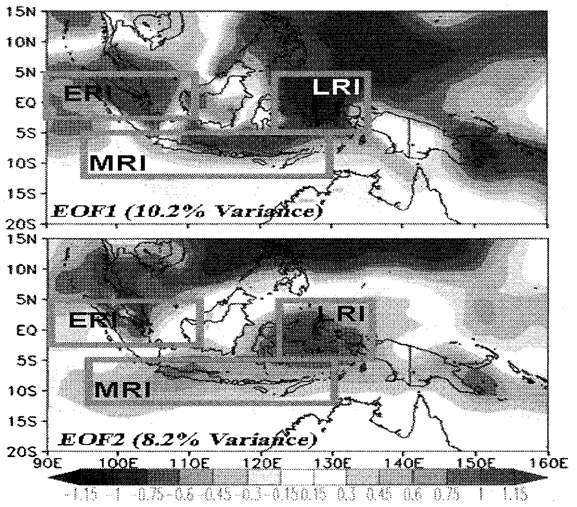

Fig. 1 Top two EOF modes of box averaged monthly mean rainfall anomaly in Indonesia region. The amplitudes are in °C. For each boxed region, a regional rainfall index (RRI) is defined: the monsoonal rainfall index (MRI), equatorial rainfall index (ERI), and local rainfall index (LRI).

reconstruction using sparse data[11]. The ENSO/IOD indices recalculated herein are based on the spatially averaged SSTs in wider regions relevant to ENSO/IOD. The obtained data are then used to generate the monthly Niño-3.4 SST anomaly index which represents the strength of EN over the eastern equatorial Pacific (5°S-5°N, 120°-170°W)[12]. Following Saji et al. (1999), we consider the IOD index as the SST anomaly difference between the tropical western Indian Ocean (10°S-10°N, 50°-70°E) and the tropical south-eastern Indian Ocean (10°S-eq, 90°-110°E). For precipitation analysis, here we use the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset based on a state-of-the-art global data assimilation system[12]. With all of these data, we first calculate monthly variables throughout the full record period (January 1948 to May 2008) and then anomalies are obtained by subtracting the average values over the preceding 30 years from the monthly values.

The empirical orthogonal function (EOF) analysis of Indonesian rainfall anomaly is employed to extract the modes of variability relevant to the regional rainfall index, defined for three separate regions representing typical rainfall patterns. Since an ordinary correlation between IOD and Indonesian rainfall might be contaminated by the concurrent EN signal, partial correlation technique and composite analysis methods are used on the monthly rainfall anomalies in the three separate regions to extract the apparent teleconnection patterns. The significance levels for composite and partial correlation analyses are obtained by the standard 2-tailed Student's t-test.

3. Results and discussion

3.1. Regional Rainfall, ENSO, and IOD indices

Using EOF analysis, the leading EOF modes of the monthly rainfall anomaly over the Indonesia region are presented in Fig 1. The first EOF (EOF1) explains about 10.2% of the total variation of anomalous rainfall for the period between January 1948 and May 2008. The second EOF (EOF2) explains about 8.0% of the anomalous rainfall variability. Characteristic to the EOF1 is a reversal in sign of SST anomaly across the basin during EN and pIOD events. To analyze the possible correlation among various parameters, we generate a set of the regional rainfall indices (RRIs) by averaging monthly anomalies of rainfall in the three regions defined in Fig. 1. Hereafter these indices are called the monsoonal rainfall index (MRI), equatorial rainfall index (ERI), and local rainfall index (LRI). The RRIs are constructed from gridded reanalysis data products based on satellite as well as ground (gauge) observations. The 2.5°×2.5° NCEP-NCAR reanalysis data is a dataset that merges satellite and rain-gauge data[13].

The long-term variations of the EN/IOD indices and the RRI for each region (MRI, ERI, and LRI) are shown in Fig. 2 (left panel), here we show appropriately normalized values. As indicated by the correlation coefficients (r_1 for EN and r_2 for IOD), we find a negative correlation between each of the regional rainfall index and EN/IOD indices. Peaks and troughs in the RRIs tend to show a time lag of a few months against the EN/IOD indices, as analyzed in the following. Although generally a good relationship is found, not every EN (or p IOD) or La Niña (or negative IOD) episode results in a peak or trough in the RRIs. The significant influence of EN and positive IOD (pIOD) variability can be highlighted by classifying the EN/IOD events according to the time series of SST-based index as shown in Fig. 2 (left panel). Here the time-periods corresponding to strong EN (La Niña) are determined by proposing a new threshold based on standard deviation. Namely, a time-period is here classified as an EN (La Niña) event if SST anomalies in the Niño-3.4 region are +0.86°C (-0.86°C) or more for at least six consecutive months, and the months should include Dec-Jan-Feb (DJF). During 1948-2008, there are nine significant EN events (1957/58, 1963/64, 1965/66, 1972/73, 1982/83, 1986/87, 1991/92, 1997/98, and 2002/03) from the SST anomalies detected in the Niño-3.4 region (Fig. 2, left panel). A positive (negative) IOD event, on the other hand, is defined when the SST difference in the IOD regions is more than +0.35°C (less than -0.35°C) for at least six consecutive months. The months of SST anomaly peak should include September-October-November (SON) for IOD event. Nine events (1961/62, 1963/64,

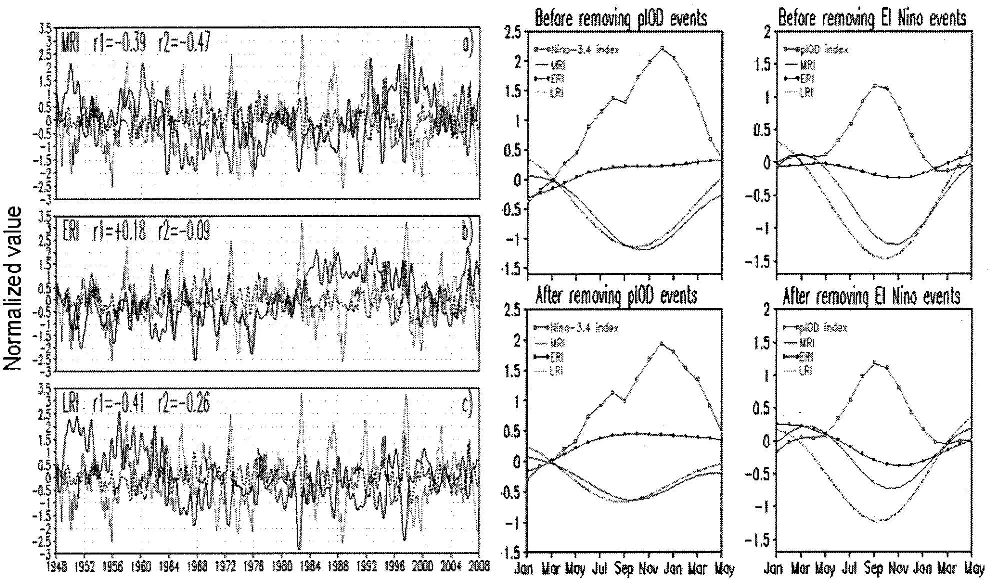

Fig 2 [Left panel] Long-term relationship between the regional rainfall indices (RRIs, solid lines) and EN (thin line)/IOD (broken line) indices: (a) MRI region (95°-130°E; 5°-12.5°S), (b) ERI region (90°-110°E; 2.5°S-5°N), and (c) LRI region (122.5°-135°E; 5°S-5°N). [Right panel] Composite analysis of the RRIs and EN/IOD index during strong EN and pIOD events as defined in the text. All indices are normalized, and correlation coefficients r_1 (RRI vs. El Niño index) and r_2 (RRI vs. IOD index) are shown in the panel.

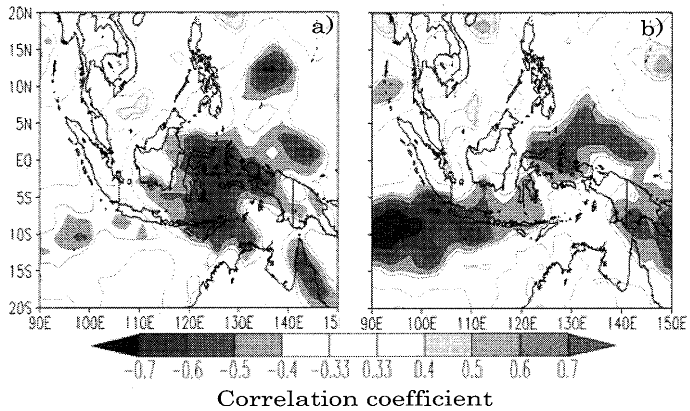

Fig. 3 Distribution of temporal correlation coefficient of the rainfall anomaly in Indonesian region with the EN index during (a) strong EN events (after removing pIOD events), and with the IOD index during (b) strong pIOD events (after removing EN events). All results are derived for strong EN and pIOD events during 1948-2008.

1967/68, 1972/73, 1977/78, 1982/83, 1994/95, 1997/98, and 2006/07) were found to be the pIOD years. Since both phenomena give phase locking to the seasonally cycle, it is useful and meaningful to derive a composite analysis for better understanding of the evolving nature of atmospheric and oceanic variables during different phases of ENSO and IOD events. Among all the warm events, we extract strong EN/pIOD events so as to study the time span corresponding to the peak phase (Fig 2, right panel). The strong EN is associated with relevant index values of $\geq 1.61^{o}$C while the strong pIOD with the value of $\geq$ 0.84°C. For the period of 1948-2008, we can identify four extreme EN events (in 1957-58, 1972-73, 1982-83 and 1997-98) and five extreme pIOD events (in 1961-62, 1972-73, 1994-95, 1997-98, and 2006-07). Any year (during 1948-2008) that does not meet the above criteria of the warm (EN/pIOD) or cold (La Niña/negative IOD) events is here defined as a normal year. Thus, there are 32 years categorized as normal years during the 60-years period of 1948-2008.

3.2. Partial correlation analysis

To provide more systematic and comprehensive features of the ENSO and IOD influences on the Indonesian rainfall both spatially and temporally, we employ two dimensional version of partial correlation method. Figures 3 show the two-dimensional representation of the partial correlation coefficient (with no time lag) of the rainfall anomaly against the Niño-3.4 index and IOD index, respectively. Here no time lag is considered in view of the relatively small time-lag effects found in Fig 2. From Fig. 2 (right panel), it is evident that highly negative correlations are found between the MRI/LRI indices and the Niño-3.4/IOD indices. It is noticeable that the impact of ENSO and IOD events on ERI region is relatively small (uncorrelated), which is consistent with Fig. 3a. Also, Fig. 3a indicates that the effect of a strong EN event is significant over a wide region of Indonesia with mostly negative correlations ($r \geq -0.33$, 95% confidence level), while a weak EN event affects only limited regions (figure not shown). On the other hand, Fig. 3(b) shows that the pIOD yields negative correlations ($r \geq -0.33$, 95% confidence level) over the western region, particularly in the south-western Indian Ocean. This result for the strong IOD is basically in agreement with the result (Fig. 4) of Saji et al. (1999).

4. Conclusions

On the basis of the present analysis, here we summarize the spatial effect of both EN and IOD on the Indonesian rainfall, paying attention to the comparison between EN and pIOD events. We have systematically studied the influence of EN and IOD on the three separate regions of Indonesia, categorized in accordance with distinct rainfall patterns. Using the empirical orthogonal function (EOF) analysis of Indonesian rainfall anomaly, we have extracted the modes of variability relevant to the regional rainfall index or RRI (MRI, ERI and LRI), defined for three separate regions. The most negative correlations are found for the strong EN/pIOD events of region MRI and region LRI. This result clearly indicates the usefulness of the categorization method in discussing the effects of global SST anomalies on the regional rainfall anomalies. In our lag-time correlation analysis, typically a delay of 2 months was found for the RRI indices against the EN index, suggesting the possible use of EN/IOD indices for early warning of drought (EN) or flood (La Niña). Correlation studies have also shown that only the strong EN can affect the entire Indonesian region. Only the western part is strongly affected by the positive IOD, but not by the negative IOD. Besides, both the EN and La Niña events are influential to the eastern region. Future work should address the effects of other modes of climatic variability, as well as the hydrologic effects of interactions between EN/IOD events and other anomalous climate patterns.

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