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Influences of IOD and ENSO to Indonesian rainfall variability: role of atmosphere-ocean interaction in the Indo-Pacific sector

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Abstract

The relative influences of Indian Ocean dipole (IOD) and El Niño–Southern Oscillation (ENSO) on Indonesian rainfall are investigated for seasonal time scales. For the period 1960–2011, observation and reanalysis products during September to November (SON) are used to assess the impacts of ENSO and IOD in Indonesian region. Composite of SSTs and Indonesian rainfall anomalies shows detailed features in the different phases of ENSO and IOD. A distinct impact on rainfall anomalies is found during the years when an El Niño and a positive IOD event or a La Nina and a negative IOD event co-occur indicating the interplay of ENSO and IOD in generating rainfall anomalies in Indonesian region. The atmospheric circulation and sea surface temperatures associated with these responses are discussed. Using composite analysis of anomalies of rainfall, sea surface temperature (SSTs), and circulation at any atmospheric levels, it is shown that positive anomalies of rainfall over Indonesia start to be decreased when SSTs surrounding Indonesia are cool and The Walker Circulation is weakened, resulting in anomalous surface easterlies across Indonesia. The composite analysis of rainfall anomalies and the SSTs showed that rainfall variability in Indonesia is clearly influenced by IOD and ENSO phenomena. This study highlights the atmosphere–ocean interaction in Indo-Pacific sector which plays an important role on Indonesian rainfall variability.

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Keywords: Indonesian rainfall; ENSO; IOD; atmosphere–ocean interaction

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1. Introduction

IOD (Indian Ocean Dipole) is a pattern of internal variability with anomalously low sea surface temperatures of Sumatra and high sea surface temperatures in the western Indian Ocean, with accompanying wind and precipitation anomalies [1]. ENSO (El Niño-Southern Oscillation) is a naturally occurring phenomenon involving fluctuating ocean temperatures in the central and eastern equatorial Pacific, coupled with changes in the atmosphere. The vertical wind motions which resulted by IOD and ENSO could be generally seen in Walker Circulation. Walker Circulation comprises east-west atmospheric circulation cells along the equatorial belt responsing the differences in ocean temperature. Fluctuations of the Walker Circulation can lead to extreme weather conditions in different parts of the world [2].

IOD in the Indian Ocean and ENSO in the Pacific Ocean are the result of interactions between the oceans and atmosphere on each respective area. Both of the phenomena can be generally identified by sea surface temperature (SSTs) anomaly, and their impact can be seen directly on rainfall that occurs around the world. Ashok et al. [3] have pointed out that the effect of single and combination of ENSO and IOD during the Indian Summer Monsoon was clearly identified. In addition, they found that the IOD significantly influences the precipitation and reduces the impact of ENSO concurrently. Moreover, the research conducted by Meyers [4] found that the probability of below average of Australian precipitation at June to November period had different condition when the phenomena of IOD, ENSO, and the both combinations were occurred. The impact of decreasing rainfall is significant when El Niño and positive IOD were concurrently occurred. Meanwhile, the rainfall is significantly increased when La Nina and negative IOD were concurrently occurred.

Rainfall variability caused by IOD, ENSO, and the both combinations is unique in several regions. Indonesia is strongly influenced by the IOD and ENSO on rainfall in dry season (June-November) and weakly influenced in wet season (December-May) [5]. Based on that, it needs a study to estimate the impacts of ENSO and IOD on Indonesian rainfall and to observe the ocean-atmosphere's conditions over Indonesia to explain the Indonesian rainfall variability on IOD, ENSO, and the both combinations.

2. Methods

The region of this study is the equatorial region of the Indian Ocean to the Pacific Ocean (20ºN-20ºS and 30ºE-60ºW). Monthly data of observational and reanalysis products from NOAA for 1960 to 2011 period are used. They are Extended Reconstructed Sea Surface Temperature V3B (ERSST) data [6], zonal-meridional-vertical wind data (u; v; ω) from reanalysis NCEP / NCAR products [7], and rainfall data from the Climatic Research Unit (CRU) [8]. These data are used to observe the ocean-atmosphere and rainfall conditions. Procedures of analysis data are carried out in two stages. They are identification of IOD and ENSO (Niño 3.4) years and the composite analysis of data when the phenomenon of IOD, ENSO, and a combination of both are occurred.

The identification of IOD and ENSO years are done by analyzing the changes of sea surface temperatures (SSTs) in their respective territories. This aspect gives a representation in upwelling which represents oceanic process that links the slow physics of thermocline dynamics to SSTs [4].The strength of upwelling in western and eastern Indian Ocean is essential to control IOD cycle and also in the central and eastern Pacific is essential to control the process in the ENSO cycle. The areas for IOD phenomena are western in 50°E to 70°E and 10°S to 10°N and eastern in 90°E to 110°E and 10°S to 0°S [1], and one of the areas for ENSO which has higher response is Nino 3.4 in 50ºN to 50ºS and 120ºW to 170ºW) [9]. Sea surface temperature (SSTs) anomaly is obtained by calculating the climatology of 30-year based periods data (January 1961 - December 1990). Smoothing average on the ENSO phenomenon is done by five months running mean, while the IOD is done by three months running mean. Smoothing average is used to define the trend of the data, and the difference in months of running mean is caused by the longer occurrence of ENSO than IOD. The results are plotted and identified, where SSTs anomaly of Niño 3.4 and IOD is higher (lower) than 0.5ºC (-0.5ºC) for six months respectively resulting El Niño and positive IOD (La Nina and negative IOD).

Composite analysis is used for investigating ocean-atmosphere physics over Indo-Pacific when the phenomena of IOD, ENSO, and combinations of both are occurred. Data for composite analysis are from IOD and ENSO years resulted from the first stage. Data during September to November (SON), dry season, are used because they have the highest correlation between Indonesian rainfall and SSTs [5, 10, 11]. Indonesian rainfall is explained based on ocean-atmosphere conditions over Indonesia. Ocean-atmosphere conditions are noticed by vertically and horizontally atmospheric conditions over Indo-Pacific, such as the Walker circulation, SSTs, and horizontal wind.

3. Result

3.1. Identification of IOD and ENSO Years

Identifications of IOD and ENSO (Niño 3.4) years are done by analyzing the changes in SSTs in their respective territories. SSTs anomaly during January 1960 to December 2011 period in index of Nino 3.4 and IOD (Figure 1) shows that it has different conditions of each other. IOD index and Nino 3.4 index show that they have independent relationship [1]. The strongest IOD is seen in 1960, 1961 and 1996, and it is not followed by ENSO phenomena. In the other side, the strongest ENSO is seen in 1965, 1987, and 1988, and it is not followed by IOD phenomena. In addition, there are several years of IOD and ENSO which they are concurrently occurred, such as 1963, 1972, 1989, and 1997. The independent relationship between IOD and ENSO may be related to decadal variation in the depth of the thermocline off of Java-Sumatera [12]. Figure 1 shows the years of IOD, ENSO, and the both combinations summarized in Table 1. The years in Table 1 are used to analyze the variability of rainfall, SSTs, horizontal wind, and the Walker circulation. They are shown by using composite method, and the selected years are represented in each phenomena. They also identify the dynamics and teleconnections of the independent relationship between IOD and ENSO.

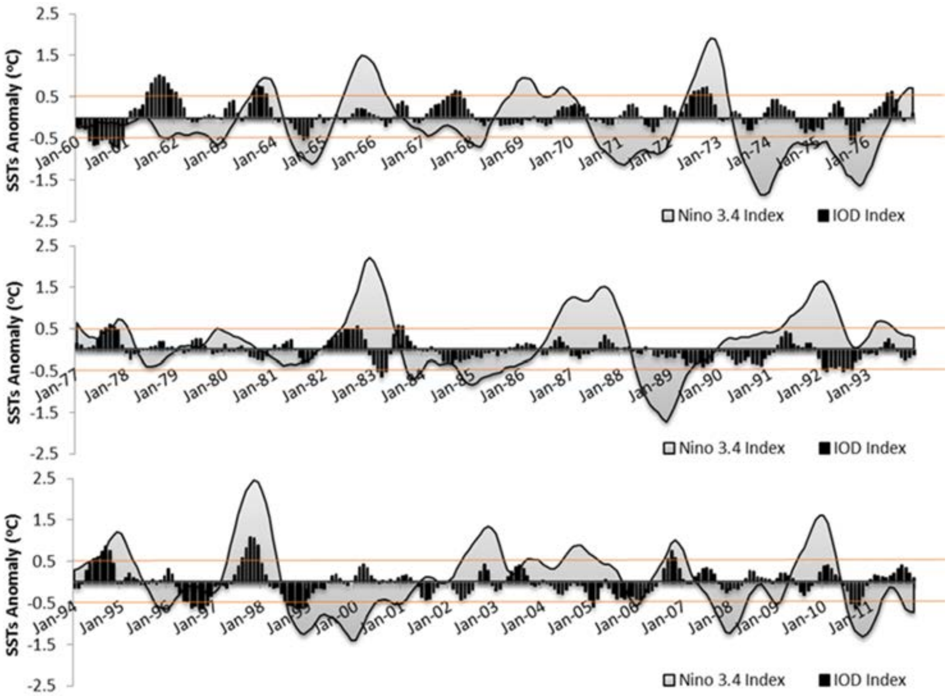

Fig. 1. Index of IOD and Nino 3.4 during January 1960 to December 2011 period 1960 to 1976 (above), 1977 to 1993 (middle), and 1994 to 2011 (bottom). Positive (Negative) Anomaly Shows El Nino (La Nina) event and Positive (Negative) IOD.

Table 1 shows that ENSO is more intensive than IOD during 1960 to 2011. There are several years of IOD and ENSO occurred together. They are positive IOD - El Nino and negative IOD - La Nina. Table 1 also shows that positive IOD - La Nina and negative IOD - El Nino are never occurred. Those unoccupied categories are approximately caused by the ENSO signals transmission of the deep thermocline through the Indonesian seas [12].

Table 1. The years of IOD, ENSO, and the both combinations

	El Nino	Normal	La Nina
Positive IOD	1963, 1972, 1982, 1997	1961, 1967	-
Normal	1965, 1986, 1987, 2002, 2009	1978, 1979, 1990, 1993, 1995	1970, 1971, 1973, 1988, 1999, 2007
Negative IOD	-	1960, 1996	1998

3.2. Indonesian Rainfall Variability and Atmosphere-Ocean Interaction

The years of IOD and ENSO in Table 1 are used for conducting composite analysis of ocean-atmosphere variables when the phenomena of IOD, ENSO, and a combination of both are occurred. The data are averaged for September to November (see Tabel 1). The results of that process are Indonesian rainfall anomaly (Figure 2), SSTs and horizontal wind anomaly (Figure 3), and the Walker circulation anomaly (Figure 4).

3.2.1. No ENSO and IOD (Normal)

Normal condition during SON shows that Indonesian regions have a rainfall anomaly (Figure 2g) which is not drastically increased or decreased. The SSTs anomaly (Figure 3g) condition in Indonesian territorial and the Walker circulation (Figure 4g) have no stricking anomaly. In this season, there is an intensively warming in western Indonesian seas, so the direction of horizontal wind motions moves to warmer area (Figure 3g), and also it increases the potential vapour which is supposed as a precipitable water. In this section, the vertical wind motions (vertical and zonal wind; ω, u) can be seen in the Walker circulation. It is done by averaging the zonal and vertical wind vector at 1000 hPa to 100 hPa and on 5^{o}N-5^{o}S. Figure 4g, the result of that process, shows that there is an upward of air masses on Indonesian regions, but there is a downdraft on The Pacific Ocean. This condition agrees with Indonesian rainfall in Figure 3g which its result is the positive rainfall anomaly on western Indonesian region.

3.2.2. El Niño

Indonesian rainfall in single El Niño event is decreased up to 100 mm/month (Figure 2a). Significant decrease of rainfall occurs in eastern Indonesian region whereas this condition is not seen on West Sumatra. There is SST anomaly occurred in all over Indonesian seas except in the western region that is cooler than the Pacific Ocean, and anomaly of horizontal wind motions moves to the Pacific Ocean carrying the potential vapour for precipitation (Figure 3a). In addition, the Walker Circulation on the Pacific Ocean and western Indonesian region are updrafts, and the other sides are downdrafts (Figure 4a). This situation shows that the Walker circulation is weakened over Indonesian region and become stronger over the Pacific ocean. It is supposed as a movement of air masses to the Pacific and West Sumatra. Vertical movement of air masses from center-east Indonesian seas to West Sumatera is caused by warming of west Indonesia seas's SSTs.

3.2.3. Positive IOD

Indonesian rainfall in positive IOD event is generally decreased (Sumatera and Borneo) and generally increased (Java, Sulawesi, and Irian Jaya) up to 150 mm/month (Figure 2c) in overall regions. This condition is supported by SSTs anomaly on western of the Indian Ocean which is warmer than Sumatera waters, and horizontal wind motion moves to warmer areas (Figure 3c). The year of positive IOD event is followed by a weak La Nina. It can be seen from the Pasific Ocean is cooler than eastern Indonesian waters, and wind flows to the eastern of Indonesian seas. These conditions cause a wetter condition at some regions over Indonesia. In addition, the Walker circulation on the western region of the Indian Ocean and the central-eastern region of Indonesian is convection (upward of air masses), and the western region of Indonesian and the eastern region of the Pacific Ocean is subsidence (downward of air masses). That condition is showed in Figure 4c.

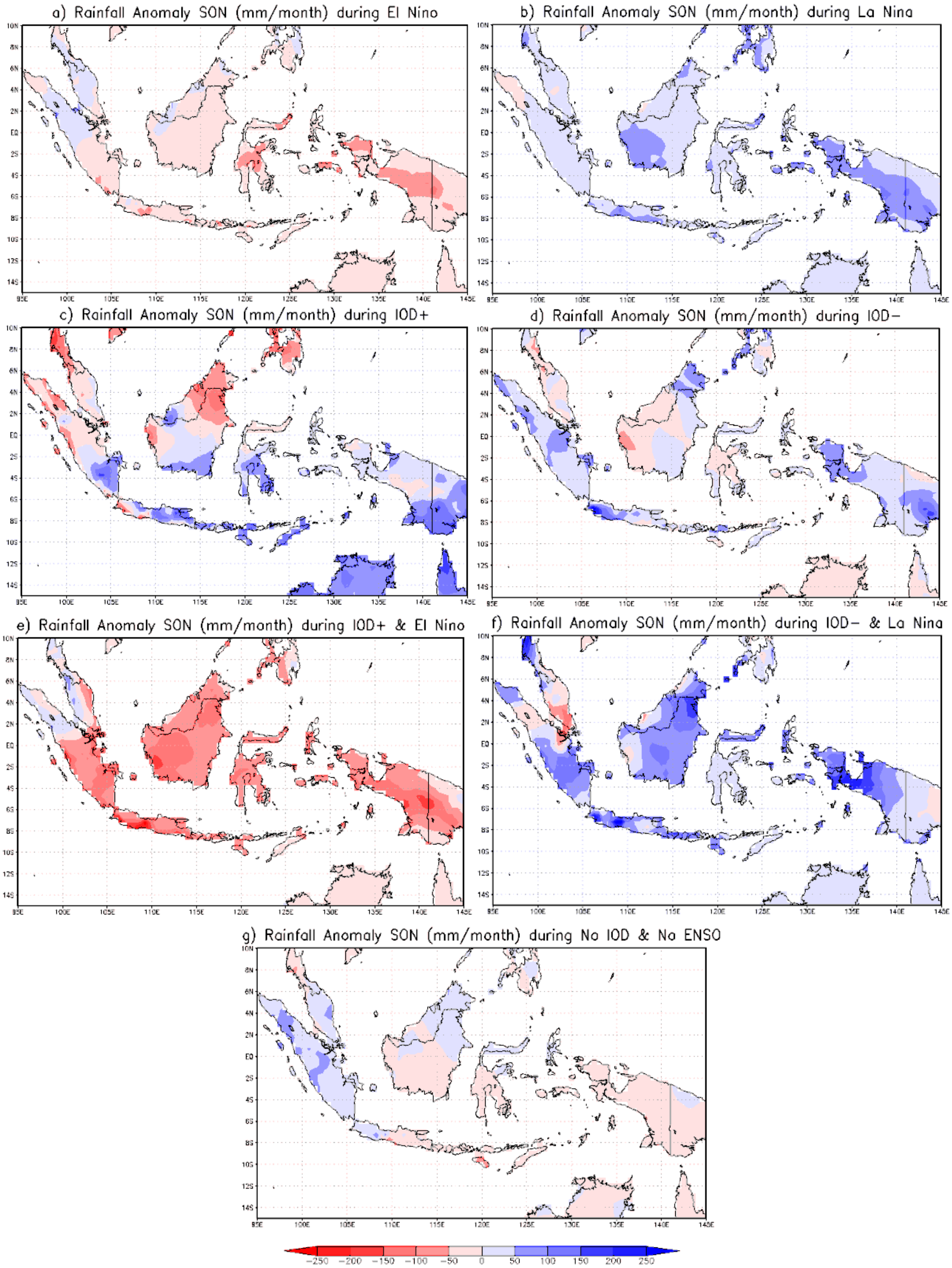

Fig. 2. Composite of Indonesian rainfall anomaly (contour; mm/month) during SON on (a) El Nino, (b) La Nina, (c) Positive IOD, (d) Negative IOD, (e) Positive IOD and El Nino, (f) Negative IOD and La Nina, and (g) No IOD and No ENSO. Positive (negative) value shows the increasing (decreasing) of rainfall.

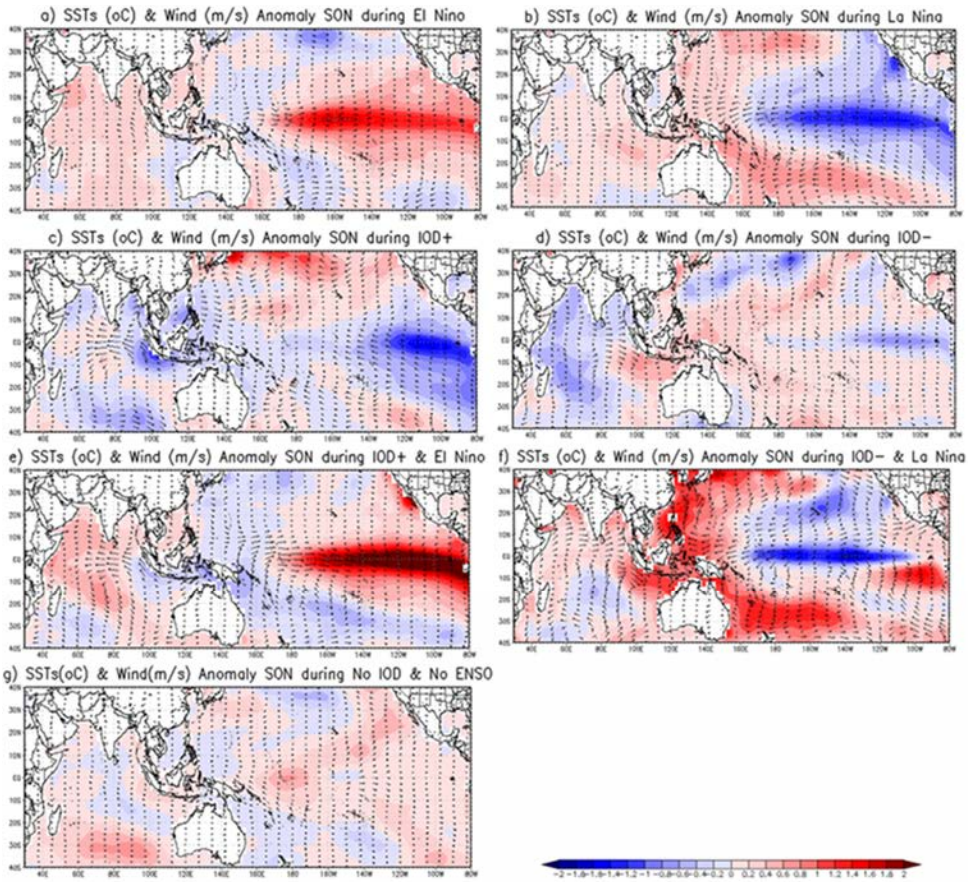

Fig. 3. Composite of SSTs (contour; °C) and horizontal wind anomaly (vector; m/s) during SON on (a) El Nino, (b) La Nina, (c) Positive IOD, (d) Negative IOD, (e) Positive IOD and El Nino, (f) Negative IOD and La Nina, and (g) No IOD and No ENSO. Positive (negative) value shows the increasing (decreasing) of SSTs.

3.2.4. Positive IOD and El Niño

Indonesian rainfall is extremely decreased up to 200 mm/month when positive IOD and El Niño occur together (Figure 2e). It is caused by cooling effect of SSTs in Indonesian waters and warming effect in the eastern of the Pacific Ocean and the western of the Indian Ocean (Figure 3e), so the wind flows from Indonesia to the surrounding area carry the air masses full of vapour. In vertical condition, the Walker circulation shows that Indonesian regions are the subsidence, and The Indian Ocean and The Pacific Ocean are the convection (Figure 4e). The effect of positive IOD and El Nino in decreasing rainfall is not only suffer Indonesia, but also Australia [4]. The probability of below average of Australian precipitation in June to November period is the highest when El Niño and positive IOD are occurred concurrently.

3.2.5. La Nina

Anomaly of Indonesian rainfall in La Nina event is wetter than normal condition (up to 100 mm/month), and the highest impact occurs in the eastern of Indonesian regions (Figure 2b). Anomaly of SSTs in Indonesian waters is warmer than in the Pacific Ocean, and anomaly of horizontal wind moves from The Pacific Ocean to Indonesian regions (Figure 3b). It shows that convection process occurs over Indonesian region and horizontal wind flows to Indonesian region on 1000 hPa. In addition, the Walker circulation causes the convection in Indonesian regions and subsidence in The Pacific Ocean (Figure 4b). It indicates that the Walker Circulation is strengthened over the Pacific ocean. It is caused by the warmer SSTs in Indonesian waters (western Pacific) than eastern Pacific. In addition, the SSTs in Indonesian waters is warmer than usually in this condition.

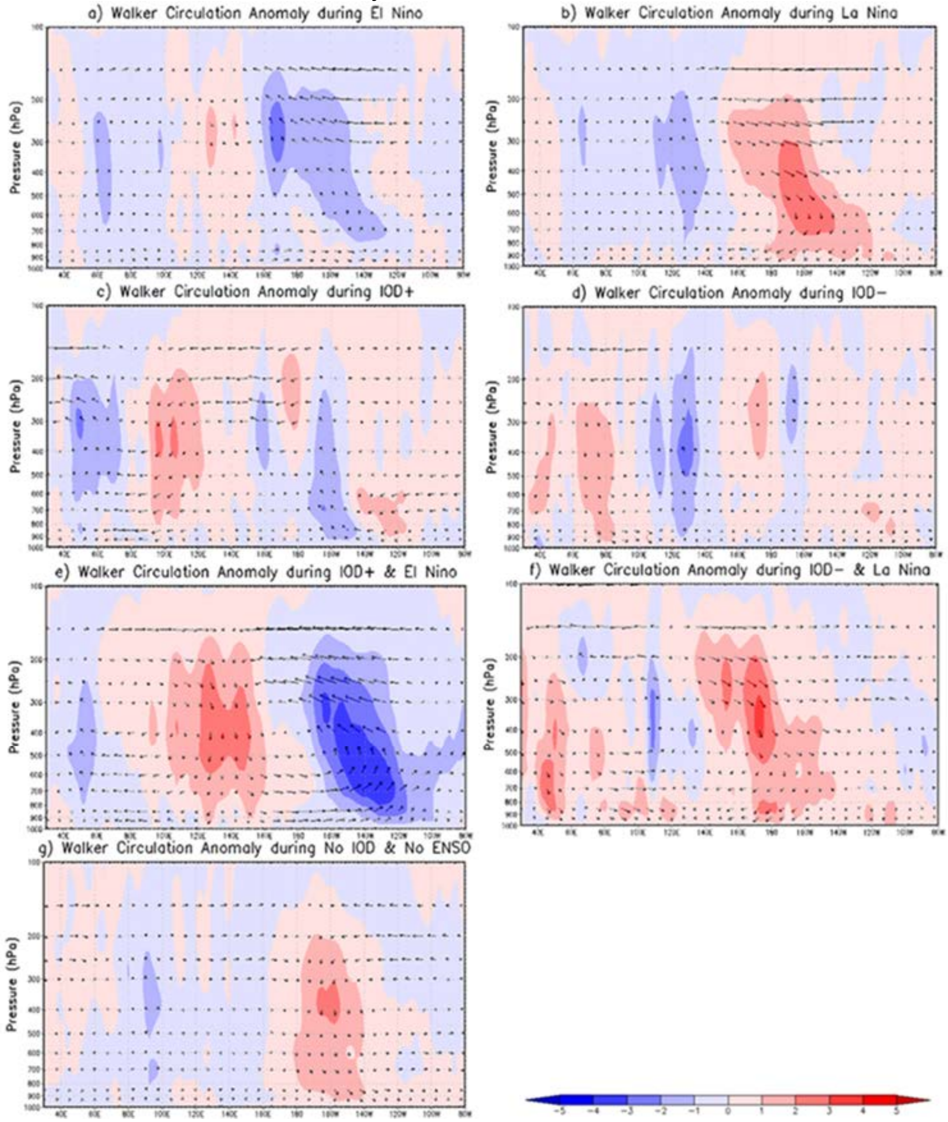

Fig. 4. Composite of The Walker Circulation anomaly (vector) and vertical wind (ω; 10^{-1} Pa/s) during SON on (a) El Nino, (b) La Nina, (c) Positive IOD, (d) Negative IOD, (e) Positive IOD and El Nino, (f) Negative IOD and La Nina, and (g) No IOD and No ENSO. Positive (negative) value shows the downward (upward) of air masses.

3.2.6. Negative IOD

Rainfall anomaly in the western and eastern of Indonesian regions is positively increased up to 100 mm/month, but it is decreased up to 50 mm/month in the central of Indonesian region (Borneo Island) during negative IOD event (Figure 2d). SSTs in Indonesian waters is warmer than in the Indian Ocean and the Pacific Ocean, and horizontal wind moves to Indonesian regions (Figure 3d). Figure 4d shows that the Walker Circulation is weakened over the Indian Ocean. It indicates the convection in Indonesian regions and subsidence in the Indian Ocean.

3.2.7. Negative IOD and La Nina

Negative IOD and La Nina event which they occur together cause an extremely increasing in Indonesian rainfall (up to 200 mm / month), except in some areas of Sumatera Island (Figure 2f). It is caused by warming effect of SSTs in Indonesian waters and cooling effect in the eastern of the Pacific Ocean and the western of the Indian Ocean (Figure 3f). Figure 3f also shows that horizontal wind moves to Indonesian regions. That motion is supposed to carry air masses full of vapour from the oceans to Indonesian region on 1000 hPa. In figure 4f, vertical condition, there is the strongest Walker Circulation over Indonesian region, and the upward of air masses is more efficient than single negative IOD or La Nina. It also shows that the air masses over the oceans are subsidence.

4. Conclusion

The impact of IOD, ENSO, and the both combinations phenomena in Indonesian rainfall variability has a different response. When a positive IOD and El Nino are concurrently occurred, Indonesian rainfall is more significantly decreased than in the single event of positive IOD or El Nino. In the other hand, when negative IOD and La Nina are concurrently occurred, Indonesian rainfall is more significantly increased than single event of negative IOD or La Nina.

Anomalies of SSTs in IOD, ENSO, and the both combination events produce a horizontally and vertically movement of air masses. Indonesian seas are cooler than the Pacific Ocean and the Indian Ocean when positive IOD and El Nino are simultaneously occurred. Wind motions move from a low-temperature region to a high-temperature region carrying the potential precipitable air masses. In addition, air masses in the Walker circulation over Indonesian regions is downward (subsidence) while in the Walker circulation over the Indian Ocean and the Pacific Ocean is upward (convection).

In another event, negative IOD and La Nina occurrences cause a cooling of SSTs over the Indian Ocean and the Pacific Ocean and a warming over Indonesian seas. Horizontal wind motions move from the oceans to Indonesian regions carrying air masses with full of vapour. Air masses in the Walker circulation over Indonesian seas is upward (convection) while in the Walker circulation over the Indian Ocean and the Pacific Ocean is downward (subsidence).

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