Relations between Interannual Variability of Regional-Scale Indonesian Precipitation and Large-Scale Climate Modes during 1960–2007

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(Manuscript received 25 October 2019, in final form 13 February 2020)

ABSTRACT

Regional-scale precipitation responses over Indonesia to major climate modes in the tropical Indo-Pacific Oceans, namely canonical El Niño, El Niño Modoki, and the Indian Ocean dipole (IOD), and how the responses are related to large-scale moisture convergences are investigated. The precipitation responses, analyzed using a high-spatial-resolution ($0.5^\circ \times 0.5^\circ$) terrestrial precipitation dataset for the period 1960–2007, exhibit differences between the dry (July–September) and wet (November–April) seasons. Canonical El Niño strongly reduces precipitation in central to eastern Indonesia from the dry season to the early wet season and northern Indonesia in the wet season. El Niño Modoki also reduces precipitation in central to eastern Indonesia during the dry season, but conversely increases precipitation in western Indonesia in the wet season. Moisture flux analysis indicates that corresponding to the dry (wet) season precipitation reduction due to the canonical El Niño and El Niño Modoki anomalous divergence occurs around the southern (northern) edge of the convergence zone when one of the two edges is located near the equator (10°S – 15°N) associated with their seasonal migration. This largely explains the seasonality and regionality of precipitation responses to canonical El Niño and El Niño Modoki. IOD reduces precipitation in southwestern Indonesia in the dry season, associated with anomalous moisture flux divergence. The seasonality of precipitation response to IOD is likely to be controlled by the seasonality of local sea surface temperature anomalies in the eastern pole of the IOD.

1. Introduction

Indonesia consists of more than 16 000 islands between the Pacific and Indian Oceans and between the Asian and Australian continents, and the main islands are mostly mountainous (Fig. 1). The seasonal evolution of the Indonesian climate is strongly influenced by the Asian–Australian monsoon systems (Qian et al. 2002; Hung et al. 2004) and is characterized by a wet season from November to April and a dry season from July to September (Fig. 2a). Climate variations, especially precipitation anomalies, can cause severe socioeconomic

problems; crop failure occurs frequently during dry events (Amien et al. 1999; Naylor et al. 2001; D'Arrigo and Wilson 2008) as well as forest and peat fires (Siebert et al. 2001; Page et al. 2002; Waple and Lawrimore 2003; Pan et al. 2018), whereas heavier than normal precipitation can cause floods (Whetton and Rutherford 1994; Lawrimore et al. 2001; D'Arrigo et al. 2008). For example, extreme drought and the prolonged dry season in 2015 caused severe forest fires in western Indonesia, which contributed to large amounts of carbon emissions and forest losses (Huijnen et al. 2016; Noojipady et al. 2017; Pan et al. 2018). Therefore, better understanding of precipitation variability on a regional scale over the Indonesian region is important.

Indonesian precipitation variability is influenced by climate variability in the Pacific and Indian Oceans. Climate phenomena influencing Indonesian precipitation include El Niño–Southern Oscillation (ENSO),

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FIG. 1. Topography (m) of Indonesia in the study area.

El Niño Modoki (Ashok et al. 2007), and the Indian Ocean dipole (IOD) (Saji et al. 1999). Previous studies have provided overviews of how these climate modes influence Indonesian precipitation. Canonical El Niño tends to reduce Indonesian precipitation between the boreal summer and winter (from the dry season to the wet season) and can cause a longer-than-normal dry season (Philander 1983a; Ropelewski and Halpert 1987; Philander 1990; Gutman et al. 2000; Hendon 2003). Ashok et al. (2007) found that El Niño Modoki has a similar impact in the dry season. A positive IOD, accompanied by negative sea surface temperature (SST) anomalies in the eastern tropical Indian Ocean, also decreases precipitation over Indonesia (Saji and Yamagata 2003; Ashok et al. 2004; Saji et al. 2006; Hamada et al. 2012; Nur'utami and Hidayat 2016; Lestari et al. 2018). These studies used the precipitation datasets of the Global Precipitation Climatology Project (Adler et al. 2003) or Climate Prediction Center Merged Analysis of Precipitation (Xie and Arkin 1997) on a $2.5^\circ \times 2.5^\circ$ grid, which are too coarse to investigate the regional-scale precipitation in Indonesia.

The relationship between regional Indonesian precipitation and climate modes has been recently investigated. As-syakur et al. (2014) analyzed the correlations between the precipitation over Indonesia and the El Niño index or Indian Ocean dipole mode index (IODMI) using a high-resolution ($0.25^\circ \times 0.25^\circ$) satellite-derived precipitation dataset. They found that the effects of climate modes are not spatially stationary but exhibit seasonal migration. However, the analysis period of their study was relatively short (13 years, from 1998 to 2010), and hence it is unclear whether the regional patterns are robust over a longer period. Using high-resolution ($0.5^\circ \times 0.5^\circ$) precipitation data from the University of East Anglia Climatic Research Unit (UEA-CRU) (Harris et al. 2014), Yanto et al. (2016) investigated the seasonally averaged precipitation variability in wet (November–April) and dry (May–October) seasons over Indonesia, and analyzed their

FIG. 2. (a) Monthly climatology (mm day^{-1}) of spatially averaged terrestrial precipitation over the area shown in Fig. 1. Seasonal climatology (mm day^{-1}) of precipitation in the (b) dry (July–September) and (c) wet (November–April) seasons for the period 1971–2000. Red and blue arrows indicate the dry and wet seasons, respectively.

relationships with ENSO and Pacific decadal oscillation (Mantua et al. 1997), but they did not examine the seasonal evolution of the effects of climate modes. Furthermore, these high-resolution studies did not investigate the effects of El Niño Modoki [and also IOD for Yanto et al. (2016)], which are expected to be important in Indonesian precipitation variability (Ashok et al. 2007).

The purpose of this study is twofold. First, we clarify the seasonal development of regional precipitation responses over the Indonesian region to the climate modes in the Indo-Pacific Oceans, namely, ENSO, El Niño Modoki, and IOD, including the seasonal evolution of their influence. To this end, we analyze a recent,

high-resolution ($0.5^\circ \times 0.5^\circ$) terrestrial precipitation dataset, the Asian Precipitation–Highly Resolved Observational Data Integration Toward Evaluation (APHRODITE) (Yatagai et al. 2012), which covers 48 years, from 1960 to 2007. Second, we examine how the regional precipitation responses to climate modes are related to moisture flux divergence by analyzing a reanalysis dataset. In particular, we focus on how variations in Indonesian precipitation are related to convergence zones, such as the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) in the western Pacific Ocean (Vincent 1994) and the oceanic tropical convergence zone (OTCZ) over the equatorial Indian Ocean (Saji et al. 1999).

These convergence zones vary with respect to the variability of the Indo–Pacific climate modes. Canonical El Niño induces the eastward (northeastward) shifts of the ITCZ (SPCZ) in the equatorial Pacific Ocean, leading to divergences in the warm pool regions (Vincent 1994; Matthews and Kiladis 1999; Folland et al. 2002; Matthews 2012). During El Niño Modoki, the convergence zone migrations are similar to those during canonical El Niño (Weng et al. 2007, 2009). Freitas et al. (2017) showed northward extreme shifts of the OTCZ over the southern Maritime Continent during IOD events. However, the relationship between the variability of convergence zones and regional-scale precipitation anomalies over Indonesia has not been examined. Furthermore, because transitions between dry and rainy seasons are closely related to the seasonal migration of convergence zones, it is important to understand how the seasonal migration modulates interannual variability of convergence zones and their influences on regional-scale precipitation variability.

The rest of this paper is organized as follows. Section 2 presents the data and methods. The basic seasonal features of Indonesian precipitation are summarized in section 3, and the overall contributions of the climate modes to Indonesian precipitation are examined in section 4. In section 5 the regional Indonesian precipitation responses to the climate modes are documented, including the role of moisture flux divergence. The summary and discussion are presented in section 6.

2. Data and methods

We used monthly APHRODITE data (Yatagai et al. 2012) from January 1960 to December 2007 with a horizontal resolution of $0.5^\circ \times 0.5^\circ$ spanning from 93° to 143°E and from 11°S to 7°N (Fig. 1), which is narrower than the original dataset covering the Asian region. APHRODITE is a project that produces gridded precipitation dataset on a high-resolution grid

based on rain gauge data over land (Yatagai et al. 2009, 2012). APHRODITE used the following data: Global Telecommunication System (GTS)-based data (global summary of the day) from the World Meteorological Organization; data precompiled by different groups or organizations; and raw observational data collected by the APHRODITE project. These incorporated data are 2.3–4.5 times greater than the number of GTS-only data and make the largest number of records in Indonesia, especially over southern regions (Yatagai et al. 2012), compared to other datasets with the same resolution, namely the UEA-CRU, University of Delaware, and Global Precipitation Climatology Centre (Schneider et al. 2008). APHRODITE uses careful gridding interpolation method by taking into account the mountains, ridges, and slopes (Schaake 2004), which should help to represent precipitation over the mountainous Indonesian area appropriately (Fig. 1). All data were also subjected to thorough quality control procedures manually and automatically, which at least may avoid the abnormality of the data as found in the GPCC product where in September 2004 Indonesian precipitation reaches $\sim 10,000 \text{ mm month}^{-1}$ (Hamada et al. 2011; Yatagai et al. 2012). Recent studies have demonstrated the usefulness of APHRODITE products to improve seasonal forecasts of Asian monsoon precipitation (Yatagai et al. 2014), to validate high-resolution climate model simulations (Yatagai et al. 2005), and to characterize regional features of extreme precipitation in Southeast Asia (Villafuerte and Matsumoto 2015).

To understand the role of large-scale atmospheric circulation in precipitation variability over Indonesia, we also use the Japanese 55-Year Reanalysis (JRA-55) dataset (Kobayashi et al. 2015; Harada et al. 2016) with a $1.25^\circ \times 1.25^\circ$ longitude and latitude grid for the same period as the APHRODITE data. By using the JRA-55 data, we estimate the vertically integrated moisture flux convergence between 1000 and 500 hPa based on monthly horizontal wind speed and specific humidity data, using the following equation:

$$-\nabla \cdot \mathbf{Q} = \frac{1}{g} \int_{p_1}^{p_0} \left(\frac{\partial uq}{\partial x} + \frac{\partial vq}{\partial y} \right) dp, \quad (1)$$

where $\mathbf{Q}$ represents the vertically integrated moisture flux, $-\nabla \cdot \mathbf{Q}$ is its convergence, x and y are the zonal meridional coordinates, u and v are the x and y components of the horizontal wind, respectively, q is the specific humidity, p is the pressure, g is the gravitational acceleration, and the interval of vertical integration is between p_0 (1000 hPa) and p_1 (500 hPa). To examine the robustness of the analyses of moisture flux convergence, we also

examined the NCEP–NCAR reanalysis dataset (Kalnay et al. 1996). The results of NCEP–NCAR reanalysis essentially confirm those of JRA-55.

To understand the relations between Indonesian precipitation anomalies and climate modes, we use three SST-based climate indices: the Niño-3 index, El Niño Modoki index (EMI), and IODMI. These indices are calculated using the monthly, $1^\circ \times 1^\circ$ grid SST dataset of the Hadley Centre Sea Ice and Sea Surface Temperature version 1.1 (HadISST1.1) data (Rayner et al. 2003). The Niño-3 index is the area-averaged SST anomaly (SSTA) over the region of $150^\circ\text{--}90^\circ\text{W}$, $5^\circ\text{S--}5^\circ\text{N}$. The EMI (Ashok et al. 2007) is defined as $[\text{SSTA}]_{\text{CP}} - 0.5 \times [\text{SSTA}]_{\text{EP}} - 0.5 \times [\text{SSTA}]_{\text{WP}}$, where the square brackets represent the area-averaged SSTA over the central Pacific (CP; $165^\circ\text{E--}140^\circ\text{W}$, $10^\circ\text{S--}10^\circ\text{N}$), eastern Pacific (EP; $110^\circ\text{--}70^\circ\text{W}$, $15^\circ\text{S--}5^\circ\text{N}$), and western Pacific (WP; $125^\circ\text{--}145^\circ\text{E}$, $10^\circ\text{S--}20^\circ\text{N}$). The IODMI (Saji et al. 1999) is the SSTA difference between the western ($50^\circ\text{--}70^\circ\text{E}$, $10^\circ\text{S--}10^\circ\text{N}$) and southeastern ($90^\circ\text{--}110^\circ\text{E}$, $10^\circ\text{S--}0^\circ$) Indian Ocean.

The relations between the climate modes and Indonesian precipitation variability are investigated using standard correlation (or Pearson correlation) analysis and partial correlation analysis of the annually sampled 3-month average data between the precipitation and the respective climate indices for each calendar month. For simplicity, the 3-month average is denoted as the value of the center month; for example, December–February (DJF) is denoted as January, unless otherwise stated. Because climate indices are not independent, the partial correlation analysis is used to access the independent contributions of climate indices to precipitation variability. A partial correlation technique has been used to study the impacts of El Niño and IOD (Ashok and Saji 2007; Cai et al. 2009; As-syakur et al. 2014) and El Niño Modoki (Ashok et al. 2007). It is noteworthy that to judge whether standard or partial correlation is more appropriate, a priori knowledge is required. For example, if the influences of climate indices *A* and *B* on variable *C* are analyzed, and if there is a priori knowledge that climate index *A* drives index *B* and not vice versa, then it is appropriate to use standard correlations for index *A* with variable *C* and partial correlations for index *B*. However, such a priori knowledge is not generally available, and the partial correlation gives a conservative measure as a correlation that holds even if the other climate indices drive the climate index in question. Please note that, in this paper, anomalies of all variables are defined as the deviations from the mean seasonal climatology (from January 1971 to December 2000), and the linear trends of anomalies are removed.

3. Basic features of Indonesian precipitation

Before examining the relationship between Indonesian precipitation and climate indices, we briefly describe the basic features of Indonesian precipitation, including the seasonal march, which is strongly controlled by the Asian–Australian monsoon (Haylock and McBride 2001; Aldrian and Susanto 2003). Figure 2a shows that area-averaged climatological terrestrial precipitation reaches its minimum in August and maximum in December. The narrow trough and wide peak mean the short dry season (July–September) and long wet season (November–April) accompanied by the rapid dry-to-wet transition in October and slow wet-to-dry transition from May to June. The spatial map of climatological mean precipitation in the dry season and wet season (Figs. 2b,c) indicates that the difference between high and low precipitation is large not only between the two seasons, but also among different regions. In the dry season, precipitation is especially low in southern Indonesia (Java and Nusa Tenggara) and relatively low in central to eastern Indonesia (Sulawesi and Maluku). In contrast, in the wet season, precipitation is high over Java and central Borneo. These regional differences in the seasonal marches are important in understanding the effects of precipitation anomalies; anomalously low (high) precipitation in the regions of climatologically low (high) precipitation can cause severe problems in the dry (wet) season.

4. Overall influence of climate modes

To measure the contribution of the climate modes to Indonesian precipitation variability, we calculate the explained variance ratios of Indonesian precipitation by the SST-based climate indices (Fig. 3). The explained variance ratio is defined as the variance of the estimated component based on a linear regression divided by the total variance. The explained variances of all climate modes are generally large between the dry season and early wet season (July–November), and reach their respective peaks in September. If 10% of explained variance is used as a threshold of substantial contribution, canonical ENSO has the largest number of months of substantial contributions from July to January, that is, from the dry season through the first half of the wet season. In most of these months, the canonical ENSO makes the largest contribution to precipitation variability compared with other modes. The IOD contribution is higher than 10% from July to November, and slightly exceeds that of canonical ENSO in September and October. The contribution of El Niño Modoki exceeds 10% from August to November and is smaller

FIG. 3. Explained variance ratio of Indonesian precipitation by SST-based climate indices with the 3-month average as a function of calendar month. Red and blue arrows indicate the dry and wet seasons, respectively. The x axis indicates the center month of the 3-month average.

than the canonical ENSO and IOD contributions in those months.

A caveat of the explained variances is that the climate modes are not independent. Thus, a certain portion of the explained variance of one climate mode may not reflect direct causality, and the variance can contain contributions from other modes. To measure the magnitude of these mode interactions, we examine correlation coefficients among the climate indices (Fig. 4). Relatively strong correlation (>0.5) occurs between canonical El Niño and IOD from September to November consistent with Ashok et al. (2003a), overlapping the period when the explained variances of these modes are generally large. The square of the correlation gives a measure of the mode interaction for variances. For example, in September, when the explained variances of all climate modes are the highest, the correlation between canonical El Niño and IOD is 0.55, which means that 30% of variance of canonical El Niño or IOD can be contributed by the other climate mode. Because it is not possible to distinguish which climate mode forces which, we examine both standard correlation and partial correlation for relations between precipitation and climate modes in the next section.

5. Role of the climate modes with regard to precipitation

a. Canonical El Niño

Figure 5 shows the seasonal evolution of correlations between precipitation and Niño-3 in each calendar

FIG. 4. Correlation coefficients among SST-based climate indices with the 3-month average as a function of calendar month. The values outside the solid lines are statistically significant at the 95% confidence level. Red and blue arrows indicate the dry and wet seasons, respectively. The x axis indicates the center month of the 3-month average.

month. Negative correlations cover a wide area over central to eastern Indonesia from July to November, namely, from the dry season to the early wet season, corresponding to the top five months of explained variances of Niño-3 (Fig. 3). Monthly evolution indicates that canonical El Niño first affects southern Borneo, Sulawesi, Maluku, and western Papua, and then its influence expands southward to Java and Nusa Tenggara. Lower precipitation in the dry season means that canonical El Niño can cause droughts in central to eastern Indonesia. Subsequently, the negative correlations occur in a more limited area over northern Indonesia in the middle and late wet season. In these months, the negative correlations occur mainly over northern Borneo, northern Sulawesi, and northern Maluku. The distinct difference in correlation patterns between dry and middle-late wet seasons suggests that precipitation responses to canonical El Niño over Indonesia are caused by at least two mechanisms.

The different patterns of precipitation response to canonical El Niño in different seasons found by correlation analysis (Fig. 5) are generally confirmed by the partial correlations between precipitation and Niño-3 after removing the contributions of El Niño Modoki and IOD (Fig. 6). The magnitudes of partial correlations are generally smaller than standard correlations, but still strong partial correlations are found in central-eastern Indonesia in the dry season and in northern Indonesia in the wet season. This means that the contrast between two seasons is not due to the mode interaction, but

FIG. 5. Spatial distribution of correlation coefficients of seasonal development of precipitation with normalized Niño-3. Correlations are calculated for 3-month averaged data, and the center month is written in each panel. Only correlations that are significant at the 95% confidence level are shown by the color shading. Red and blue frames indicate the dry and wet seasons, respectively.

FIG. 6. As in Fig. 5, but for partial correlation coefficients. The rectangular areas in September and March denote the regions for which the area-averaged precipitation is shown in Fig. 7.

occurs intrinsically as the precipitation response to the canonical El Niño.

The influence of El Niño and La Niña events on precipitation in Indonesia is examined by comparing

the time series of the Niño-3 index and area-averaged precipitation anomalies. The time series are chosen for central to eastern Indonesia between August and October from the dry season (Fig. 7a) and northern

Normalized time series

FIG. 7. Time series of normalized Niño-3 and normalized and sign-reversed precipitation averaged over the area in Fig. 6, namely, (a) the rectangular areas in eastern Indonesia (118° – 135° E, 7° S– 4° N) between August and October and (b) northern Indonesia (111° – 130° E, 0° – 7° N) between February and April. The center month of the 3-month average is shown in the panel title for a consistency with other figures. The sign of precipitation is reversed for an easier comparison with Niño-3.

Indonesia between February and April from the wet season (Fig. 7b). In central to eastern Indonesia, the two time series are generally consistent throughout the analysis period, but in northern Indonesia there is a strong relationship apparent only after the 1980s, including a large precipitation reduction of more than two standard deviations for the 1982/83 and 1997/98 El Niños, known as extreme El Niños (Philander 1983b; McPhaden 1999). This change in relationship after 1980 may be associated with the 1970s climatic regime shift (Minobe 1997; Mantua et al. 1997). To examine if such a change of relationship occurs in other data than APHORODITE, we analyze station data, combining

daily station data obtained from the Indonesian Meteorological, Climatological, and Geophysical Agency and monthly station data of Global Historical Climatology Network version 2. We need to combine the two datasets to obtain continuous monthly time series for the present analysis period (i.e., 1960–2007). There are three stations in northern Indonesia that have available data for the whole analysis period. They are Polonia in northern Sumatra, Tarakan in northern Borneo, and Manado in northern Sulawesi. Correlation coefficients between station precipitation and Niño-3 in March after (before) the 1980s are 0.57 (0.32), 0.64 (0.01), and 0.79 (0.38) in Polonia, Tarakan, and Manado, respectively. Therefore, the weak and strong correlations roughly before and after the 1970s regime shift, respectively, are confirmed by the station data analysis.

To understand how the seasonal development of canonical El Niño influences is related to large-scale atmospheric fields, we conduct a partial correlation analysis between the convergence of the vertically integrated horizontal moisture flux and Niño-3 (Fig. 8). In both the dry and wet seasons, shown for September and March, respectively, the precipitation partial correlations in Fig. 6 are closely associated with moisture flux convergence partial correlations. The regions of precipitation partial correlations, central to eastern Indonesia in the dry season (July–September) and northern Indonesia in the wet season (November–April), are covered by the area of negative partial correlations of moisture flux convergence, corresponding to divergent anomalies. This means that the canonical El Niño reduces Indonesian precipitation on regional scales through larger-scale moisture divergence.

The negative partial correlations of moisture convergence in Fig. 8 generally occur around the climatological zero contours in both seasons, but their relations to ITCZ and SPCZ, which are somewhat merged over Indonesia, are different between the two seasons. In the dry season, negative partial correlations occur around the southern edge of the SPCZ, whereas they occur around the northern edge of the ITCZ in the wet season. This means that SPCZ (ITCZ) contracts northward (southward) in its southern (northern) flank in the dry (wet) season. Since the SPCZ and ITCZ are somewhat merged over Indonesia, zero contours occur only along the southern edge of the SPCZ and the northern edge of the ITCZ. Consequently, the rain reductions influenced by canonical El Niño over Indonesia are explained by the two different areas of divergent moisture flux anomalies; one occurs in central to eastern Indonesia in the dry season, and the other occurs in the Philippine

Partial correlation between Niño3 & moisture flux convergence

FIG. 8. Spatial distribution of partial correlation coefficients between the vertically integrated moisture flux convergence and Niño-3 (shading) and climatology of the vertically integrated moisture flux convergence (contours; $10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$) in (a) September and (b) March. Correlations and climatologies are calculated for 3-month averaged data, and the center month is shown in the panel title for consistency with other figures. Only correlations that are significant at the 95% confidence level are shown by the color shading. The solid (dashed) contours shown are 0.2, 0.4, 0.6, 0.8, and 1 (-0.2 , -0.4 , -0.6 , -0.8 , and -1), and the thick contour is the zero contour.

Sea and covers northern Indonesia in the wet season, associated with the northward contraction of the southern flank of the SPCZ and the southward contraction of the northern flank of the ITCZ, respectively. Next, we examine how the seasonality of the anomalous moisture flux divergence is related to the seasonal migration of convergence zones.

Figure 9 shows the seasonal evolution of the partial correlations between Niño-3 and moisture flux convergence zonally averaged between 110° and 150°E along with the climatologies of the convergence. The negative partial correlations corresponding to anomalous divergence occur between the equator and 10°S in the dry season and between the equator and 15°N in the wet season, consistent with Fig. 8. This feature can be explained if two conditions constrain the anomalous divergence in response to canonical El Niño.

FIG. 9. Time-latitude sections (110° – 150°E) of partial correlation coefficients between the vertically integrated moisture flux convergence (MF-conv) and Niño-3 (shading) and climatological MF-conv (contours; $10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$) for 3-month averaged data. Only correlations that are significant at the 95% confidence level are shown by the color shading. The solid (dashed) contours shown are 0.2, 0.4, 0.6, 0.8, and 1 (-0.2 , -0.4 , -0.6 , -0.8 , and -1), and the thick contour is the zero contour. Red and blue arrows indicate the periods of the dry and wet seasons, respectively. The x axis indicates the center month of the 3-month average.

The anomalous moisture flux divergence occurs if the following two conditions are satisfied: 1) around the southern edges of the SPCZ or the northern edges of the ITCZ and 2) only in the latitudinal range between 10°S and 15°N . These conditions roughly constrain when and where the anomalous divergences occur, because they are satisfied only when the southern boundary of SPCZ comes within 10°S – 0° or the northern boundary of ITCZ comes within 15°N – 0° . The former occurs in the dry season in the Southern Hemisphere with moisture divergence anomalies occurring between 12°S and 3°N , whereas the latter occurs in the wet season in the Northern Hemisphere with moisture divergences occurring between 2° and 15°N (Fig. 9). Although these two conditions are observed features, we do not know what their underlying mechanisms are. Nevertheless, the interpretation combined with the spatial distribution of the moisture flux convergence anomalies shown in Fig. 8 can explain why precipitation reduction occurs due to canonical El Niño in central to eastern Indonesia in the dry season and in northern Indonesia in the wet season, consistent with the precipitation anomalies shown in Fig. 5.

b. El Niño Modoki

In this subsection, we examine how El Niño Modoki influences precipitation in Indonesia. Figure 10 shows correlation coefficients between the EMI and precipitation.

FIG. 10. Spatial distribution of correlation coefficients of the seasonal development of the precipitation with normalized EMI. Correlations are calculated for 3-month averaged data, and the center month is written in each panel. Only correlations that are significant at the 95% confidence level are shown by the color shading. Red and blue frames indicate the dry and wet seasons, respectively.

The correlations are negative in the dry season (July–September) and dry-to-wet transition (October) in central to eastern Indonesia and in the northern region in the middle of the wet season (January–March). In the wet season, however, a more salient feature is the positive correlations in western Indonesia, especially in Sumatra. The negative correlations for El Niño Modoki generally overlap with the negative correlation for canonical El Niño, whereas the positive correlations occur only for El Niño Modoki.

The partial correlations between the precipitation and EMI confirm that the relations found in correlations are contributed by El Niño Modoki (Fig. 11). In the dry season and dry-to-wet transition negative partial correlations occur in central to eastern Indonesia. Although in this region, partial correlations for canonical El Niño are also significant, as shown in section 5a, there are subtle but interesting differences between El Niño Modoki and canonical El Niño. In the late dry season (September), El Niño Modoki has significant partial correlations in southern Indonesia (Nusa Tenggara) but canonical El Niño does not. In the dry-to-wet transition (October), El Niño Modoki has a stronger influence in central to eastern Indonesia than canonical El Niño. In the wet season, the positive partial correlations in western and central Indonesia, which are not seen for canonical El Niño, are consistent with those in standard correlations (Figs. 10 and 11). The negative correlations of precipitation over Indonesia for El Niño Modoki were also reported by Ashok et al. (2007) using a coarse-resolution ($2.5^\circ \times 2.5^\circ$) dataset, but our high-resolution ($0.5^\circ \times 0.5^\circ$) analysis reveals the influence of El Niño Modoki in greater detail, including positive partial correlations in western and central Indonesia. The positive correlation in the wet season means that El Niño Modoki can bring floods in western Indonesia, contrary to the general expectation that El Niños cause droughts in the Maritime Continent, including Indonesia.

To know better the relation between precipitation and El Niño Modoki for the increase in precipitation due to El Niño Modoki in western and central Indonesia, we plot time series of area-averaged precipitation anomalies and EMI in the wet season (Fig. 12). Close covariability is apparent between central Sumatra precipitation and the EMI in November (Fig. 12a), and between central Sumatra and southern Borneo precipitation and the EMI in March (Fig. 12b). Interestingly, the time scales for El Niño Modoki and corresponding precipitation are longer than those for canonical El Niño (Fig. 7), consistent with the fact that El Niño Modoki exhibits large decadal variability (Ashok et al. 2007; Weng et al. 2007).

Partial correlation analysis of moisture flux convergence with EMI shows two different areas of anomalous divergences in different seasons (Fig. 13), corresponding to the anomalous Indonesian precipitation during El Niño Modoki. The negative partial correlation of moisture flux convergence occurs in the dry season in central to eastern Indonesia. This negative partial correlation with El Niño Modoki is located slightly south of those with Niño-3 (Figs. 8a and 13a), which may explain the aforementioned stronger influence of El Niño Modoki on precipitation in southern Indonesia (Nusa Tenggara) compared with canonical El Niño (Figs. 6 and 11). Another negative partial correlation also occurs in the wet season (Fig. 13b) in the Philippine Sea, corresponding to a brief precipitation reduction in northern Indonesia (Figs. 10 and 11). For the positive precipitation correlations with El Niño Modoki in western Indonesia, no corresponding significant correlations are found in the moisture flux convergence. Consequently, the precipitation decrease due to El Niño Modoki in central to eastern Indonesia in the dry season and northern Indonesia in the wet season can be explained by the anomalous moisture flux convergence, whereas the precipitation increase in the western region is not explained.

The zonally averaged partial correlation between EMI and moisture flux convergence along with the climatologies of the convergence (Fig. 14) indicates that the seasonality of the El Niño Modoki influence is related to the seasonal migration of convergence zones. Similar to the case of the canonical El Niño (Fig. 9), anomalous moisture flux divergence occurs when the edges of the convergence zones (zero climatology contours) are located near the equator between 10°S and 15°N (Fig. 14). However, there is an interesting difference: moisture flux divergence anomalies related to El Niño Modoki are more intense on the area of climatological divergence (Figs. 13 and 14) than those related to canonical El Niño (Figs. 8 and 9). Furthermore, in the dry-to-wet transition, anomalous divergences with El Niño Modoki are stronger than those with canonical El Niño (Figs. 9 and 14). This is consistent with the difference of precipitation responses; precipitation responses for El Niño Modoki compared with those for canonical El Niño in the dry (wet) season occur in more southern (northern) areas in central to eastern (northern) Indonesia (Figs. 6 and 11) and precipitation is more strongly reduced for El Niño Modoki than for canonical El Niño in the dry-to-wet transition.

c. IOD

Figure 15 shows that negative precipitation correlations with the IODMI occur over a wide area of

FIG. 11. As in Fig. 10, but for partial correlation coefficients. The rectangular areas in November and March denote the regions for which the area-averaged precipitation is shown in Fig. 12.

Indonesia from the dry season to the early wet season (July–November). In July, significant correlations cover the western–central parts, and then they increase their magnitudes until September with eastward expansion,

followed by weakening in October and November. The pattern substantially overlaps with that of the correlations with Niño-3 (Fig. 5), and the strong correlation between Niño-3 and the IODMI shown in Fig. 4 suggests

Normalized time series

— Area-averaged precipitation
— EMI

FIG. 12. Time series of normalized EMI and normalized precipitation averaged over the area in Fig. 11, namely, (a) the rectangular areas in western Indonesia (97° – 105° E, 6° S– 2° N) between October and December and (b) central to western Indonesia (97° – 118° E, 6° S– 2° N) between February and April. The center month of the 3-month average is shown in the panel title for consistency with other figures.

that substantial parts of the correlations shown in Fig. 15 can come from the interaction between the impacts.

Partial correlations between the precipitation and IODMI (Fig. 16) are strong in southwestern Indonesia, especially in southern Sumatra and Java in the dry season (July–September) and dry-to-wet transition (October) and in central Indonesia (i.e., southern Borneo and Sulawesi), with weaker magnitudes. The highest absolute correlation reaches 0.7, much higher than that reported by As-syakur et al. (2014), which was lower than 0.4 (Fig. 3 in their paper). In these regions and seasons, partial correlations of IOD are much stronger than those of canonical El Niño or El Niño Modoki (Figs. 6 and 11), thereby indicating that

Partial correlation between EMI & moisture flux convergence

the IOD is a dominant driver. This is consistent with the correlation analysis by Saji et al. (1999) and the partial correlation analysis by Ashok et al. (2007) (Fig. 9d in their paper). Our analysis using higher-resolution data than those used in previous studies not only confirms the robust relation between IOD and Indonesian precipitation in general, but also reveals

FIG. 15. Spatial distribution of correlation coefficients of the seasonal development of the precipitation with normalized IODMI. Correlations are calculated for 3-month averaged data, and the center month is written in each panel. Only correlations that are significant at the 95% confidence level are shown by the color shading. Red and blue frames indicate the dry and wet seasons, respectively.

FIG. 16. As in Fig. 15, but for partial correlation coefficients. The rectangular area in September denotes the region for which the area-averaged precipitation is shown in Fig. 17.

the IOD's influence on Sulawesi, which was not found in earlier studies.

The precipitation time series of the regions influenced by IOD events in southwestern Indonesia negatively

correlates with the IODMI in September (Fig. 17). Although some mode interaction between IOD and canonical El Niño is expected (Fig. 4), these time series for IOD have different features from those for canonical

FIG. 17. Time series of normalized IODMI and normalized and sign-reversed precipitation averaged over the area in Fig. 16, namely, the rectangular area in southwestern Indonesia (100° – 113° E, 10° – 2° S) between August and October. The center month of the 3-month average is shown in the panel title for consistency with other figures.

El Niño. For example, the events of strong precipitation reduction in 1961, 1994, and 2006 are caused by the strong IOD events without canonical El Niños (Yamagata et al. 2004; Meyers et al. 2007; Vinayachandran et al. 2007). Moreover, the precipitation time series are not strongly affected by major El Niño events in 1972, 1982, and 1997, consistent with the weak influence of El Niño in southwestern Indonesia (Figs. 5 and 6).

The partial correlation between moisture flux convergence and the IODMI (Fig. 18) indicates that anomalous moisture flux divergences develop in June in the southeastern Indian Ocean and reach their peak in September, as shown for July and September (see also Fig. 19 for seasonal development). Negative partial correlations occur around the zero contour of the climatological moisture flux convergence, which is the southeastern edge of the OTCZ, and this indicates the northwestward contraction of the eastern OTCZ in the dry season. The spatial–seasonal distribution of anomalous divergences is consistent with the spatial pattern of the precipitation response to the IOD shown in Fig. 16. Therefore, the IOD reduces precipitation over southwestern Indonesia via the northward contraction of the OTCZ's southern boundary in the dry season and dry-to-wet transition.

The development of anomalous moisture flux divergence related to IOD probably has a different cause from those related to canonical El Niño and El Niño Modoki. For the latter climate modes, seasonal migration of the ITCZ and SPCZ plays an important role, as shown in sections 5a and

FIG. 18. As in Fig. 8, but for IODMI in (a) July and (b) September.

5b, but we find no relation between the seasonal OTCZ migration and the seasonal dependence of the anomalous moisture flux divergence in the eastern Indian Ocean. To understand what determines the seasonality of the IOD influences on moisture flux convergence, we analyze the seasonal march of the SST anomalies in the eastern pole of the IOD (Fig. 19). Consistent with the seasonal development of the negative partial correlations between the moisture flux convergence and the IODMI, the strong negative partial correlations ($r < -0.7$) between the SST and IODMI start to develop in June, reach their peak in September, and then decline. This is consistent with the previously reported seasonal march of SST anomalies associated with IOD (Saji et al. 1999; Delman et al. 2018). This seasonality in the IOD's eastern pole is also consistent with the seasonality of the precipitation responses to the IOD (Fig. 16). Therefore, these results strongly suggest that seasonality of the precipitation response to IOD is controlled by the seasonality of the IOD itself.

6. Summary and discussion

We have investigated Indonesian precipitation responses to the three climate modes, namely, the canonical El Niño, El Niño Modoki, and IOD, for their regional and seasonal

FIG. 19. Time–latitude sections (90° – 110° E) of partial correlation between the vertically integrated moisture flux convergence (MFconv) and IODMI (shading) and partial correlation between SST and IODMI (contours) for 3-month averaged data. Only correlations that are significant at the 95% confidence level are shown by the color shading. The solid (dashed) contours shown are 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 (-0.3 , -0.4 , -0.5 , -0.6 , -0.7 , and -0.8). Red and blue arrows indicate the periods of the dry and wet seasons, respectively. The x axis indicates the center month of the 3-month average.

distribution and their relation to large-scale moisture flux convergence by using a high-resolution ($0.5^{\circ} \times 0.5^{\circ}$) terrestrial precipitation dataset APHRODITE (Yatagai et al. 2012) and JRA-55 reanalysis (Kobayashi et al. 2015) from January 1960 to December 2007. Although several studies have investigated precipitation in Indonesia related to climate modes using high-resolution data (see section 1), the present study provides a more comprehensive understanding of seasonally dependent regional-scale responses to climate modes and how regional-scale responses are related to the large-scale variability of the ITCZ and SPCZ.

Canonical El Niño and El Niño Modoki have some similarities. These two climate modes reduce precipitation in central and eastern Indonesia in the dry season (July–September) and dry-to-wet transition (October), and in northern Indonesia in the wet season (November–April) (Figs. 5, 6, 10, and 11). Canonical El Niño has a stronger influence than El Niño Modoki in northern Indonesia in the wet season, but a weaker influence in central and eastern Indonesia in the dry-to-wet transition. The main features of these precipitation reductions can be explained by the large-scale moisture flux divergence. Anomalous moisture flux divergence occurs only when either the northern or southern edges of the merged convergence zone of ITCZ and SPCZ are located near the equator between 10° S and 15° N. This can occur in the

dry or wet seasons when the southern or northern edge reaches this latitudinal range, respectively (Figs. 8, 9, 13, and 14). The anomalous divergences of moisture flux occur around the convergence zone edges for canonical El Niño, inducing convergence zone contractions. The anomalous divergences occur mainly on the area of climatological divergence for El Niño Modoki, namely, higher latitudes than for canonical El Niño. In addition, the dry-to-wet transition divergent anomalies are stronger for El Niño Modoki than for canonical El Niño. These differences in moisture flux divergence between the canonical El Niño and El Niño Modoki explain the differences in precipitation responses between the two modes. It is also found that El Niño Modoki increases precipitation in western Indonesia, contrary to the widely accepted view that El Niños decrease precipitation on the Maritime Continent. This precipitation increase cannot be explained by the moisture flux convergence.

The standard and partial correlation analyses indicate that the IOD strongly influences southwestern Indonesia (southern Sumatra and Java) (Figs. 15 and 16). This large precipitation reduction is closely associated with anomalous divergences of the moisture flux in the equatorial eastern Indian Ocean over the southern flank of OTCZ (Fig. 18), indicating the northward contraction of the OTCZ. The seasonality of the moisture flux divergence associated with the IOD is controlled by the seasonality of the SST anomalies of the IOD's eastern pole (Fig. 19).

The methods used in this study to identify the roles of climate modes in some regions also become a limitation owing to mode interactions, especially that between the IOD and canonical El Niño, which has relatively high correlations (Fig. 4). For example, strong negative correlations are found in southern Borneo both for canonical El Niño and the IOD in the dry season, accompanied by much weaker partial correlations for both modes. In this region and season, therefore, it is not possible to identify which of the two modes plays a dominant role in precipitation responses. Nevertheless, in most regions and seasons the results of the standard and partial correlations essentially the same. Consequently, the present results provide useful information for understanding of regional-scale Indonesian precipitation responses to climate modes in different seasons and how they are related to large-scale atmospheric conditions represented by convergence zones.

Although we have examined simultaneous correlations, lead–lag correlations might provide different patterns associated with development and decay years of canonical El Niño and El Niño Modoki. For instance, the ENSO-related Indian summer monsoon precipitation shows different patterns during the concurrent summer and following summer (Mishra et al.

2012). To examine this possibility, lead–lag partial correlations are calculated with respect to December Niño-3 and December EMI against precipitation with 3-month running average (figure not shown). December is taken as an index because it is usually the peak phase of ENSOs (Xie et al. 2009). The patterns of lead–lag partial correlations are, in general, qualitatively similar to those of simultaneous partial correlations for the same calendar month of precipitation for lags of 3–4 months with smaller correlation values for the former than the latter. An exception is that partial correlations of March–April lagged to December Niño-3 are much weaker than simultaneous partial correlations. Please note that a 3-month period is the minimum lag so that the months in two time series are not overlapped in association with the 3-month running average. For leads or lags of 5 months or larger, lead–lag partial correlations become very small. Consequently, the simultaneous correlation analyses presented in this paper capture the main features of canonical El Niño and El Niño Modoki influences onto Indonesian precipitation.

It is also worth considering the influences of other tropical climate modes, namely, basinwide warming in the tropical Indian Ocean (Klein et al. 1999) and Atlantic Niño in the tropical Atlantic Ocean (Zebiak 1993). Previous studies suggested that the Indian Ocean basinwide (IOBW) mode has significant influences on climate anomalies over the Indo–western Pacific from boreal winter to the following summer (Yang et al. 2007; Xie et al. 2009). Atlantic Niño may affect the tropical Pacific variability (Rodríguez-Fonseca et al. 2009; Ding et al. 2012) and may modulate the regional climate variability such as in India in boreal summer (Kucharski et al. 2007). To investigate the influences of these climate modes, we calculate the partial correlation of Indonesian precipitation with the IOBW index and Atlantic Niño index for each calendar month by removing the influences of the two types of Pacific El Niño. The IOBW index (Atlantic Niño index) is defined as the area-averaged SST anomalies over the region of 40°–100°E, 20°S–20°N (20°W–0°, 3°S–3°N). The partial correlations of precipitation with the two indices show that there are no significant values of correlation coefficients found over the Indonesian region in all seasons (figure not shown). This may indicate that both IOBW and Atlantic Niño have no substantial influences to precipitation over Indonesia.

Further studies are necessary to understand the underlying mechanisms for anomalous moisture flux divergence and regional precipitations. For example, future studies are needed to explain why anomalous moisture flux divergence occurs around the convergence zone edges for canonical El Niño and El Niño

Modoki and why the occurrences are limited between 10° and 15°N. The distance from the equator for this sensitive response is on the order of the equatorial Rossby radius of deformation, and thus we speculate that dynamics, such as equatorial waves, may be important. In particular, Matsuno–Gill dynamics may play some role, as it is known that it is important in atmospheric response for El Niños and IODs (Ashok et al. 2003b; Guan et al. 2003; Lee et al. 2009; Ratnam et al. 2014). Numerical models should be useful for understanding the mechanisms. Probably large-scale convergence zone responses can be studied by global models (e.g., Preethi et al. 2015), but in order to understand the regional precipitation responses over mountainous Indonesian areas higher-resolution models than standard AGCMs are required. Along this direction, recent model intercomparison projects provide important research assets including regional model intercomparison of the Coordinated Regional Climate Downscaling Experiment (Ngo-Duc et al. 2017) and high-resolution global model intercomparison, the HighResMIP (Haarsma et al. 2016; Roberts et al. 2018).

The information obtained in this work may be useful to both the research community and society. Operational predictions using climate modes are conducted by a number of climate research centers over the world (e.g., Doi et al. 2016). Although the numerical model resolutions used for those predictions are not high enough to resolve the regional-scale precipitation variability, the climate mode predictions and the present results can be combined to add values of these predictions. For example, if El Niño Modoki is predicted, central to eastern Indonesia should prepare for droughts, especially in the south, whereas western Indonesia should prepare for floods. Furthermore, the information of the present study can also be useful for determining how the influence of El Niño on Indonesian precipitation will change by future climate change. Previous studies have suggested that the frequency of El Niño Modoki events will increase due to global warming (Ashok et al. 2007; Ashok and Yamagata 2009; Yeh et al. 2009; Lee and McPhaden 2010), which may weaken the overall effects of El Niños on Indonesia because canonical El Niño has a stronger effect than El Niño Modoki. However, the change in type of El Niño may bring worse conditions in some regions, as shown by the different regionality between the canonical El Niño and El Niño Modoki. Hui and Zheng (2018) pointed out that IOD amplitudes in the eastern pole of the IOD will be enhanced in the future, thereby suggesting that the IOD may cause more severe effects on precipitation in southwestern Indonesia. To address the changes in relationships between climate modes and Indonesian precipitation, analyses of climate models, such as those

in the Coupled Model Intercomparison Project, are necessary. For those studies, the present results can be used to know how future climate mode changes are related to Indonesian precipitation on finer scales that are not resolved by those models. Also, the present results can be used to know which climate models are appropriate for such studies, by judging whether the responses of large-scale convergence zones to climate modes are realistic in those models.

Acknowledgments. GA was supported by the Indonesian Endowment Fund for Education (LPDP) in providing a scholarship for the master's program (PRJ-255/LPDP/2016) and by the scholarship for foreign student offered by Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan for the doctoral program. SM was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI (19H05704). APHRODITE data were provided by the Research Institute for Humanity and Nature and the Meteorological Research Institute of Japan Meteorological Agency from their website at <http://www.chikyu.ac.jp/precip/>. JRA-55 data, the reanalysis product of the Japan Meteorological Agency, were downloaded from <http://jra.kishou.go.jp/>. We thank the Hadley Centre, United Kingdom Met Office, for the HadISST data.

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