Interannual Variability of Rainfall over Indonesia: Impacts of ENSO and IOD and Their Predictability

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Abstract. Northwestern Java and Makassar rainfall variations are examined in relation to the tropical air-sea coupled phenomena referred to as the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) using retrospective forecasts known as SINTEX-F. The model predicts the rainfall and its variability realistically in September-November (SON) and in general successfully predicts the interannual variation of northwestern Java rainfall up to 3 months ahead and Makassar rainfall up to 6 months ahead. This indicates potential societal benefits of rainfall predictability in Indonesia. Simple correlation analysis based on observations and model predictions reveals significant influence of IOD and ENSO on the northwestern Java and Makassar. However, the correlation between ENSO and the northwestern Java rainfall becomes insignificant if the IOD influence is excluded. Similarly, the correlation between IOD and Makassar rainfall becomes insignificant if excluding the ENSO influence. These results confirm that a major portion of interannual variation of the northwestern Java (Makassar) rainfall is related to IOD (ENSO) event.

1. Introduction

Regional impacts of El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) on the climate variations in the Indo-Pacific rim countries including Indonesia have attracted much attention in past decades. The climate of Indonesia has been considered to be closely linked to ENSO in the Pacific Ocean. For example, the boreal summer and fall precipitation anomalies in Indonesian region were found to be associated with a drier condition over most part of the country during El Niño or the warm phase of ENSO [1, 2].

After the IOD was identified by Saji et al [3], a number of studies have pointed out the impact of the IOD on anomalies pattern in precipitation over the tropical and mid-latitude regions through its atmospheric teleconnection pattern. A positive IOD event is characterized by cooler-than-normal water in the tropical eastern Indian Ocean and warmer-than-normal water in the tropical western Indian Ocean. This is associated with the condition that the normal convection situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over the east Africa and Srilanka and severe droughts over Indonesia and Australia [4, 5, 6]. In addition, Sahu et al [7] pointed out that the extreme high streamflows of the Citarum River in northwestern Java are related to La Niña and negative phase IOD of the Indian Ocean. Meanwhile, the extreme low streamflows of the river are found to be associated with the positive IOD events. Moreover, recent study of Hamada et al [8] described that the IOD events clearly influence rainfall variation in the dry season in northwestern Java.

As the Java Island has a large population and is an important economic region, rainfall variability has strong influence on economic growth and daily activity of millions of people. Extreme dry events lead to devastating drought with losses in crop production over the region, while persistent heavy rains have led to flooding and landslides. Moreover, this is an Island where much of the nation's rice is grown that vulnerable to climate extremes and water shortages. [9] have pointed out that prediction of the Java rainfall is very important for the regional society in order to mitigate drought and flood disaster and agricultural decision making for planting season. In addition, water-related issues are of critical interest to be considered in sustainability and climate risk management efforts in drought and flood of the regions. Thus further study on predictability of rainfall variation resulted from a coupled model would be important as both a scientific motivation and in terms of disaster mitigation. In light of this, the purpose of this work is to investigate modulation of interannual rainfall variability over Indonesia by ENSO and the IOD during boreal fall season by analyzing retrospective forecast of SINTEX-F coupled model, which simulates ENSO and IOD events realistically [10, 11].

2. Data

Nine-member ensemble mean retrospective forecast of total precipitation and sea surface temperature (SST) during 1983-2009 from the ocean-atmosphere-land coupled general circulation model – the Scale Interaction Experiment-Frontier Research Center for Global Change (SINTEX-F) are used in the present study (see [12] for detailed description). The model shows good skill in predicting the IOD up to 2 seasons ahead and ENSO up to 2 years ahead [12, 13]. Observed rainfall anomalies during 1983 to 2007 are collected from nine stations in northwestern Java and one station in Makassar south Sulawesi (Table 1). Quality control of the observed data has been conducted by Hamada et al [8]. We define an index for northwestern Java rainfall by simply averaging the observed rainfall at nine stations. In order to examine spatial pattern of rainfall anomalies Global Precipitation Climatology Project (GPCP) [14] and the Japanese 25-year Reanalysis (JRA-25) [15] with same period are used.

SST anomalies are computed from Extended Reconstructed Sea Surface Temperature (ERSST) v.3 dataset [16] from 1979 to 2008. The dipole mode index (DMI) is adopted from Saji et al [3] which is derived from SST anomalies by taking difference between averaged regions of the western (50°E– 70°E, 10°S–10°N) and eastern (90°E–110°E, 10°S–Eq) tropical Indian Ocean. Influence of Pacific Ocean is represented by Niño3.4 index which is derived by taking area average of SST anomalies over central/eastern equatorial Pacific (5°S–5°N, 170°W–120°W).

Motivated by previous studies that the relationships between the tropical climate indices of ENSO/IOD and Indonesian rainfall are strongest in boreal fall season when there is the greatest coherency between Indonesian climate and large-scale Indo-Pacific Ocean variability [17], we focused our analysis only on the SON season that includes the end of the dry season and onset of the wet season in Indonesia.

In order to separate the influence of IOD and ENSO on northwestern Java and Makassar rainfall, a partial correlation is employed to show a partial relationship between two variables while excluding influences arising from another independent variable. In this way, the partial correlation between DMI and rainfall anomalies excludes the influence due to the correlation between Niño3.4 and the rainfall anomalies. It is written as:

$$r_{13,2} = \frac{\left(r_{13} - r_{12}.r_{23}\right)}{\sqrt{\left(1 - r_{12}^2\right)}\sqrt{\left(1 - r_{23}^2\right)}} \quad (1)$$

where r_{13} refer to the correlation between DMI and rainfall anomalies, r_{12} denotes the correlation between DMI and Niño3.4 index and r_{23} is the correlation between Niño3.4 and rainfall anomalies. Statistical significance of the correlation coefficients is estimated based on a 2-tailed Student t-test.

3. Annual variations of northwestern Java and southern Sulawesi rainfall

Figure 1a shows annual cycle of the northwestern Java rainfall index which was averaged from nine observation stations. The seasonal variation of rainfall over the region show a distinct annual cycle which the maximum in the months from December to February and the minimum from June to September. The rainfall is at the lowest level in July-August (about 3 mm/day) and peaking up in January - February (about 12 mm/day). A similar annual rainfall pattern is seen over Makassar southern Sulawesi (Figure 1c). In these regions, the peak rainy season corresponds to the northwest monsoon period in boreal winter across the Austral-Indonesian and dry season coincides with the southeast monsoon period in boreal summer. It is noted that the standard deviations of rainfall are relatively high during June to October, revealing most variability is along boreal summer-fall seasons.

Overall features of the observed annual cycle of rainfall (Figures 1a and 1c) are captured by 1-month lead model prediction (Figures 1b and 1d): it shows a wet season that peaks in January and a dry season that peaks in August. This suggests that the pattern of annual variation is predicted well by the SINTEX-F model despite that rainfall amplitude during rainy season (December to April) is weaker in the model.

4. Interannual variations of northwestern Java and southern Sulawesi rainfall

Figures 2a and 2b show interannual variations of the SON model rainfall anomalies of northwestern Java and Makassar superimposed with the associated observed rainfall, DMI and Niño3.4 index, respectively. We find that DMI and Niño3.4 are significantly correlated with temporal rainfall variations for both observed and 9-member ensemble mean prediction at 1-month lead time (predictions initiated from 1 August, 1 September and 1 October for September, October, and November respectively). Years of negative rainfall anomalies are seen to be linked to El Niño and positive IOD years when the eastern pole of IOD is colder than normal. In contrast, years of positive rainfall anomalies are found during La Nina and negative IOD events. Several exceptions are noted for the observed rainfall (Figure 2a) in which positive rainfall anomaly in northwestern Java is seen in 1986 (El Niño year) and negative rainfall anomalies over the two regions in 1989 and 1990 (negative IOD year). Despite some discrepancies in magnitude for certain years, the rainfall variations over northwestern Java and Makassar can be correctly predicted with correlation skill of 0.72 and 0.80, respectively. Besides, the 9-member mean prediction would reduce noise signals and hence better represent the cause-effect relationship between the rainfall and IOD/ENSO forcing.

The significant relationship between ENSO and rainfall variation over Indonesia during SON seasons is consistent with the previous studies based on rain-gauge rainfall data [1]. In El Niño years, the rising branch of the Walker circulation that corresponds to the maximum rainy region shifts toward the east, and the anomalous descending region is located slightly east of Indonesia. Thus, the low-level easterly anomalies over Indonesia reinforce the mean monsoonal winds (i.e. southeasterly) during SON. As a result, this favors to reduce local rainfall. The relation among ENSO and IOD and Indonesian rainfall anomaly is expected since nearly one third of positive IOD events have co-occurred with El Niño events over the past 2-3 decades [18].

In order to investigate the unique relation of rainfall anomalies with IOD from that with ENSO, we employ a partial correlation technique. The strong relationship between IOD/ENSO and Indonesian rainfall anomalies is supported by significant correlation between DMI, Niño3.4 and temporal variation of northwestern Java and Makassar rainfall (Table 2). For comparison, we also examine the correlation for the model predictions in both locations. The model northwestern Java index is negatively correlated with the DMI with a significant correlation of -0.87 (exceeding the 0.01 level of significance), higher than the observed correlation of -0.58. This is not surprising since the model ensemble mean has reduced the noises, which make the correlation coefficients in observed values relatively low. These correlation coefficients remain significant even when ENSO influence is excluded (-0.80 in model and -0.41 in observations). The simultaneous correlation between model northwestern Java rainfall and Niño3.4 is also significant with the value of -0.56, which is slightly higher than -0.47 in the observation. However, the correlation coefficients become insignificant when the IOD influence is excluded, i.e. -0.10 (model) and -0.15 (observed). We also noted that the Niño3.4 index has strong correlation with both model predicted and observed Makassar rainfall anomaly (i.e. -0.76 and -0.74). These correlations remain significant even if we exclude the IOD influence. In contrast, IOD has an insignificant correlation after removing the ENSO influence.

The significant correlation between IOD and rainfall over Indonesia was partly described by Ashok et al 2013 [19]. They pointed out the SST dipole is significantly correlated with the rainfall variability over the eastern and western part of Indian Ocean. As a consequence the East African (Indonesia) region receives above- (below-) normal precipitation during a positive IOD event. In addition, Saji and Yamagata (2003) described that the baroclinic structure of the zonal wind anomaly is suggestive of a zonal overturning cell in the equatorial Indian Ocean. There are two localized anomalous Walker cells: one is over the equatorial Indian Ocean associated with IOD, the other is from 120^0E to the entire equatorial Pacific Ocean in association with ENSO. In association with these anomalous cells, zonal contrast of correlation pattern is reflected in both observation and model prediction (Figure 3).

Figures 3e and 3f show partial correlation between model rainfall anomalies with model DMI and Niño3.4 index, respectively. It is seen that the correlations with IOD in the eastern Indian Ocean are significantly negative, but they become insignificant in the central to eastern part of Indonesian region (Figure 3e). Interestingly, the partial correlation with ENSO does not show a significant dipole correlation pattern in the Indian Ocean. Rather the negative correlation coefficients confined to the central/eastern Indonesia and are accompanied by positive correlation over the tropical Pacific (Figure 3f). These spatial patterns of the correlation coefficient are in general similar to those obtained from GPCP observation and JRA-25 reanalysis data (Figures 3a - 3d), though the negative partial correlations with IOD appear to be confined in eastern Indian Ocean in the GPCP and JRA-25 results (Figures 3a and 3c). The partial correlation with ENSO is centered in central/eastern Indonesia in all the results (Figures 3b, 3d, and 3f). These results suggest that the IOD is dominantly responsible for rainfall variation in eastern Indian Ocean/western Indonesia while most of rainfall variation in central/eastern Indonesia is associated with ENSO events.

5. Rainfall predictability

The interannual variability of rainfall predictions at 1-month lead time for the period 1983-2009 (Figure 2) have shown that the model produces useful skill of rainfall predictions in northwestern Java and Makassar. The predicted rainfall variation over these regions, however, gradually decreases as the lead time increases. Table 3 shows the correlation skill of rainfall predictions gradually decrease to about 0.52 (0.60) at the 3-month (6-month) lead times in northwestern Java (Makassar). The model predictions show significant predictabilities in Makassar region, where the rainfall variation are largely associated with ENSO (Table 3). This is because signals associated with ENSO events are able to be predicted at long lead times [13]. In northwestern Java, on the other hand, where the rainfall variations are mostly affected by IOD, the rainfall predictability is seen to be shorter (i.e. up to 3-month lead time). This might be partly associated with lower predictability of IOD (1-2 seasons ahead) in presence of strong intraseasonal disturbances in the Indian Ocean [12].

6. Concluding remarks

We have documented significant impact of the IOD and ENSO event on Indonesian rainfall variability and their predictability by analyzing retrospective forecast of SINTEX-F coupled model. The model predicts northwestern Java and the Makassar rainfall and its variability realistically with a wet season that peaks in January and a dry season that peaks in August. It is noted that the model predicted rainfall amplitude during December to April is weaker than the observed due partly to model ensemble mean. We have examined relationship among northwestern Java and Makassar rainfalls, IOD and ENSO. Partial correlation coefficients with IOD are found significant in the western Indonesian region including the northwestern Java, while significant partial correlation coefficients with ENSO are found over the central/eastern part of Indonesian region. It is suggested that the interannual rainfall variation over northwestern Java is essentially related to IOD, in consistent with the IOD-induced changes in atmospheric and oceanic conditions [10]. It is encouraging that rainfall variation in northwestern Java and Makassar can be predicted up to about 3 to 6 months ahead, respectively, with significantly correlation skill (Table 3), according to 9-member mean retrospective forecast experiments for the period 1983–2009.

The skilful prediction of model rainfall during boreal fall season would be beneficial for assessing the potential predictability of Indonesian rainy season onset which is occurred around October-November. This has particular implication for rice production areas over the highly populated island of Java and southern Sulawesi. In this context the onset of the rainy season is particularly critical for the agriculture sector in Indonesia.

Acknowledgments

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7. References

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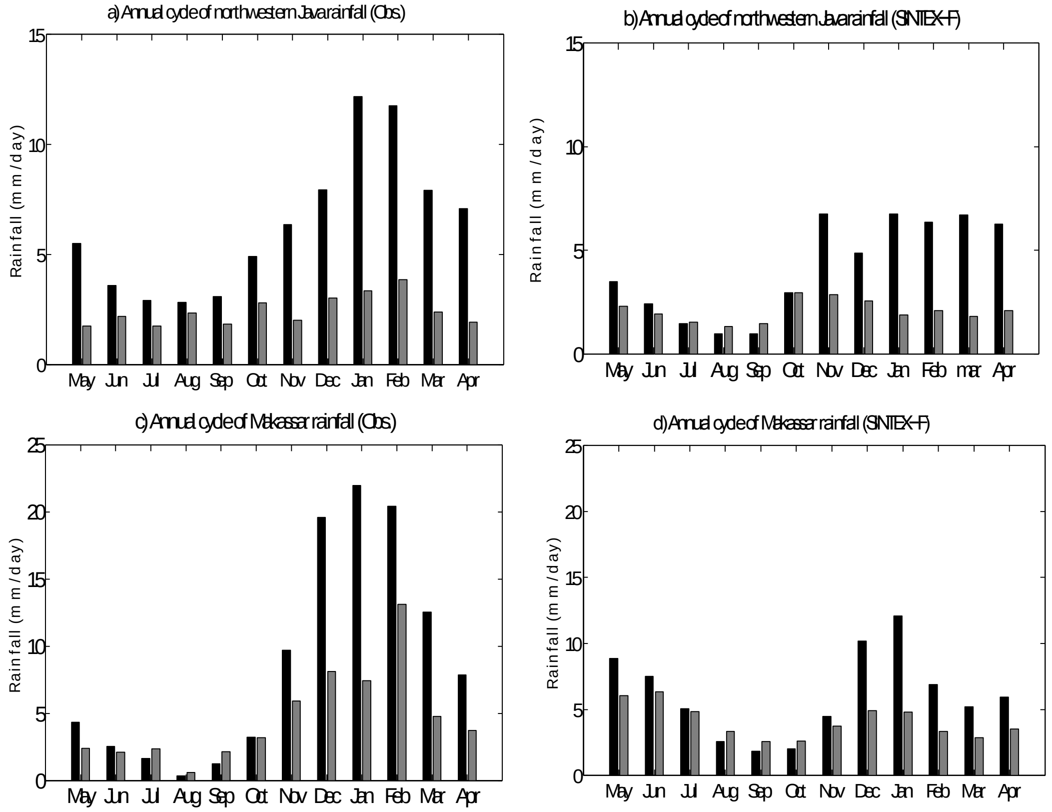

Figure 1. Annual mean (black) and standard deviation (grey) of northwestern Java rainfall derived from (a) observed rain gauges and (b) 1-month lead forecast of SINTEX-F. (c) and (d) As in (a) and (b), but for Makassar/southern Sulawesi. Note that the annual cycle could be weakened in the model due to the 9-member ensemble mean.

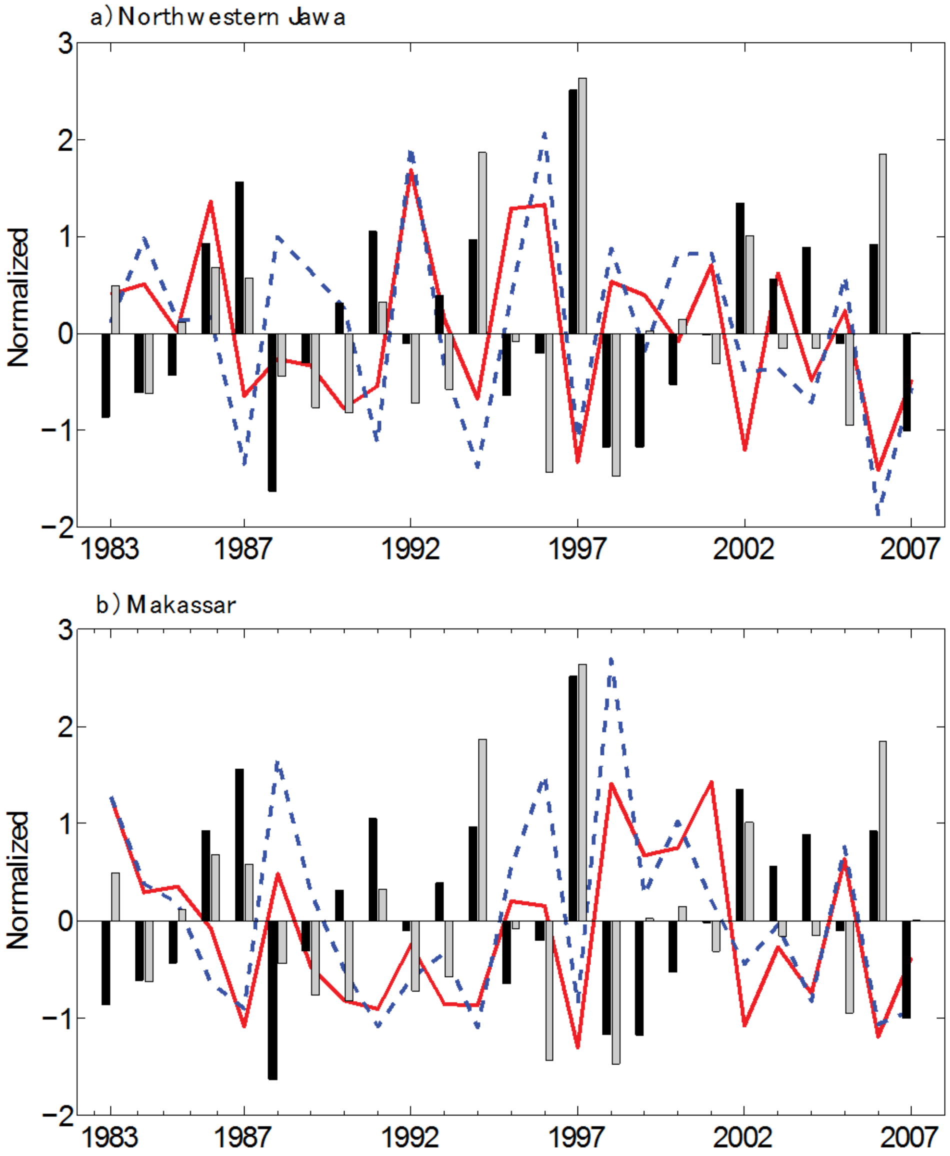

Figure 2. (a) Normalized time series of SON model (observed) northwestern Java rainfall is depicted by dashed blue line (solid red line). Black (grey) bar is observed Niño3.4 (DMI). (b) As in Figure 2a, but for Makassar. The model results are based on 9-member mean prediction at 1-month lead.

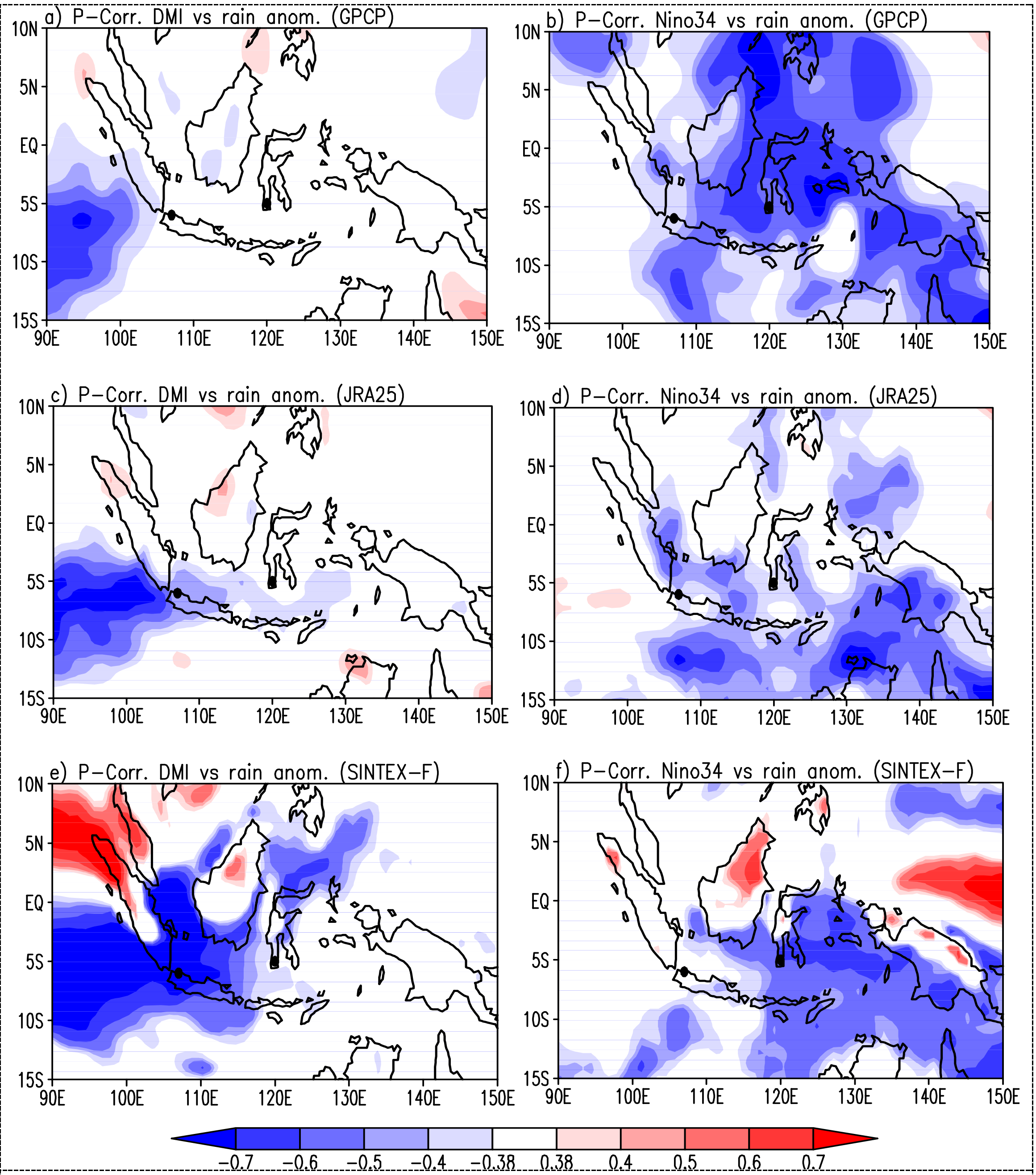

Figure 3. (a) Partial correlation between GPCP rainfall anomalies and observed DMI after removing the effects of ENSO. (b) As in (a), but for the correlation between GPCP rainfall anomalies and Niño3.4 index. (c-f) As in (a-b), but for the results based on JRA25 and 1-month lead prediction of SINTEX-F, respectively. Color shading indicates a significant correlation exceeding 95% confidence level. Black circles indicate northwestern Java and Makassar stations.

Table 1. List of rainfall observation stations observed by Indonesian Agency for Meteorology, Climatology, and Geophysics of Indonesia (BMKG).

WMO No.	Station Name	Lat.	Lon.	Alt.
96733	Pondok Betung	6.25^{0}S	106.61^{0}E	-
96737	Serang	6.21^{0}S	106.10^{0}E	40 m
96739	Curug	6.23^{0}S	106.65^{0}E	46 m
96741	Tanjung Priok	6.10^{0}S	106.87^{0}E	2 m
96745	Jakarta Headquarter	6.17^{0}S	106.82^{0}E	7 m
96747	Halim	6.27^{0}S	106.88^{0}E	26 m
96749	Cengkareng	6.11^{0}S	106.65^{0}E	-
96751	Citeko	6.70^{0}S	106.93^{0}E	-
96753	Bogor	6.50^{0}S	106.75^{0}E	250 m
97180	Makassar	5.04^{0}S	119.33^{0}E	14 m

Table 2. The seasonal correlations between SON rainfall anomalies at northwestern Java and Makassar and the DMI and Niño3.4 index based on observations and SINTEX-F model predictions at 1-month lead. pN (pD) is the partial correlation of rainfall with Niño3.4 (DMI) after removing the effects of DMI (Niño3.4). Value exceeding 95% (99%) confidence level is shown with * (**).

	Northwestern Java				Makassar			
	Niño3.4	DMI	pN	pD	Niño3.4	DMI	pN	pD
Obs.	-0.47*	-0.58**	-0.15	-0.41*	-0.76**	-0.51**	-0.65**	-0.04
Model	-0.56**	-0.87**	-0.10	-0.80**	-0.74**	-0.64**	-0.57**	-0.34

Table 3. The seasonal correlations between SON observed rainfalls and 1-month to 6-month lead of SINTEX-F predictions. Value exceeding 99% confidence level is shown with **.

	Northwestern Java			Makassar/Southern Sulawesi					
	1-mo	2-mo	3-mo	1-mo	2-mo	3-mo	4-mo	5-mo	6-mo
Obs	0.72**	0.58**	0.52**	0.80**	0.77**	0.70**	0.63**	0.60**	0.60**