

Abstract

The possible impact of El Niño–Southern Oscillation (ENSO) events on the main components of CO₂ and H₂O fluxes in a pristine mountainous tropical rainforest growing in Central Sulawesi in Indonesia is described. The fluxes were continuously measured using the eddy covariance method for the period from January 2004 to June 2008. During this period, two episodes of El Niño and one episode of La Niña were observed. All these ENSO episodes had moderate intensity and were of Central Pacific type. The temporal variability analysis of the main meteorological parameters and components of CO₂ and H₂O exchange showed a very high sensitivity of Evapotranspiration (ET) and Gross Primary Production (GPP) of the tropical rain forest to meteorological variations caused by both El Niño and La Niña episodes. Incoming solar radiation is the main governing factor that is responsible for ET and GPP variability. Ecosystem Respiration (RE) dynamics depend mainly on the air temperature changes and are almost insensitive to ENSO. Changes of precipitation due to moderate ENSO events did not cause any notable effect on ET and GPP, mainly because of sufficient soil moisture conditions even in periods of anomalous reduction of precipitation in the region.

1 Introduction

The contribution of tropical rainforests to the global budget of greenhouse gases, their possible impact on the climatic system, and their sensitivity to climatic changes are key topics of numerous theoretical and experimental studies (Clark and Clark, 1994; Grace et al., 1995, 1996; Malhi et al., 1999; Ciais et al., 2009; Lewis et al., 2009; Phillips et al., 2009; Malhi, 2010; Fisher et al., 2013; Moser et al., 2014). The area covered by tropical rainforests was drastically reduced during the last century, mainly due to human activities and presently there are less than 11.0 million km² remaining (Malhi, 2010). While deforestation rates in the tropical forests of Brazil are now declining, countries in South-East Asia, particularly Indonesia, show globally the largest increase in

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forest loss (Hansen et al., 2013), resulting in major changes in carbon and water fluxes between the land surface and the atmosphere. Therefore, during the last decade the tropical forest ecosystems of South-East Asia and especially Indonesia are the focus area of intensive studies of biogeochemical cycle and land surface–atmosphere interactions. On the one hand, it is necessary to know how these tropical forests influence the global and regional climate, and on the other hand, how they respond to changes of regional climatic conditions.

Climate and weather conditions in the equatorial Pacific and South-Eastern part of Asia are mainly influenced by the Intertropical Convergence Zone (ITCZ) which is seasonally positioned north and south of the equator. Another very important factor affecting the climate of South-East Asia is the well-known coupled oceanic and atmospheric phenomenon, El Niño–Southern Oscillation (ENSO). During the warm phase of ENSO, termed “El Niño”, sea surface temperature (SST) in the central and eastern parts of the equatorial Pacific sharply increases, and during a cold phase of the phenomenon, termed “La Niña”, the SST in these areas is lower than usual. Both phenomena, El Niño and La Niña, lead to essential changes of pressure distribution and atmospheric circulation and, as a result, to anomalous changes of precipitation amount, solar radiation, and temperature fields, both in the regions of sea surface temperature anomalies and in a wide range of remote areas through the mechanism of atmospheric bridges (Wang, 2002; Graf and Zanchettin, 2012). Typically, in Indonesia El Niño results in dryer conditions and La Niña results in wetter conditions, potentially impacting the land vegetation (Erasmí et al., 2009). ENSO events are irregular, characterised by different intensity and, are usually observed at intervals of 2–7 years.

To describe the possible effects of ENSO events on CO₂ and H₂O exchange between land surface and the atmosphere, many studies for different Western Pacific regions were carried out during recent decades (Feely et al., 1998; Malhi et al., 1999; Rayner and Law, 1999; Aiba and Kitayama, 2002; Hirano et al., 2007; Erasmí et al., 2008; Gerold and Leemhuis, 2010). They are mainly based on the results of modelling experiments and remote sensing data (Rayner and Law, 1999). Experimental results

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cloudiness and precipitation, being more pronounced as it falls into the dry period of the year.

A relatively poor correlation between ΔT_{MA} patterns and ENSO activity and a insignificant influence of ΔT on ΔGPP and ΔET can be mainly explained by the small annual amplitude of the air temperature in the study area not exceeding 1.0°C , as well as by the low dependence of the air temperature on incoming solar radiation. The mean monthly temperatures ranged in the annual course between 19.5 and 20.5°C . Maximal air temperatures do not exceed 28.5°C , even on sunny days. Such optimal thermal conditions with high precipitation amount provide sufficient soil moistening and relatively comfortable conditions for tree growth during the whole year.

The analysis of absolute and relative changes of GPP and ET during the periods of maximal El Niño and La Niña activity showed that GPP during the El Niño culminations of 2005 and 2007 increased by about $20\text{ gC m}^{-2}\text{ month}^{-1}$ (6–7%). ΔGPP_{MA} was about $9\text{ gC m}^{-2}\text{ month}^{-1}$ (2–3%), ΔET – about 40 mm month^{-1} (30%) and ΔET_{MA} – about 10 mm month^{-1} (6–7%). Thus, the maximal ΔGPP was two times lower than the mean annual amplitude of GPP (Fig. 2). The maximal ΔET was equal to the annual amplitude of ET (Fig. 2). During the La Niña culmination of 2008 the maximal relative changes of GPP were higher than the relative changes observed during El Niño events: ΔGPP was about $-22\text{ gC m}^{-2}\text{ month}^{-1}$ (8%), ΔGPP_{MA} – about $-12\text{ gC m}^{-2}\text{ month}^{-1}$ (4%). The maximal decrease of ΔET in the period was relatively small: ΔET – about -12 mm month^{-1} (10%) and ΔET_{MA} – about -5 mm month^{-1} (4%). ΔET was about 3 times lower than the mean annual amplitude of ET. It can be expected that more intensive ENSO events can result in much larger changes of GPP and ET.

Additionally, we investigated the influence of other climatic anomalies in the region on CO_2 and H_2O fluxes of the tropical rain forest, such as the Madden–Julian oscillation (MJO) and the Indian Ocean Dipole (IOD). The MJO is characterised by an eastward propagation of large regions of enhanced and suppressed deep convection from the Indian ocean toward central Pacific (Zhang, 2005). Each MJO cycle lasts approximately 30–60 days and includes wetter (positive) and drier (negative) phases. As an

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estimation of deep convection intensity in the tropics, the outgoing long-wave radiation (OLR) measured at the top of the atmosphere is commonly used. It was recently shown that 6–12 months prior to the onset of an El Niño episode a drastic intensification of the MJO occurs in the Western Pacific (Zhang and Gottschalck, 2002; Lau, 2005; Hendon et al., 2007; Gushchina and Dewitte, 2011). Furthermore, MJO behaviour varies significantly during the ENSO cycle: it is significantly decreased during the maxima of conventional El Niño episodes, while it is still active during the peak phase of central Pacific events. MJO rarely occurs during La Niña episodes (Gushchina and Dewitte, 2012). As MJO is strongly responsible for intra-seasonal variation of precipitation in the study region, the occurrence of MJO events was compared to the significant anomalies of ET/P ratio and of key meteorological variables. No evidence of MJO influence is observed: the positive and negative anomalies of ET/P ratio are associated to positive, negative and zero anomalies of OLR, filtered in the MJO interval. Also, no significant relation emerged from the correlation analysis.

Correlations between MJO index (Wheeler and Kiladis, 1999; Gushchina and Dewitte, 2011), and the deviations of key meteorological parameters from monthly averages during the study period were very low: $r^2 = 0.03$ for T , $r^2 = 0.03$ for P and $r^2 = 0.01$ for G ($p > 0.05$, in both cases).

The Indian Ocean Dipole (IOD) is characterised by changes of the SST in the western Indian Ocean, resulting in intensive rainfall in the western part of Indonesia during the positive phase and corresponding precipitation reduction during the negative phase (Saji et al., 1999). To find a possible influence of IOD events on temporal variability of meteorological parameters and CO_2 and H_2O fluxes, the monthly mean IOD index (Dipole Mode Index, DMI) was used. Results showed that with respect to the western part of Indonesia situated close to Indian Ocean the IOD phenomenon has no significant impact on meteorological conditions and fluxes of the area of Central Sulawesi.

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5 Conclusions

CO₂ and H₂O fluxes, in the mountainous tropical rain forest in Central Sulawesi in Indonesia, showed a very high sensitivity of monthly GPP and ET to ENSO intensity for the period from January 2004 to June 2008. It is mainly governed by a high sensitivity of incoming solar radiation to Nino4 and Nino3.4 SST changes and the influence of incoming solar radiation on GPP and ET. In contrast, RE pattern is mainly influenced by air temperature variation, which is however not significantly influenced by ENSO activity. Thus, there is no significant relationship between Nino4 and Nino3.4 SST dynamics and RE pattern. Correlation between ENSO intensity and variation of monthly mean NEE values is also relatively low. Precipitation variation has no influence on CO₂ and H₂O fluxes, mainly due to the permanently sufficient soil moisture condition in the study area.

Other climatic anomalous events in the Western Pacific region, such as the Indian Ocean Dipole and the Madden–Julian oscillation, did not show any significant effect on meteorological conditions or CO₂ and H₂O fluxes in the tropical rain forest in Central Sulawesi.

It is important to emphasise that the considered observation period does not cover the period with extreme El Niño events, such as, e.g., the 1982–1983 and 1997–1998 events, when the anomaly of Nino3.4 SST, during several months, exceeded 2.6 and more significant changes of surface moistening conditions could be observed. It can be also expected that in lowland parts of Sulawesi, characterised by higher temperatures and lower precipitation, the response to ENSO events can be also more pronounced.

All observed ENSO events during the selected period are classified as Central Pacific type. Recently, Yeh et al. (2009) showed that under projected climate change the proportion of Central Pacific ENSO events might increase. Furthermore, Cai et al. (2014, 2015) showed that current projections of climate change for the 21st century are associated with a general increase of both El Niño and La Niña events. Taking this into account the results of the present study indicate possible substantial variations of the

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CO₂ and H₂O exchange between atmosphere and the tropical rain forests in Indonesia under future climatic conditions.

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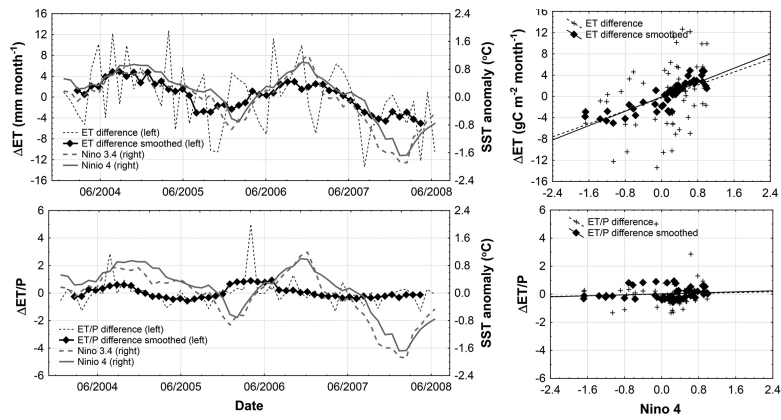


Figure 5. Comparisons of interannual pattern of SST anomalies in Nino4 and Nino3.4 zones of equatorial Pacific with variability of both deviations and 6 months running mean deviations of monthly ET rate and ratio ET/P from mean monthly ET rate and ET/P averaged over the entire measuring period from 2004 to 2008.