Dear editor,

we are very thankful the referees for helpful and constructive comments and recommendations. We have revised the paper in accordance with the reviewers' suggestions to produce an improved version of our manuscript.

Answers to reviewer comments.

Reviewer 1

Comment: *However, before it can be published in Biogeosciences, the authors need to take the major concern into account that I highlighted in the online discussion. It is my concern that this study has several limitations due to the fact that the results are based on only a single fluxtower site, while analysing the impact of a large scale phenomenon (ENSO). In their response letter the authors agree with this comment. But in the manuscript this limitation is not discussed.*
I fully understand that the authors are now not able to include additional fluxtowers for this data poor region. But the authors should include at least an additional paragraph in the discussion section that discusses thoroughly the limitations of using only 1 site for this type study. Is the site representative for the region? Is the site affected by local climate phenomena that interact with the ENSO responses? ... Maybe refer to other studies where multiple fluxtowers in the same region responded similar/differently to large scale climate patterns...

Answer:
Yes, we agree with reviewer, that the limitations of the "one-site study" should be mentioned and discussed. We added following text in the Discussion section:
"Even though remote sensing analyses have shown that the site is representative for the region (Ibrom et al. 2007, Popastin et al. 2012), the response to ENSO might differ in the region dues to differences in altitude and land-use (Erasmi et al. 2009). In general, anthropogenic deforestation has removed most parts of lowland forests so that the remaining forest cover consists mostly of mountainous forests. At the moment, there are no other FLUXNET sites situated in equatorial mountainous rainforests of South-East Asia with which we could directly compare our findings and investigate whether similar response to ENSO can be observed. Most of the existing FLUXNET sites (AsiaFlux) are not comparable with the investigated site as they are situated in subequatorial and tropical climate zones. These are characterized by higher seasonality of air temperature and precipitation compared to our equatorial site. Thus, our site provides a unique opportunity to investigative the response of an equatorial mountainous rainforest to ENSO in the Western pacific region"

Comment: *In a similar way, the authors should acknowledge the limitations of using an open-path sensor.*

Answer.
We used an open-path sensor due to the low power availability at the site (only solar power). In the manuscript we now extended the explanation how we circumvented the usual consequences of open-path sensor measurements by using a process model for gap-filling. (see page 6 of the manuscript, line 8 to 33) :
"For filling the gaps in the measured Net Ecosystem Exchange (NEE) and evapotranspiration, net radiation, sensible and latent heat flux records as well as to quantify GPP, RE and forest canopy transpiration the process-based Mixfor-SVAT model (Olchev et al., 2002; 2008) was used.
Mixfor-SVAT is a one-dimensional model of the energy, H_2O and CO_2 exchange between vertically structured mono- or multi-specific forest stands and the atmosphere. The main model advantage is its ability both to describe seasonal and daily patterns of CO_2 and H_2O fluxes at

individual tree and entire ecosystem levels and to estimate the contributions of soil, different forest layers, and various tree species into the total ecosystem fluxes taking into account individual structure, biophysical properties and responses of plant species to changes in environmental conditions. The model also allows to take into account the non-steady-state water transport in the trees, rainfall interception, dew generation, turbulence and convection flows within the canopy and plant canopy energy storage. As model input the measured meteorological variables (air temperature, water vapor pressure, wind speed, precipitation, CO_2 concentration, global solar radiation) are used. The model was tested with long-term meteorological and flux data from different experimental sites including the investigated forest under well-developed turbulent conditions and showed a good agreement over a broad spectrum of weather and soil moisture conditions (Olchev et al., 2002; Falk et al., 2005; Falge et al., 2005; Olchev et al., 2008). Using the model is superior to common statistical gap-filling approaches, because these depend on calibration under all relevant weather conditions, including those that were systematically excluded when the open-path sensor did not work, e.g. under rain. For this reason one might argue that statistical gap-filling is biased by calibration during dry weather conditions. The process-based model is, however, able to take these weather situations into account, because it is based on general physical principles. As it was shown in previous studies the model is able to predict both CO_2 and water fluxes under various weather and soil moisture conditions at sites where closed-path sensors were used (Olchev et al., 1996; Falge et al., 2005).”

Reviewer 2

Comment: *Although I acknowledge the fact that the authors now explicitly limit their conclusions to monthly anomalies, their answer to my question about the absolute magnitude of NEE (as shown in Fig. 2) is insufficient. In their response letter, the authors compare GPP with that of other tropical forests (with which it agrees) and argue that RE must be lower than in those other forests due to the lower temperatures prevailing in the mountains and, as a consequence, NEE must be very large. Well, a continuous net uptake at a record-high average rate of nearly 1 kg C m-2a-1 must correspond to a steady and sustainable carbon accumulation in either wood or litter or soil (or in several components). How could this be possible and where do the authors think that the carbon goes? Can they provide any independent validation, e.g. through measurements of wood or biomass increment or soil carbon stock? This I would consider as a pre-requisite for defending the NEE rates shown in the ms. If there are no such data available yet, the authors may consider asking foresters for advice on how to conduct such measurements at a remote site without too much effort. The reason why I am insisting on this point is that the results shown in Fig. 2 would have a huge impact if it really was true that old-growth forests are such extremely strong carbon sinks.*

Answer.
We thank for the advice to track the carbon in the system. This additional data will certainly lead to an interesting new study on the carbon budget of the site. However it will hardly be possible to achieve the requested accuracy in a short time period and still the uncertainty of below ground carbon allocation will remain. The focus of this study is not the carbon budget, but its sensitivity on seasonal weather anomalies. We discuss deviations from the mean and not the carbon budget.
In our first revisions we have corroborated our values with additional analyses on daytime NEE, which is independent from nighttime low turbulence phenomena. These analyses have shown that the findings using whole day NEE were robust.
On the other hand we do not see why we should not mention the measured budget. Annual estimations of NEE of CO_2 for our tropical forest is 7.29±0.32 t C ha^{-1} (not 10 t C ha^{-1}). As it was already mentioned our GPP, Re and NEE values are reasonably close to the average values for tropical forests as it was reported in Luyssaert et al. (Global Change Biology, 2007, 13, 2509–2537), 75-538 g C m^{-2} yr^{-1}. In present time in the literature it can be found a much larger estimations of the net CO_2 uptake rates for old but at the same time rapidly growing tropical forests (e.g. of the annual NEE in the mangrove forests of Everglades National Park (Florida, USA) showed that the NEE can reach 1200 g m^{-2} yr^{-1} (Barr, J. G., Engel, V.C., Fuentes, J.D., Zieman, J.C., O'Halloran, T.L., Smith III, T.J., Anderson, G.H., 2010. Controls on mangrove forest-atmosphere carbon dioxide exchanges in western Everglades National Park. J. Geophys. Res. Biogeosci.).
In the manuscript, we have briefly discussed that these numbers are high, and which potential reason there are for this, e.g. site history and regrowth after selected use of large individual trees by the local population (chapter 4.1, page 11-12).

Comment: *Filtering with ustar > 0.25 m/s does not remove the doubts about the soil CO2 efflux data, either, since it is not clear, given the nevertheless sloping terrain and the maximum tree height of 36 m, whether any eddies at all penetrate to the ground. It is still possible that the CO2 efflux from the soil remains always decoupled from the eddy flux above the canopy, with most of the soil CO2 flowing down the slope. Are there any CO2 chamber measurements of soil respiration that could be shown for comparison or any turbulence data from within the canopy? Alternatively, are there any other studies that show such data in tall tropical forests and that could be cited?*

Answer.
If we understand the reviewer correctly she or he wants to consider the theoretical possibility that all or a constant fraction of the CO2 transport from the soil is entirely decoupled from the air layer

above the forest. We show that the nighttime fluxes increase with u* and that they level off beyond a certain ustar threshold value. This would imply a flux loss component that is u* dependent and a component that is independent from u*. We don't know of any published empirical findings or theoretical analyses that back such an assumption. On the contrary it has been shown that at some sites the night time fluxes increase over the whole range of ustar, .i.e. no ustar threshold could be found (Fig. 3 in Loescher, H., Oberbauer, S.H., Gholz, H.L. and Clark, D.A., 2003. Environmental control on net ecosystem-level carbon exchange and productivity in a Central American tropical wet forest. Global Change Biology, 9: 396-412.). In such sites, the problem limited mixing is permanent, we have shown that this is not the case at our site.
To minimise a potential bias on the flux sums, we used a process-based forest model that is not biased by a lack of data in wet and low turbulence conditions. Model estimations (calibrated using the chamber data) of annual soil respiration for Bariri site is about 11.1±0.3 t C ha^{-1} yr^{-1}. This value is close to averaged estimates of the soil CO_2 efflux obtained by van Straaten et al. (2011) for the central Sulawesi region (11.7 t C ha^{-1} yr^{-1}).

Comment: A*lternatively, are there any other studies that show such data in tall tropical forests and that could be cited.*
See the first answer to Reviewer 2
Also we refer in our study to Luyssaert et al. (Global Change Biology, 2007, 13, 2509–2537

Comment: *Last, but not least, I am irritated by the fact that the authors, in some places, did in fact not change the manuscript text according to what they announced in the response letter. Examples: "In our revised manuscript, we will describe the gap-filling approach and the model in more detail." They did not.*

Answer:
We are sorry for any irritation the response might have caused.
In page 6 we indicated that for the gap filling in the time series of CO2 fluxes, as well as for the gaps in net radiation, sensible and latent heat flux records the process-based Mixfor-SVAT model (Olchev et al., 2002; 2008) was applied. The general description of the model is given in many previous publication e.g. Olchev et al., 2002; 2008 , Falk et al., 2005; Falge et al., 2005. We included the references in the manuscript. According to the reviewers' suggestion a more detailed description of the gap filling procedure is provided on page 6:
"For filling the gaps in the measured Net Ecosystem Exchange (NEE) and evapotranspiration, net radiation, sensible and latent heat flux records as well as to quantify GPP, RE and forest canopy transpiration the process-based Mixfor-SVAT model (Olchev et al., 2002; 2008) was used.
Mixfor-SVAT is a one-dimensional model of the energy, H_2O and CO_2 exchange between vertically structured mono- or multi-specific forest stands and the atmosphere. The main model advantage is its ability both to describe seasonal and daily patterns of CO_2 and H_2O fluxes at individual tree and entire ecosystem levels and to estimate the contributions of soil, different forest layers, and various tree species into the total ecosystem fluxes taking into account individual structure, biophysical properties and responses of plant species to changes in environmental conditions. The model also allows to take into account the non-steady-state water transport in the trees, rainfall interception, dew generation, turbulence and convection flows within the canopy and plant canopy energy storage. As model input the measured meteorological variables (air temperature, water vapor pressure, wind speed, precipitation, CO_2 concentration, global solar radiation) are used. The model was tested with long-term meteorological and flux data from different experimental sites including the investigated forest under well-developed turbulent conditions and showed a good agreement over a broad spectrum of weather and soil moisture conditions (Olchev et al., 2002; Falk et al., 2005; Falge et al., 2005; Olchev et al., 2008). Using the model is superior to common statistical gap-filling approaches, because these depend on calibration under all relevant weather conditions, including those that were systematically excluded when the open-path sensor did not work, e.g.

under rain. For this reason one might argue that statistical gap-filling is biased by calibration during dry weather conditions. The process-based model is, however, able to take these weather situations into account, because it is based on general physical principles. As it was shown in previous studies the model is able to predict both CO_2 and water fluxes under various weather and soil moisture conditions at sites where closed-path sensors were used (Olchev et al., 1996; Falge et al., 2005)."

Comment: *The respective text (last 9 lines of section 2.3) was left completely unchanged. (Only the preceding sentences about the ustar filtering were added.) "The discussion about data uncertainty will be added to the revised version of the manuscript." It wasn't! No error margins at all are presented in the text, just a few standard deviations for some multi-year records. Whether this was simply forgotten or deliberately omitted I cannot judge, but in any case the authors should keep the promises they made in their response letter.*

Answer:
The explanation was added in the first part of discussion (chapter 4.1 " Uncertainty of the analysis ", page 11-12):
"Eddy covariance flux measurements in tropical mountainous conditions are challenging. Our tower and eddy covariance system was designed to minimise power consumption by using an open-path sensor, which had the consequence that rainy conditions systematically caused gaps in the flux data. To minimise a potential bias on the flux sums, we used a process-based forest model that is not biased by a lack of data in wet conditions as the often used statistical gap-filling algorithms (Reichstein et al., 2005, see also section 2.3). The weather in the tropics typically has a relatively high percentage of calm nights. The selected forest is located on a plateau in a mountainous region and this increases the risk of CO_2 rich air draining downhill in calm night. We investigated this effect very carefully and found that the CO_2 fluxes showed a very clear u_* threshold above which the night time CO_2 emission rates did not depend on u_* anymore. Using only data from nights with sufficient turbulence ($u_* > u_*$ threshold value) we minimised advection and drainage affecting the NEE estimates. Also, here we benefitted from the use of the process model for gap-filling.
In addition we compared the model predicted mean annual soil respiration rate with soil CO2 efflux data that were measured in the study region with soil chambers (van Straaten et al. 2011). The Mixfor-SVAT model estimated an average annual soil respiration rate of 1110±30 g C m-2 yr-1 for the investigated site. This value was very close to the measured average soil CO2 efflux of for the central Sulawesi region of 1170 g C m-2 yr-1 which shows realistic behavior of the model.
We then analysed the statistical relationships between our gap-filled monthly fluxes with climate anomaly indices and corroborated these analyses also with midday NEE data only. As time data are independent from night time data, we made sure that our analysis was not affected by night time flux loss. The correlations with midday data and ENSO indices were very similar to those with daily mean NEE data. This demonstrated the robustness of our analysis.
The relatively high annual NEE sums need further investigation. After applying all corrections including the correction for open-path sensor heating, and after gap filling we found an average annual uptake of 729±32 g C m-2 yr-1 (standard deviation between 5 different years). This value is higher as the range found in lowland rain forests, i.e. ranging from e.g. 75 to 538 g C m-2 yr-1 (Luyssaert et al., 2007). The clarification of this very interesting phenomenon, maybe relating to the site history and regrowth after selected use of large individual trees by the local population, lies however not within the scope of this article.

Response of CO_2 and H_2O fluxes of a mountainous tropical rainforest in equatorial Indonesia to El Niño events

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Abstract

The possible impact of El Niño-Southern Oscillation (ENSO) events on the main components of CO_2 and H_2O fluxes between tropical rainforest and atmosphere is investigated. The fluxes were continuously measured in a old-growth~~pristine~~ mountainous tropical rainforest growing in Central Sulawesi in Indonesia 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 CO_2 and H_2O exchange showed a high sensitivity of Evapotranspiration (ET) and Gross Primary Production (GPP) of the tropical rainforest 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 km^2 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 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; Yuan and Yan, 2013). Typically, in Indonesia El Niño results in dryer conditions and La Niña results in wetter conditions, potentially impacting the land vegetation (Erasmi 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 CO_2 and H_2O exchange between land surface and the atmosphere, many studies for different Western Pacific regions were carried out during the recent decades (Feely et al., 1998; Malhi et al., 1999; Rayner and Law, 1999; Aiba and Kitayama, 2002; Hirano et al., 2007; Erasmi 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 based on direct measurements of CO_2 and H_2O fluxes, which allow studying the response of individual terrestrial ecosystems to anomalous weather conditions, are still very limited (e.g. Hirano et al., 2007; Moser et al., 2014). Existing monitoring networks in equatorial regions of the Western Pacific are associated mainly with lowland areas and do not cover mountainous rainforest regions, even though mountainous regions cover some of the last remaining undisturbed rainforest in South-East Asia. Most attention in former studies was paid to the description of plant response to anomalously dry and warm weather during El Niño events (Aiba and Kitayama, 2002; Hirano et al., 2007; Moser et al., 2014). The possible changes in plant functioning during La Niña events are still not clarified. In particular, Malhi et al. (1999) reported that for Amazon region in the South America El Niño periods are strongly associated with enhanced dry seasons that probably result in increased carbon loss, either through water stress causing reduced photosynthesis or increased tree mortality. Aiba and Kitayama (2002) examined the effects of the 1997–98 El Niño drought on nine rainforests of Mount Kinabalu in Borneo using forest inventory and showed that El Niño increased the tree mortality for lowland forests. However, it did not affect the growth rate of the trees of upland forests (higher than 1,700 m) where mortality was restricted by some understorey species only. Eddy covariance measurements of the CO_2 fluxes in a tropical peat swamp forest in Central Kalimantan, Indonesia, for the period from 2002 to 2004, provided by Hirano et al. (2007), showed that during the El Niño event in the period November-December 2002 the annual net CO_2 release reached maximal values, mainly due to strong decrease of GPP in the late dry season, because of dense smoke emitted from large-scale fires. Effects of El Niño on annual RE in 2002 were insignificant.

There is a lack of experimental data on CO_2 and H_2O fluxes in mountainous rainforests in equatorial regions of the Western Pacific, and on their response to ENSO. Hence, the main objective of this study was to evaluate and quantify the impact of ENSO events on the main components of CO_2 and H_2O fluxes in an old-growth~~pristine~~ mountainous tropical rainforest growing in Central Sulawesi, Indonesia. The methodology used was analysis of long-term eddy covariance flux measurement data.

2. Materials and Methods

2.1 El Niño's types and intensity

Nowadays, two types of ENSO can be distinguished: 1) the canonical or conventional El Niño, which is characterised by SST anomalies located in the eastern Pacific near the South American coast (Rasmusson and Carpenter, 1982) and 2) the Central Pacific El Niño or El Niño Modoki (Larkin and Harrison, 2005; Ashok et al., 2007; Kug et al., 2009; Ashok and Yamagata, 2009; Gushchina and Dewitte, 2012). In 2003, a~~the~~ new definition of the conventional El Niño was accepted by the National Oceanic and Atmospheric Administration (NOAA) of the USA, in referring to the warming of the Pacific region between 5°N - 5°S and 170° - 120°W. According to Ashok et al. (2007) the Central Pacific El Niño/El Niño Modoki - i.e. unusually high SST - occurs roughly in the region between 160°E - 140°W and 10°N - 10°S.

As criteria to assess the intensity of ENSO events, a wide range of indexes based on different combinations of sea level pressure and SST data in various areas of the Pacific are used. For diagnostics of the central Pacific El Niño, the SST anomalies (in °C) in Nino4 region (5°N - 5°S and 160°E - 150°W) are broadly used (Figure 1). The monthly SST anomalies (in °C) in Nino3.4 region (5°N - 5°S and 170° - 120°W) are used to diagnose both types of El Niño phenomenon: canonical and Central Pacific (Download Climate Timeseries, 2013).

2.2 Experimental site

The tropical rainforest selected for the study is situated near the village Bariri in the southern part of the Lore Lindu National Park of Central Sulawesi in Indonesia (1°39.47'S and 120°10.409'E or UTM 51S 185482 м east and 9816523 м north) (Figure 1). The site is located on a large plateau of several kilometres in size at about 1,430 m above sea level surrounded by mountain chains surmounting the plane by another 300 m to 400 m. Within 500 m around the tower the elevation varies between 1,390 and 1,430 metres. Wind field measurement with a sonic anemometer indicate a slope of around 2-3°, which is similar to many Fluxnet sites. About 1,000 m to the east from the experimental site, the forest is replaced by a meadow; in all other directions the forest extends several kilometres ~~.~~(Ibrom et al., 2007).

According to the Köppen climate classification the study area relates to tropical rainforest climate (*Af*) (Chen ~~D.~~ and Chen ~~H.W.~~, 2013). Weather conditions of the region are mainly influenced by the ITCZ. During the wet season (typically, from November to April) the area is influenced by very moist northeast monsoons coming from the Pacific. Maximum precipitation during the observation period from January 2004 to July 2008 was observed in April - with 258.0±148.0 mm month^{-1}. The drier season usually lasts from May to October. The precipitation

minimum was observed in September with 195.0±48.0 mm month^{-1}. The September-October period was also characterised by maximal incoming solar radiation, up to 650±47.0 MJ m^{-2} month^{-1}, mainly because of a significant decrease of convective clouds, due to the reversing of oceanic northeast monsoon to a southeast monsoon blowing from the Australian continent. The mean annual precipitation amount exceeded 2000 mm. The mean monthly air temperature varies between 19.4 °C and 19.7 °C. The mean annual air temperature was 19.5 °C (Falk et al., 2005; Ibrom et al., 2007).

The vegetation at the experimental site is very diverse and ~~very~~ representative ~~to~~ for the mountainous~~montane~~ ~~tropical~~ rainforest communities of ~~the~~ Central Sulawesi. ~~It is represented by~~There are about ~~more than~~ 88 different tree species per hectare. Among the dominant species are *Castanopsis accuminatissima* BL. (29%), *Canarium vulgare* Leenh. (18%) and *Ficus spec.* (9.5%). The density of trees, with diameter at breast height larger than 0.1 m, is 550 trees per ha. In addition, there is more than a 10-fold larger number of smaller trees per hectare with stem diameter lower than 0.1 m. The total basal area of trees reached 53 m^2 per ha. Leaf area index (LAI) is about 7.2 m^2 m^{-2}. LAI has been estimated using an indirect hemispherical photography approach with a correction for leaf clumping effects. The height of the trees, with diameters at breast height larger than 0.1 m, varies between the lowest at 12 m and the highest at 36 m. The mean tree height is 21 m (Ibrom et al., 2007).

2.3 Flux measurements and gap filling

CO_2 and H_2O fluxes were measured from 2004 to 2008 within the framework of the STORMA project (Stability of Rainforest Margins in Indonesia, SFB 552), supported by the German Research~~Science~~ Foundation (DFG). E~~The eddy~~ covariance equipment for flux measurements was installed on a meteorological tower of 70 m height at the 48 m level, i.e. ca. 12 m higher than the maximal tree height. The measuring system consists of a three-dimensional sonic anemometer (USA-1, Metek, Germany) and an open-path CO_2 and H_2O infrared gas analyzer (IRGA, LI-7500, Li-Cor, USA) (Falk et al., 2005; Ibrom et al., 2007; Panferov et al., 2009). The open-path IRGA was chosen due to its smaller power requirements compared to~~, e.g.,~~ closed-path sensors. The sensor ~~was chosen to provide continuous flux measurements in the field mainly due reduced power requirements comparing with e.g. close path sensors available at that time. The sensor~~ was calibrated with calibration gases two times per year and showed no considerable sensitivity drift within one year of operation. Turbulence data were sampled at 10 Hz and stored as raw data on an industrial mini PC (Kontron, Germany). All instruments were powered by batteries, which were charged by solar panels, mounted on the tower. The system is entirely self-sustaining

and has been proven to run unattended over a period of several months. Post-field data processing on eddy covariance flux estimates was carried out strictly according to the established recommendations for data analysis (Aubinet et al., 2012). In addition to the procedures described in Falk et al. (2005) and Ibrom et al. (2007), we corrected the flux data for CO_2 or H_2O density fluctuations due to heat conduction from the open-path sensor (Burba et al., 2008; Järvi et al. 2009) using finally the suggested method as described in Reverter et al. (2011).

The system operated at ca. 70% of the time. Ca. 30% of the measured flux data were negatively affected by rain and other unfavourable conditions and removed. From night time ecosystem respiration data a friction velocity (u_*) threshold value of 0.25 m s^{-1} was estimated (Aubinet et al., 2000), i.e. at u_* values above this threshold the measured night time flux became independent from u_*. Night time flux values that were measured at $u_* < 0.25$ m s^{-1} were removed, which left 15% of the measured night time flux data in the data set. For filling the gaps in the measured Net Ecosystem Exchange (NEE) and evapotranspiration, net radiation, sensible and latent heat flux records as well as to quantify GPP, RE and forest canopy transpiration the process-based Mixfor-SVAT model (Olchev et al., 2002; 2008) was used.

Mixfor-SVAT is a one-dimensional model of the energy, H_2O and CO_2 exchange between vertically structured mono- or multi-specific forest stands and the atmosphere. The main model advantage is its ability both to describe seasonal and daily patterns of CO_2 and H_2O fluxes at individual tree and entire ecosystem levels and to estimate the contributions of soil, different forest layers, and various tree species into the total ecosystem fluxes taking into account individual structure, biophysical properties and responses of plant species to changes in environmental conditions. The model also allows to take into account the non-steady-state water transport in the trees, rainfall interception, dew generation, turbulence and convection flows within the canopy and plant canopy energy storage. As model input the measured meteorological variables (air temperature, water vapor pressure, wind speed, precipitation, CO_2 concentration, global solar radiation) are used. The model was tested with long-term meteorological and flux data from different experimental sites including the investigated forest under well-developed turbulent conditions and showed a good agreement over a broad spectrum of weather and soil moisture conditions (Olchev et al., 2002; Falk et al., 2005; Falge et al., 2005; Olchev et al., 2008). Using the model is superior to common statistical gap-filling approaches, because these depend on calibration under all relevant weather conditions, including those that were systematically excluded when the open-path sensor did not work, e.g. under rain. For this reason one might argue that statistical gap-filling is biased by calibration during dry weather conditions. The process-based model is, however, able to take these weather situations into account, because it is based on general physical principles. As it was shown in previous studies the model is able to predict both CO_2 and water fluxes under

various weather and soil moisture conditions at sites where closed-path sensors were used (Olchev et al., 1996; Falge et al., 2005).

2.4 Micrometeorological measurements

Air temperature, relative humidity and horizontal wind speed were measured at 4 levels above and at 2 levels inside the forest canopy using ventilated and sheltered thermo-hygrometers and cup anemometers (Friedrichs Co., Germany) installed on the tower. Short- and long-wave radiation components were measured below and above the canopy with CM6B and CG1 sensors (Kipp & Zonen, The Netherlands). Rainfall intensity was measured on top of the tower with a tipping bucket in a Hellman-type rain gauge. To fill the gaps in measuring records the meteorological data from an autonomic meteorological station, situated about 900 m away from the tower outside the forest on a nearby meadow, were used. For the analysis, the monthly mean values of air temperature and monthly sums of precipitation and solar energy were calculated.

2.5 Data analysis

To estimate the possible impact of ENSO events on CO_2 and H_2O fluxes in the tropical rainforest at Bariri the temporal variability of monthly NEE, GPP, RE and ET in periods with different ENSO intensity was analysed. To quantify the ENSO impacts on meteorological parameters and fluxes and to distinguish them from effects caused by the seasonal migration of the ITCZ, the intra-annual patterns of CO_2 and H_2O fluxes as well as meteorological conditions during the measuring period were also evaluated.

In the first step to assess the possible impact of ENSO events on meteorological parameters (global solar radiation (G), precipitation amount (P), air temperature (T) and CO_2 and H_2O fluxes), the correlation between the absolute values of monthly G, P, T, NEE, GPP, RE, ET and monthly SST-anomalies in Nino4 and Nino3.4 regions (Nino4 and Nino3.4 indexes) were analysed.

In the second step, we analyzed the correlation between the deviations of monthly meteorological parameter and flux values from their monthly averages over the entire measuring period and the Nino4/Nino3.4 indexes. The deviation in the case of GPP (ΔGPP) was estimated as

$$\Delta GPP_{Month,Year} = GPP_{Month,Year} - \frac{1}{N}\sum_{Year=2004}^{2008} GPP_{Month,Year}$$

where $GPP_{Month,Year}$ is total monthly GPP for a particular month (January to December) and corresponding year (2004 to 2008), $\frac{1}{N}\sum_{Year=2004}^{2008} GPP_{Month,Year}$ is monthly GPP for this particular month averaged for the entire measuring period (2004 to 2008); N is number of years. Positive

values in ΔGPP, ΔRE, and ΔNEE indicate GPP, RE higher and NEE (carbon uptake) lower than average.

The typical timescale of full ENSO cycle is estimated ~~to~~ be about 48-52 months (Setoh et al., 1999) whereas the timescale of the main meteorological parameters (global solar radiation (G), precipitation amount (P), air temperature (T)) is characterized by much higher month-to-month variability even after annual trend filtering. In order to filter the high-frequency oscillation in the time-series of atmospheric characteristics and monthly NEE, GPP, RE, ET anomalies the simple centered moving average smoothing procedure was applied. The moving averages (MA) of variables were calculated over 7 months (centered value ±3 months).

Statistical analysis included both simple correlation and cross-correlation analysis (Chatfield, 2004). Cross-correlation analysis was used to take into account the possible forward and backward time shifts of maximal anomalies of meteorological parameters and CO_2 and H_2O fluxes in respect to time of the ENSO culmination. To describe the relationships between atmospheric fluxes and meteorological parameters the monthly non-smoothed values were used.

3. Results

During the measuring period, two El Niño (August 2004 - March 2005 and October 2006 - January 2007) and one La Niña (November 2007 - April 2008) phenomena were observed. All events had moderate intensity. Both warm events could be classified as the Central Pacific or Modoki type, according to Ashok et al. (2007), since the SST-anomalies were centred in Nino3.4 and Nino4 regions (Figure 1).

Analysis of the intra-annual pattern of CO_2 and H_2O fluxes shows a relatively weak seasonal variability (Figure 2). The maximal values of GPP were obtained during the second part of the drier season - from August to October (278±13 g C m^{-2} $month^{-1}$) - which is also characterised by maximal values of incoming solar radiation. The mean monthly air temperature in the period varied from minimal values in August (19.2±0.2 °C) to maximal values in October (19.8±0.2 °C). The minimal GPP values were obtained in transition periods between more wet and dry seasons - in May - June and November - December (240±15 and 249±21 g C m^{-2} $month^{-1}$, respectively). These periods are also characterised by minimal amounts of incoming solar radiation (512±40 MJ m^{-2} $month^{-1}$). Maximal RE (206±10 g C m^{-2} $month^{-1}$) and values were obtained in October, which corresponds to the period of maximal air temperature and insolation. The local maximum of RE in April - May (199±4 g C m^{-2} $month^{-1}$) is also well correlated with a small increase of the air temperature in these months. The minimal RE was observed in February and June-August (174±10 and 187±15 g C m^{-2} $month^{-1}$, respectively). The intra-annual pattern of ET was closely related to the

seasonal variability of GPP. The maximum values of ET were also observed in October (136±4 mm), in the month of maximal incoming solar radiation and highest values of air temperature. In spite of a large amount of precipitation and a high air temperature during the period from March to June, ET in this period was much lower than in September and October (e.g. 105±8 mm in April).

Comparisons of monthly NEE, GPP, RE, ET and absolute values of SST-anomalies in Nino4 and Nino3.4 regions (henceforth Nino4 and Nino3.4 indexes) indicate relatively low correlations. Changes of the Nino4 index can explain about 12% of the observed variability in GPP (coefficient of determination, r^2=0.12 under significance level $p<0.05$), 9% of RE (r^2=0.09, $p<0.05$), 9% of NEE (r^2=0.09, $p>0.05$), 6% of ET (r^2=0.06, $p<0.05$) and only about 1% of transpiration (TR) (r^2=0.01, $p>0.05$). Similar values were obtained ~~in correlation analysis~~ for the Nino3.4 index. In the periods of El Niño peak phases (September 2004 - January 2005 and October 2006 - January 2007) the values ET and GPP tend to increase in the study area. An increase of RE was indicated only during the second El Niño event from October 2006 to January 2007. The effect of El Niño on NEE was insignificant. The effect of La Niña on CO_2 and H_2O flux components was very small and manifested only in a slight increase of NEE.

Analysis of the temporal variability of the centered moving average values of ΔGPP (ΔGPP_{MA}) (Figure 3) in contrast to comparisons of absolute monthly GPP indicates a relatively high correlation between ΔGPP_{MA} and both Nino4 (r^2=0.52, $p<0.05$) and Nino3.4 (r^2=0.60, $p<0.05$) indexes. Close correlation between the intensity of ENSO events and ΔGPP_{MA} can be explained by the influence of ENSO initiating processes and ENSO itself on total cloud amount in the region and, as a result, on monthly sums of incoming G (Figure 4). Variability of G (ΔG_{MA}) is very closely correlated with Nino4 and Nino3.4 indexes (r^2=0.48, $p<0.05$ for both indexes) (Figure 4) and it can explain 69% of variability of GPP (r^2=0.69, $p<0.05$). The maximal deviations of ΔGPP_{MA} and ΔG_{MA} from mean values (averaged for the entire measuring period) are occurring 2-3 months before the peak phase of the ENSO events (Figure 5). The maximal cross-correlation coefficients in this period reached 0.76 for ΔG_{MA}, and 0.86 - for ΔGPP_{MA}. The effect of T changes (ΔT) on ΔGPP is very low (r^2=0.01, $p>0.05$).

The correlation between ΔT_{MA} and Nino4, Nino3.4 indexes are relatively low (r^2=0.15, $p>0.05$ for Nino4 and r^2=0.05, $p>0.05$ for Nino3.4) and it can explain the very weak correlations between ΔRE_{MA} and ENSO indexes (r^2=0.10, $p<0.05$ for Nino4 and r^2=0.04, $p>0.05$ for Nino3.4) (Figures 3-4). The maximal deviations of T_{MA} and RE_{MA} from mean values (averaged for the entire measuring period) are occurring 2 months after the peak phase of the ENSO events and it has negative sign (Figure 5). The cross-correlation coefficient in this period is -0.53 ($p<0.05$).

Despite the relatively close dependence of ΔGPP_{MA} on ENSO intensity, the correlations between ΔNEE_{MA} and Nino4, Nino3.4 indexes are lower (r^2 = 0.31, $p<0.05$ for Nino4 and r^2 = 0.37,

$p<0.05$ for Nino3.4), mainly because of their very low correlation during the first part of the measuring period (before December 2005). During the second part of the considered period (from June 2006 to June 2008) with one strong El Niño (October 2006 - January 2007) and one La Niña (November 2004 - April 2008) events ΔNEE_{MA} and Nino4, Nino3.4 indexes are correlated much better. It can be explained by the influence of ΔRE_{MA} on ΔNEE_{MA} dynamics that is mainly governed by temperature variability and which is, as already mentioned, very poorly correlated with Nino4/Nino3.4 indexes (Figures 3-4).

Taking into account that the monthly anomalies of NEE might be biased by a still unaccounted advection effects at night-time, despite $u*$ filtering, we additionally examined NEE at midday (10:00-14:00), when turbulent mixing is typically well developed. Data analysis based on midday NEE shows a similar clear relationship with the ENSO index (Figure 6) with $r^2 = 0.59$ under $p<0.05$. The maximal deviations of both NEE_{MA} and midday NEE_{MA} from the their mean values occurred simultaneously within the peak phase of the ENSO events (Figure 5).

Analysis of the temporal variability of the moving average values of monthly ET (ΔET_{MA}) showed a high correlation to ENSO activity as well: $r^2 = 0.72$, $p<0.05$ for Nino4 and $r^2 = 0.70$, $p<0.05$ for Nino3.4 (Figure 7), probably also triggered by G_{MA}, which in turn correlated strongly with both the Nino4 and the Nino3.4 index. Periods of extreme ΔET_{MA} values and maximal ENSO intensity occurred simultaneously (Figure 5). Correlations between ΔET and ΔT, as well as between ΔET and ΔP, are insignificant - $r^2=0.09$ ($p>0.05$) and $r^2=0.01$ ($p>0.05$), respectively. However, figures 4 and 5 clearly show a time delay in ΔP_{MA} oscillation, relative to Nino4 and Nino3.4 patterns. The maximal negative deviations of ΔP_{MA} are observed about eight months before (cross-correlation between ΔP_{MA} and Nino 4 index 0.72, $p<0.05$) and maximal positive deviation of ΔP_{MA} - about four-five months after the peak phases of ENSO (cross-correlation between ΔP_{MA} and Nino 4 index - 0.40, $p<0.05$), respectively.

To explain a very low sensitivity of ET to P changes, we analysed the intra-annual variability of the ratio between ET and potential evaporation (PET), as well as between ET and P. PET was derived using the well-known Priestley and Taylor (1972) approach and it is equal to evaporation from wet ground or open water surface.

The mean annual ET during the measuring period is considerably lower than P (ET/P=0.742). Over the annual course, the ratio varied between 0.58 (in March and November) to 1.85 (in August and October). During dry periods before the positive phase of ENSO, the mean values of the ET/P ratio grow up to 1.9-2.1. During the periods of negative Nino4 and Nino3.4 anomalies the mean monthly ET/P ratio fell, in some months, down to 0.3. Correlation analysis of temporal variability of $\Delta(ET/P)$ and $\Delta(ET/P)_{MA}$ ratios and Nino4 and Nino3.4 indexes (Figure 7) did not show any statistically significant relationships. However, it should be mentioned that the

temporal pattern of $\Delta(ET/P)$ and $\Delta(ET/P)_{MA}$ is characterised by two peaks that were observed in July of 2005 and April 2007, about 6-8 months prior to the El Niño culmination (Figure 7).

The monthly mean ET/PET ratio has a feeble intra-annual course with maximum in June (0.93±0.03) and with minima in February and October (0.84±0.06). The averaged annual ET/PET ratio for the entire measuring period was 0.880±0.055. The minimal values of $(ET/PET)_{MA}$ ($(ET/PET)_{MA}$=0.81) were observed during the El Niño culmination in 2005-2006, and the maximal values, during the period of maximal intensity of La Niña in 2008 ($(ET/PET)_{MA}$=0.93). Thus, monthly ET rates are relatively close to PET values during the whole year including the periods of maximal ENSO activity. The relative soil water content of the upper 30 cm horizon calculated using the Mixfor-SVAT model during the entire period of the field measurements, including the periods with maximal values of the ET/P ratio, was always higher than 80%. This, together with the ET/PET ratio, is a clear indicator of permanently sufficient soil moisture conditions in the study area, including periods of El Niño and La Niña culminations, explaining the very low sensitivity of ΔET to ΔP.

4. Discussion

4.1. Uncertainty of the analysis

Eddy covariance flux measurements in tropical mountainous conditions are challenging. Our tower and eddy covariance system was designed to minimise power consumption by using an open-path sensor, which had the consequence that rainy conditions systematically caused gaps in the flux data. To minimise a potential bias on the flux sums, we used a process-based forest model that is not biased by a lack of data in wet conditions as the often used statistical gap-filling algorithms (Reichstein et al., 2005, see also section 2.3). The weather in the tropics typically has a relatively high percentage of calm nights. The selected forest is located on a plateau in a mountainous region and this increases the risk of CO_2 rich air draining downhill in calm night. We investigated this effect very carefully and found that the CO_2 fluxes showed a very clear u_* threshold above which the night time CO_2 emission rates did not depend on u_* anymore. Using only data from nights with sufficient turbulence ($u_* > u_*$ threshold value) we minimised advection and drainage affecting the NEE estimates. Also, here we benefitted from the use of the process-based model for gap-filling. We then analysed the statistical relationships between our gap-filled monthly fluxes with climate anomaly indices and corroborated these analyses also with midday NEE data only. As time data are independent from night time data, we made sure that our analysis was not affected by night time flux loss. The correlations with midday data and ENSO indices were very similar to those with daily mean NEE data. This demonstrated the robustness of our analysis.

To estimate the performance of the model applied for gap-filling as it was already mentioned the model was compared with eddy covariance flux data obtained under well developed turbulent conditions. The coefficient of determination (r^2), absolute fractional bias (AFB) and Willmott's index of agreement (IA) between modeled and measured fluxes were calculated (Olchev et al., 2008). Comparisons showed a relatively good agreement between the modeled and measured H_2O and CO_2 fluxes. In particular the determination coefficients ranged between 0.62 for CO_2 to 0.64 for H_2O fluxes Calculated AFBs were about 0.52 for CO_2 and about 0.54 for H_2O fluxes. Both values are located within a critical interval of AFB (between 0 and 0.67). Willmott's indexes of agreement indicating the degree to which model predictions are error free were about 0.87 for CO_2 and about 0.86 for H_2O fluxes that also indicates a good agreement of the model and field data.

In addition we compared the model predicted mean annual soil respiration rate with soil CO_2 efflux data that were measured in the study region with soil chambers (van Straaten et al. 2011). The Mixfor-SVAT model estimated an average annual soil respiration rate of 1110±30 g C m^{-2} yr^{-1} for the investigated site. This value was very close to the measured average soil CO_2 efflux of for the central Sulawesi region of 1170 g C m^{-2} yr^{-1} which shows realistic behavior of the model.

The relatively high annual NEE sums need further investigation. After applying all corrections including the correction for open-path sensor heating and after gap filling we found an average annual uptake of 729±32 g C m^{-2} yr^{-1} (standard deviation between 5 different years). This value is higher as the range found in lowland rain forests, i.e. ranging from e.g. 75 to 538 g C m-2 yr-1.(Luyssaert et al., 2007). The clarification of this very interesting phenomenon, maybe relating to the site history and regrowth after selected use of large individual trees by the local population, lies however not within the scope of this article.

4.2 Effects of large scale climate anomalies on carbon and water exchange in the investigated site

The ~~provided analysis of the temporal variability for the~~ main components of carbon and water balances in the tropical rainforest showed a high correlation ~~between with~~between Nino4 and Nino3.4 SST anomalies~~, characterising the ENSO intensity with~~and ΔGPP_{MA}~~GPP_{MA}~~ and ΔET_{MA} values ~~deviations from monthly averages~~ over the entire measuring period. The ~~Application of the centered moving average~~ smoothing procedure allow~~ed~~s us to ~~filter~~ remove the high-frequency month-to-month oscillations in the time-series of atmospheric characteristics. These are caused by local and regional circulation processes that are not directly connected with ENSO activity and disturb thus the analysis. The relationships between ΔGPP_{MA}, ΔET_{MA} and Nino4 and Nino3.4 indexes are ~~mainly~~ governed ~~on the one hand by~~ via the dependency of the incoming solar radiation on ENSO development – surface water warming in Nino 3.4 and 4 regions generally results in a

decrease of cloudiness above the study region and thus —in an increase of incoming solar radiation. ~~On the other hand there are many data about a~~ The high correlation ~~between~~ of monthly GPP and ET rates ~~and~~ with incoming and absorbed solar radiation at this site is well described (e.g. Ibrom et al., 2008). The effects of monthly air temperature and precipitation changes on ΔGPP and ΔET variability are on the contrary relatively poor. ~~, mainly due to the low correlations between~~ ΔT_{MA}, ΔP_{MA} and ENSO intensity are not very much related.

The cross-correlation analysis (Fig. 5) shows that the ΔGPP_{MA} and ΔG_{MA} have a small 2-3 month backward shift relatively to the course of Nino4 SST, i.e. the maxima in GPP_{MA} occur earlier than ENSO culmination in the central Pacific (Nino4 SST anomaly). The maximal values of ΔE_{MA} occurred simultaneously with El Niño and La Niña culminations. Such an effect of El Niño episodes on G can be explained, as mentioned above, by a decrease of the cloud ~~amount~~ cover in the region of Indonesia, due to the El Niño-associated shift of the Walker circulation cell, and corresponding zone of deep convection, from the maritime continent of Indonesia toward the dateline following SST anomalies displacement. El Nino usually begins in April, and toward August-September the ascending branch of the Walker cell leaves Indonesia and migrates eastward to the Pacific. Therefore, 3-4 months before the El Niño culmination in December-January, a decrease in cloud amount is observed over Indonesia. Weakening of El Niño, in turn, leads to a backward shift of intensive convection zone westward. It can result in increasing precipitation amounts in the region during the second half of the wet period after passing the maximal El Niño activity and also the gradual increase of the cloudiness and decrease of incoming solar radiation. The opposite effect takes place during the La Niña with similar phase shift: simultaneously, with the spreading of a negative SST anomaly over the Pacific, the increasing of deep convection over Indonesia occurs, which results in an increase of cloudiness and precipitation, being more pronounced as it falls into the dry period of the year. The lower panels of Figure 4 indicate however, that the decrease of radiation due to increase of cloudiness does not depend linearly on La Nina intensity, reaching a saturation state at approximately -20..-30 MJ m^{-2} $month^{-1}$.

A relatively poor correlation between ΔT_{MA} patterns and ENSO activity and an insignificant influence of ΔT on ΔGPP and ΔET can be mainly explained by the small intra-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 intra-annual course between 19.5 °C 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. As is was already mentioned even during the El Niño culmination in 2005-2006 the ET/PET did not

decrease below 0.74, $(ET/PET)_{MA}$>0.81, and the relative soil water content of the upper 30 cm horizon was always higher than 80%.

The analysis of absolute and relative changes of GPP and ET during the periods of maximal El Niño and La Niña activities showed that GPP during the El Niño culminations of 2005 and 2007 increased by about 20 g_C m^{-2} $month^{-1}$ (6-7%). ΔGPP_{MA} was about 9 g_C m^{-2} $month^{-1}$ (2-3%), ΔET - about 40 mm $month^{-1}$ (about 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 (Figure 2). The maximal ΔET was equal to the annual amplitude of ET (Figure 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 g_C m^{-2} $month^{-1}$ (8%), ΔGPP_{MA} - about -12 g_C m^{-2} $month^{-1}$ (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. Interestingly the radiation dependent GPP (as represented by smoothed 7 month mean) does not demonstrate any prolonged constant period during La Nina phases though the radiation does. During the first cold event the GPP-reduction is not as strong as during the second one, although the G-reductions are nearly of same strength. It could be assumed that in the first case the effect of radiation decrease on GPP was compensated by other factors like slight increase of the air temperature.

Additionally, we investigated the influence of other climatic anomalies in the region on CO_2 and H_2O fluxes of the tropical rainforest, 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 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~~ all 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.

Our case study showed a high sensitivity of the main components of CO_2 and H_2O fluxes of the investigated mountainous tropical rainforest in Bariri to El Niño and La Niña phenomena as well as a low sensitivity to IOD and MJO events. The time lag between the respective indices and their effect on the fluxes at our site indicates that the timing and the extent of the effects are site specific. The fluxes respond to the local weather and only indirectly to the large scale weather anomalies, i.e. in the way the local weather is affected by the large scale weather phenomena. The observed phenomena are thus not representative for all mountainous forest sites in the tropics. The conclusion is that large scale weather anomalies do have systematic effects on local fluxes but the timing and the extent are likely to differ across different regions.

Even though remote sensing analyses have shown that the site is representative for the region (Ibrom et al. 2007, Popastin et al. 2012), the response to ENSO might differ in the region dues to differences in altitude and land-use (Erasmi et al. 2009). In general, anthropogenic deforestation has removed most parts of lowland forests so that the remaining forest cover consists mostly of mountainous forests. At the moment, there are no other FLUXNET sites situated in equatorial mountainous rainforests of South-East Asia with which we could directly compare our findings and investigate whether similar response to ENSO can be observed. Most of the existing FLUXNET sites (AsiaFlux) are not comparable with the investigated site as they are situated in subequatorial and tropical climate zones. These are characterized by higher seasonality of air temperature and precipitation compared to our equatorial site. Thus, our site provides a unique opportunity to investigative the response of an equatorial mountainous rainforest to ENSO in the Western pacific region.

5. Conclusions

CO_2 and H_2O fluxes in the mountainous tropical rainforest in Central Sulawesi in Indonesia showed a high sensitivity of monthly GPP and ET to ENSO intensity for the period from January 2004 to June 2008. This was mainly governed by the high dependency of incoming solar radiation (*G*) to Nino4 and Nino3.4 SST changes and the strong sensitivity of GPP and ET on *G*.

Interestingly, we observed time shifts between the SST anomalies and smoothed GPP anomalies driven by radiation anomalies. The maximal deviations of GPP and G from their mean values occurred 2-3 months before the peak phase of the ENSO events. The effect of ENSO intensity on ecosystem respiration, RE, was relatively low, mainly due to its weak effect on air temperature. Anyway, the small cross-correlation between RE and ENSO intensity had a compensatory effect on the respective timing of NEE, which thus was - like evapotranspiration - in synchrony with El Niño culminations. -Unlike the observations in other tropical sites, precipitation variations had no influence on the CO_2 and H_2O fluxes at study site, mainly due to the permanently sufficient soil moisture condition in the study area.

Other climatic anomalies in the Western Pacific region, such as the Indian Ocean Dipole and the Madden–Julian oscillation, did not show any significant effect on neither the meteorological conditions nor the CO_2 and H_2O fluxes in the investigated ~~mountainous tropical~~ rainforest in Central Sulawesi.

It is important to emphasise that the ~~considered~~ observation period does not cover any period with extreme El Niño events, such as, e.g., the 1982-83 and 1997-98 events, when the anomaly of Nino3.4 SST, during several months, exceeded 2.6°C and more significant changes of surface water availability were observed. Also, in lowland parts of Sulawesi, characterised by higher temperatures and lower precipitation, the vegetation response to ENSO events is likely to be different and more pronounced (Erasmi et al., 2009).

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 suggest an increased future likelihood of both El Niño and La Niña events. Based on the results of our study, potential increases in ENSO activity would results in an increased variability of the CO_2 and H_2O exchange between atmosphere and the tropical rainforests in ~~such~~ these and similar regions.

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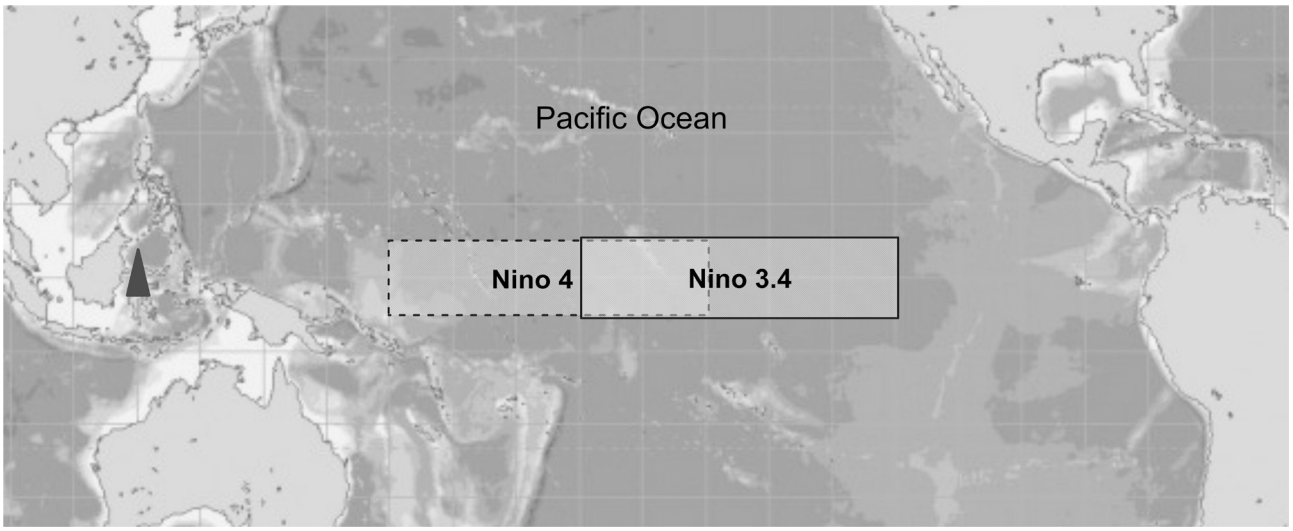

Figure 1. Geographical location of a study area (marked by black triangle) in tropical rain forest in Central Sulawesi (Indonesia) and Nino4 and Nino3.4 regions.

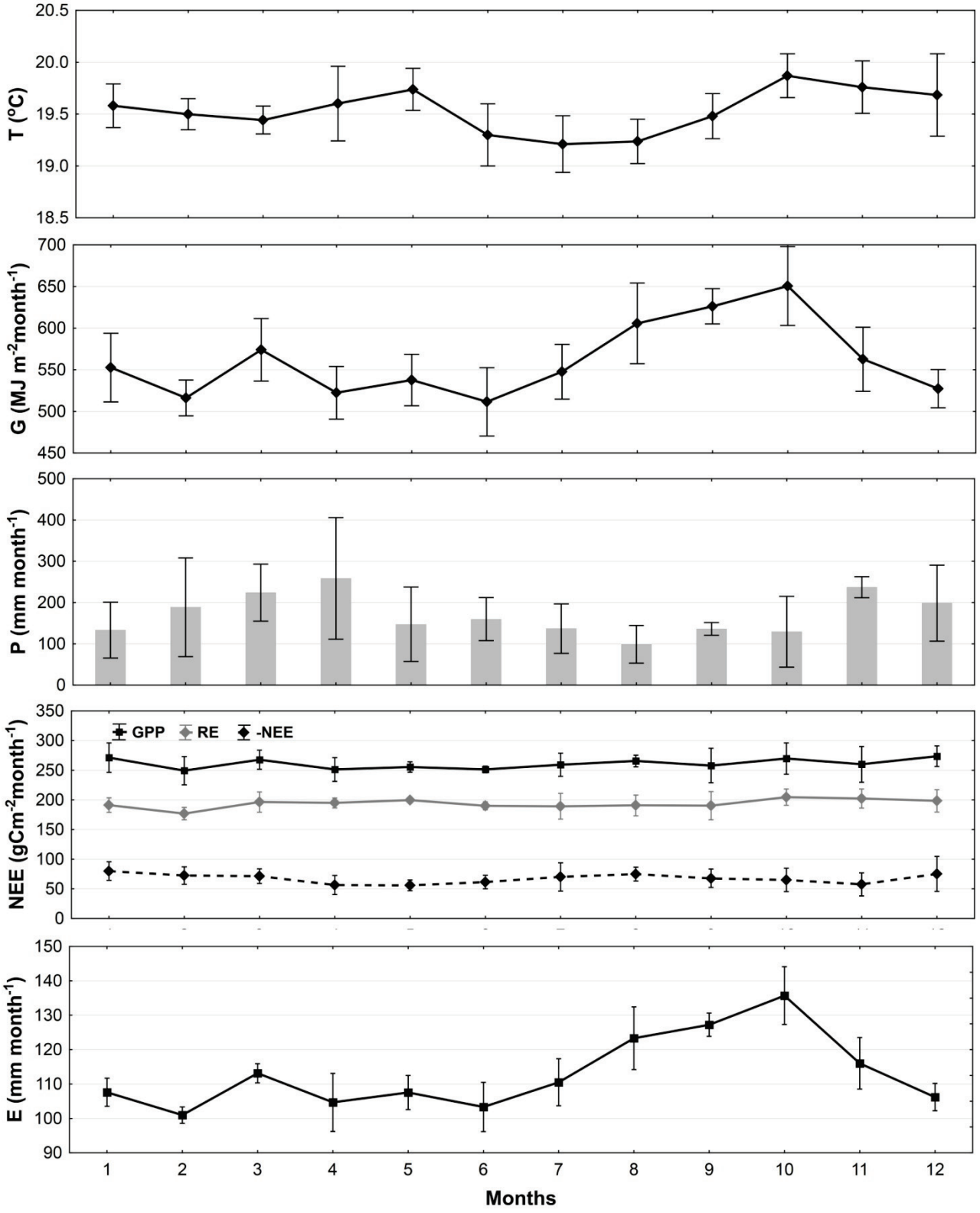

Figure 2. Mean intra-annual courses of air temperature (T), global solar radiation (G), precipitation (P), NEE, GPP, RE and ET for the tropical rain forest in Bariri. Vertical whiskers indicate standard deviations (SD).

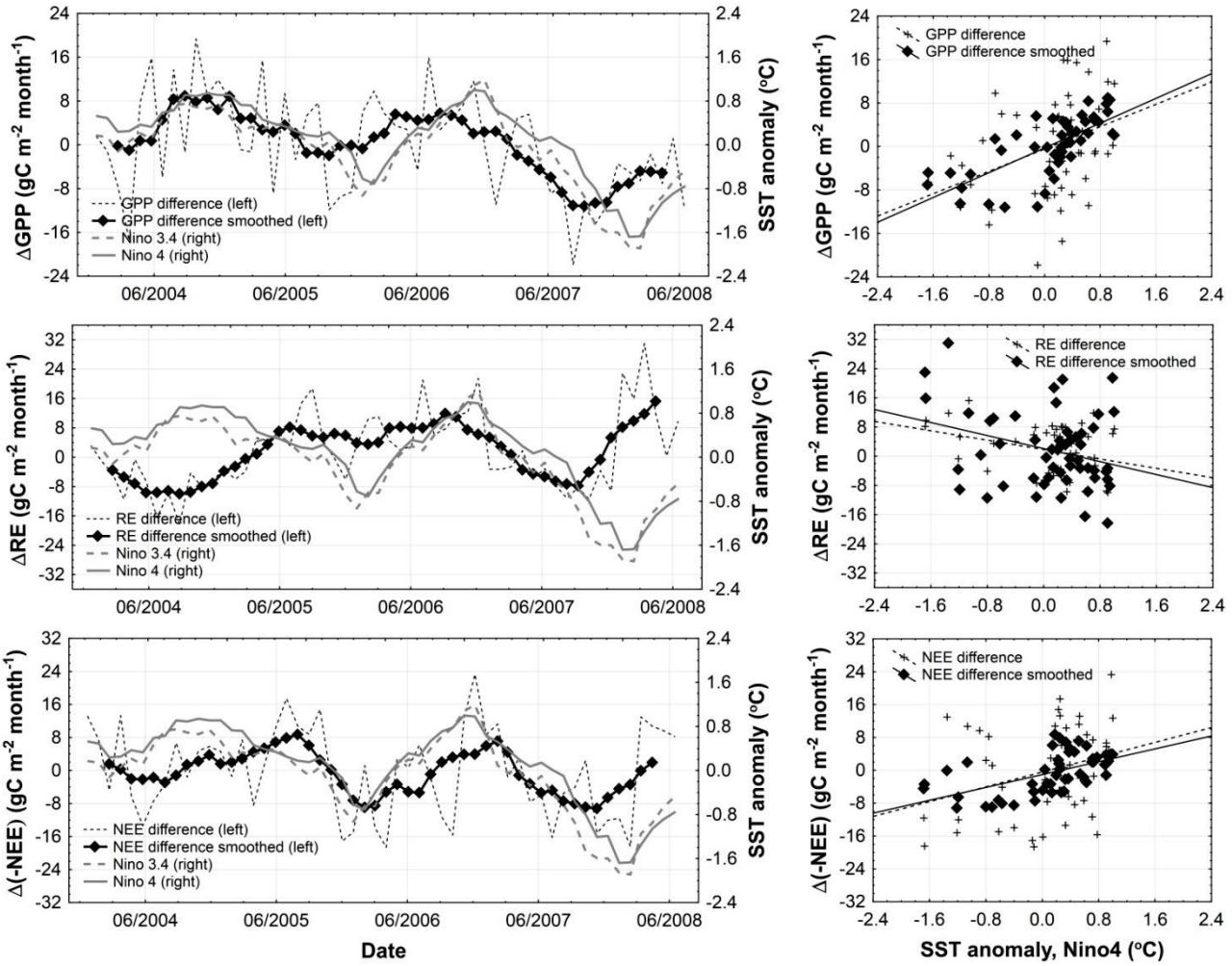

Figure 3. Comparisons of inter-annual pattern of SST anomalies in Nino4 and Nino3.4 zones of equatorial Pacific with variability of both deviations and 7 month (±3 months) moving average deviations of monthly GPP, RE and NEE values from mean monthly values of GPP, RE and NEE averaged over the entire measuring period from 2004 to 2008.

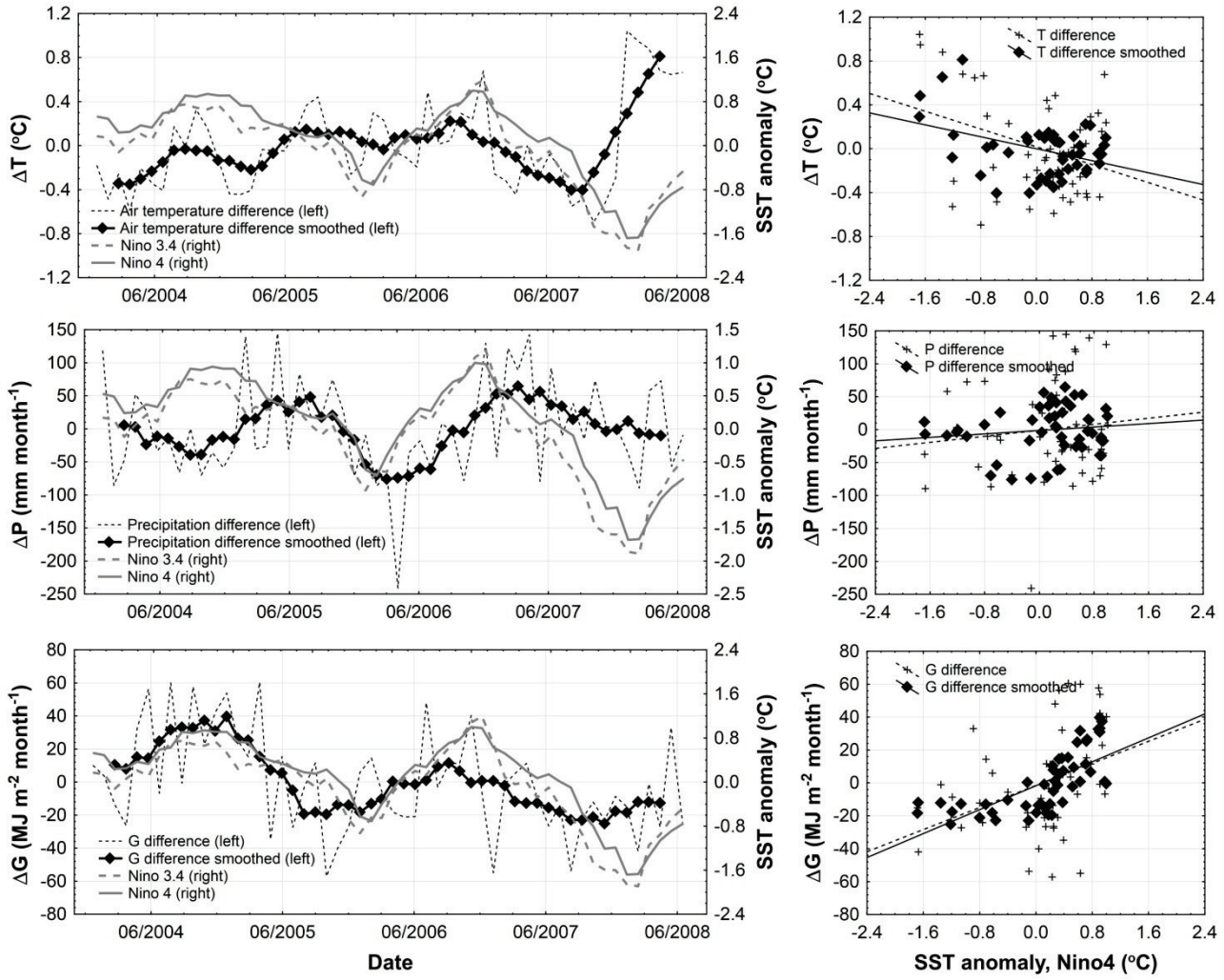

Figure 4. Comparisons of inter-annual pattern of SST anomalies in Nino4 and Nino3.4 zones of equatorial Pacific with variability of both deviations and 7 month (±3 months) moving average deviations of monthly air temperature (T), precipitation (P) and global radiation (G) values from mean monthly values of T, P and G averaged over the entire measuring period from 2004 to 2008.

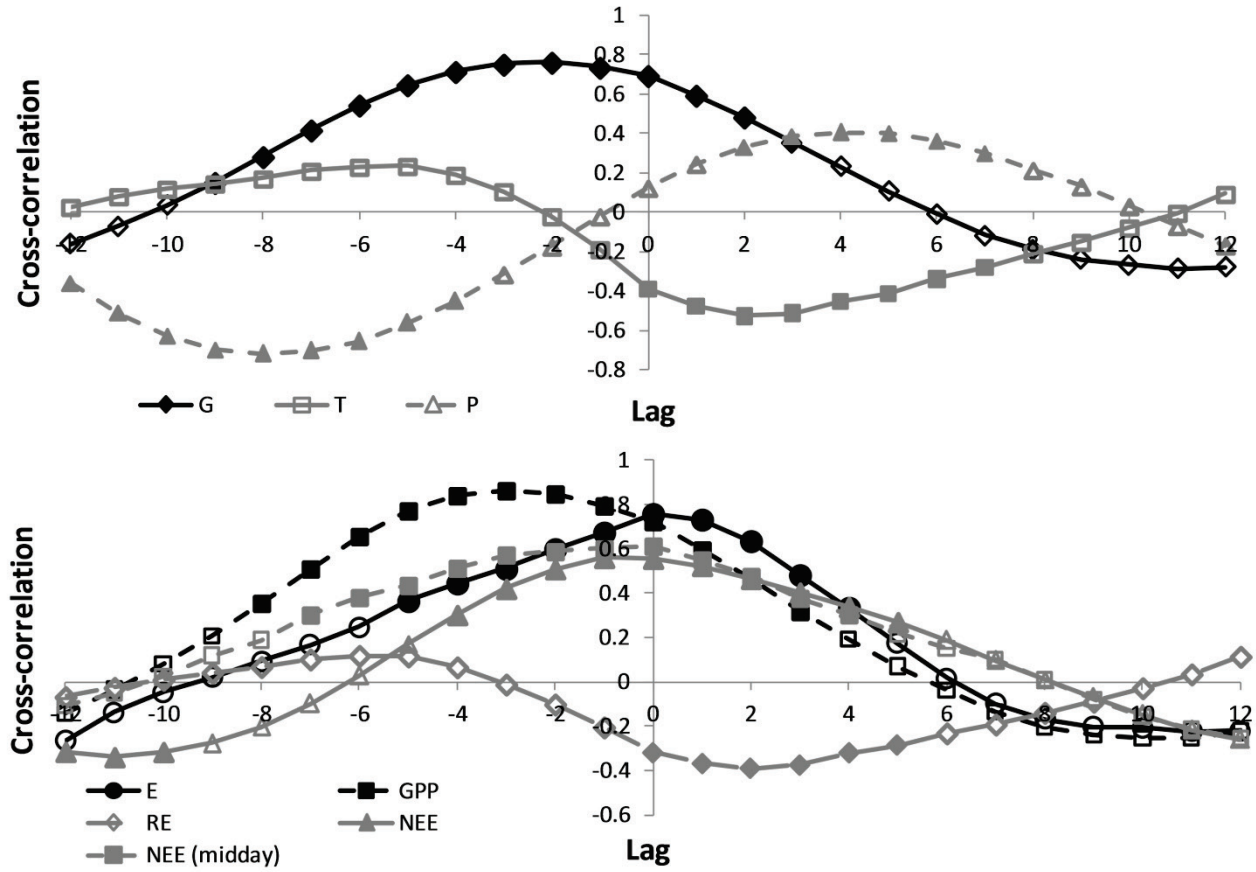

Figure 5. Cross-correlation functions between ΔG_{MA}, ΔT_{MA}, ΔP_{MA}, ΔE_{MA}, ΔGPP_{MA}, ΔRE_{MA}, ΔNEE_{MA} and midday ΔNEE_{MA} values and SST anomalies in Nino4 zone of equatorial Pacific. Filled symbols are corresponded to p-value <0.05 and non-filled symbols - to p>0.05. Lag step is 1 month.

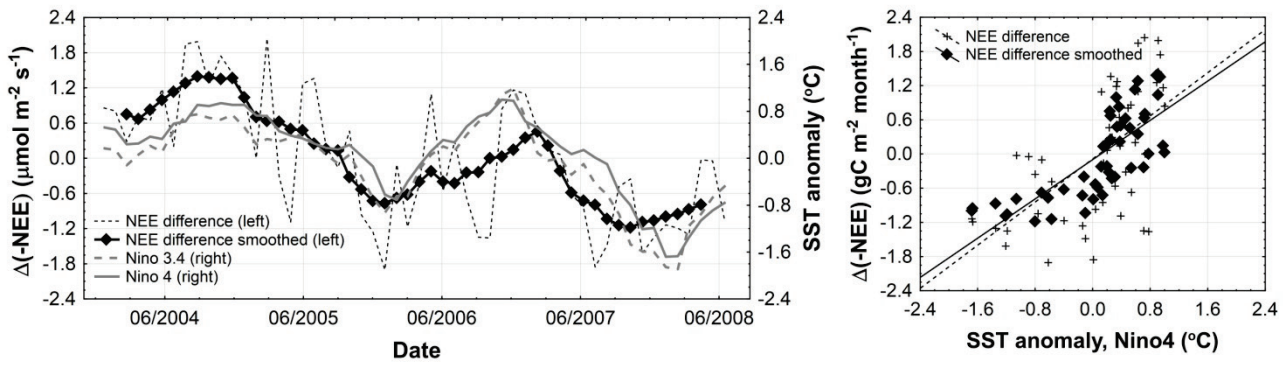

Figure 6. Comparisons of inter-annual pattern of SST anomalies in Nino4 and Nino3.4 zones of equatorial Pacific with variability of both deviations and 7 month (±3 months) moving average deviations of midday NEE (10:00-14:00) values from mean monthly midday values of NEE averaged over the entire measuring period from 2004 to 2008.

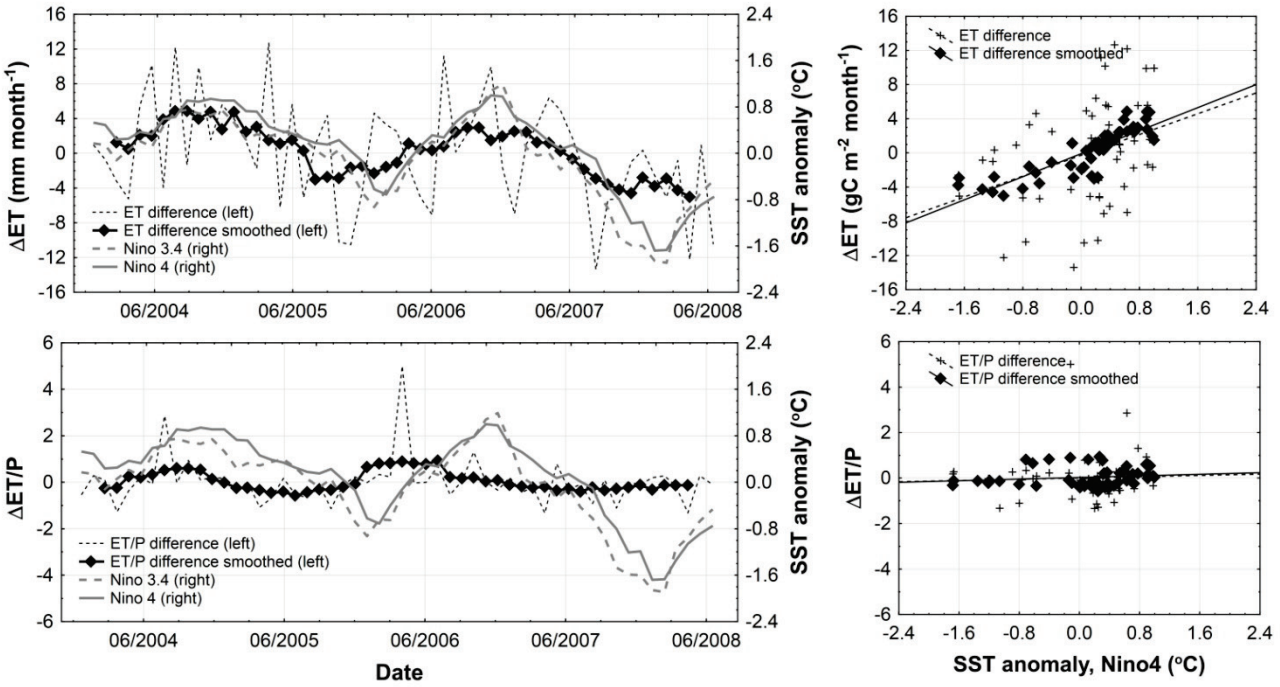

Figure 7. Comparisons of inter-annual pattern of SST anomalies in Nino4 and Nino3.4 zones of equatorial Pacific with variability of both deviations and 7 month (±3 months) moving average deviations of monthly ET rate and ratio ET/P from mean monthly ET rate and ET/P averaged over the entire measuring period from 2004 to 2008.