

Equatorial Atmospheric Variability Modulates Carbon and Energy Fluxes in a Wallacean Tropical

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Abstract

Wet tropical montane forests are critical components of the global carbon cycle; however, conventional seasonal indices often oversimplify the responses of these forests to climate anomalies. Prevailing perspectives suggest that extreme droughts, such as those induced by the El Niño–Southern Oscillation (ENSO), consistently reduce the carbon sink capacity of tropical forests. This study challenges this generalization by applying a novel methodological approach: space–time wavenumber–frequency filtering of high-resolution eddy covariance data (2013–2017) from Tropical rain forest Lore Lindu, Indonesia. This technique enables the separation of high-frequency synoptic influences from the Madden–Julian Oscillation (MJO), Kelvin Waves (KW), and Equatorial

Rossby Waves (ERW) from background climate conditions. The findings indicate weak daily coupling between carbon assimilation and Latent Heat Flux (LE), with gross primary production (GPP) variability more strongly linked to incoming shortwave radiation. Surface-layer soil moisture from ECWWF ERA5-Land remained relatively high throughout most of the observation period, further supporting the conclusion that short-term carbon flux variability at this site is primarily driven by energy availability. Convective phases associated with the MJO and ERW coincided with reduced incoming radiation and lower GPP. In contrast, the GPP response to Kelvin Wave passage varied with background ENSO state: during the 2015–2016 El Niño, positive GPP anomalies were observed around peak KW passage, whereas under normal and La Niña conditions, the response was predominantly negative. These results underscore the significance of high-frequency equatorial atmospheric variability in modulating ecosystem carbon and energy fluxes and suggest that synoptic-scale processes can alter ecosystem responses within broader seasonal climate anomalies.

Keywords: "Carbon-water decoupling", "Convectively coupled equatorial waves", "Tropical montane forest, light limitation, Maritime Continent.

1. INTRODUCTION

The understanding of carbon fluxes in tropical ecosystems has been greatly enhanced via technological developments in observational techniques, such as Eddy Covariance (EC) system, and by the use of reanalysis-based modelling. A major area of research has examined the dynamics of Gross Primary Production (GPP), Net Ecosystem Exchange (NEE), and Ecosystem Respiration (R_{eco}) in relation to tropical atmospheric variability, such as the MJO, KW, ERW, and ENSO.

The basic methods for separating the photosynthetic and respiratory components from NEE data were first developed by Baldocchi (2003) and Reichstein et al. (2005). These studies confirmed that the EC system dataset could be used as a reliable means of quantitatively measuring carbon fluxes. However, there are problems with applying these techniques in tropical areas due to the highly changing nature of both vegetation and climate.

In recent years, research has increasingly focused on the complex interactions between mesoscale atmospheric variability and ecosystem biological responses. Current flux estimates for tropical regions, including Indonesia, frequently diverge from national reports, highlighting the need for robust ground-based verification to address the limited spatial and temporal resolution of satellite observations (Heinrich et al., 2023; Misiukas et al., 2021). Accurate estimation of carbon and water fluxes requires consideration of seasonal, intraseasonal, and diurnal cycles of radiation and atmospheric moisture demand (Gnanamoorthy et al., 2022; Lu et al., 2024). For instance, in Tropical Montane Cloud Forests (TMCFs), persistent fog and reduced radiation lead to lower rates of carbon assimilation and transpiration than in lowland forests, while also affecting overall water productivity and efficiency

(Gnanamoorthy et al., 2022; Gotsch et al., 2016). These factors underscore the value of site-specific EC data, such as those collected at the Bariri Flux Site (BFS) in Lore Lindu National Park, Sulawesi, Indonesia.

On a wider timescale, climate extremes, changes in vegetation, and year-to-year anomalies collectively determine the terrestrial net ecosystem exchange of CO₂, thereby fundamentally affecting carbon stores and atmospheric greenhouse gas concentrations (Mamkin et al., 2022; Schaefer et al., 2002; Zhang et al., 2025). The impact of ENSO on regional carbon and water cycles is especially marked but highly dependent on specific circumstances (Pereira et al., 2020; Takamura et al., 2023). Although the different phases of ENSO are usually linked to changes in annual gross ecosystem exchange (Zhang et al., 2011), ecosystem responses to extreme drought events vary with regional climatic conditions. For instance, in equatorial Indonesia, the 2015–2016 El Niño caused a pronounced increase in solar radiation and air temperature, along with variable precipitation (Gushchina et al., 2019). Unexpectedly, under these severe conditions, evapotranspiration and GPP increased in some tropical mountainous rainforests, while ecosystem respiration remained largely unchanged (Olchev et al., 2015). Even when ENSO drives severe moisture deficits, ecosystems may still function as limited carbon sinks (Pereira et al., 2020), highlighting the complex, non-linear associations among sea surface temperatures, atmospheric forcing, and the terrestrial carbon cycle.

While the effects of ENSO and other large-scale climate anomalies on tropical carbon exchange are well established, the role of higher-frequency equatorial atmospheric fluctuations in modulating ecosystem fluxes within these background climate states remains less understood. Monthly and seasonal climate indices may mask transient responses linked to changes in convection, radiation, and atmospheric moisture demand. This study integrates continuous Eddy Covariance observations with space–time wavenumber–frequency filtering Outgoing Long-range Radiation (OLR), and Superposed Epoch Analysis to investigate the influence of the MJO, KW, and ERW on carbon and energy fluxes in a Wallacean tropical montane forest. The research specifically addresses whether (1) short-term GPP variability is more closely associated with radiation or LE flux, (2) ecosystem carbon and energy fluxes respond systematically to equatorial atmospheric disturbances, and (3) the response to KW differs between El Niño and non-El Niño background conditions. This approach enables the resolution of ecosystem responses on timescales shorter than those typically captured by seasonal climate indices.

2. DATA AND METHOD

2.1. The general approach and conceptual framework

We employed daily interpolated Outgoing Longwave Radiation (OLR) data from NOAA (<https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html>), covering the global domain (0–360° longitude) for the period 2013–2017. To derive anomalies, each daily OLR value was subtracted from the corresponding long-term

mean (LTM) for the same calendar day. For example, the observed OLR on 5 December 2013 was compared against the climatological mean OLR for 5 December from the LTM dataset.

Because tropical forest canopies exhibit highly nonlinear, lagged responses to synoptic and intraseasonal weather anomalies (e.g., shifts from water-limitation to light-limitation), standard linear regression approaches are insufficient. Therefore, our procedure relies on extracting daily meteorological anomalies, using the Super Epoch Analyses (SEA) technique to capture temporal lags, and partial correlation networks to isolate the independent drivers of GPP and NEE.

2.2. In-situ Flux Data and Pre-processing

EC dataset and micrometeorological observations were obtained from the Bariri Flux Site (BFS) in Lore Lindu National Park, Central Sulawesi, Indonesia (1°39.476' S, 120°10.409' E; 1416 m a.s.l.). BFS is part of the Stability of Rainforest Margins in Indonesia (STORMA) project, funded by the German Research Foundation (DFG) (Falk et al., 2005; Olchev et al., 2015). Continuous half-hourly observations covering December 2013 to April 2017 were used in this study, encompassing the strong 2015–2016 El Niño event. This time period was chosen because it includes a wide range of weather extremes, particularly the intense El Niño event from 2015 to 2016 (Caruthers, 2017).

Quality control of the BFS Flux Tower data followed the standard FLUXNET protocol, which includes applying FLUXNET quality flags and adhering to established guidelines (Pastorello et al., 2020), as well as statistical thresholding and outlier detection procedures (see documentation at <https://flux-data-qaqc.readthedocs.io/en/latest/>). In the output files, the variable *qc_flag* indicates the quality of the flux data. These flags are derived from two canonical tests in the EC system: the steady-state test, which evaluates whether turbulence remains sufficiently stable during the averaging period, and the developed turbulent conditions test, which assesses whether turbulence is adequately evolved to yield representative fluxes (Göckede et al., 2006; Mauder & Foken, 2006). Each test assigns a score ranging from 1 (best) to 9 (worst), and software integrates the results into a single *qc_flag* for each flux: CO₂, H₂O, momentum, sensible heat, and latent heat. Flags 1–2 denote high-quality data suitable for direct use; flags 3–6 indicate intermediate quality, acceptable with caution (e.g., for seasonal analyses but not for precision flux calculations); while flags 7–9 correspond to poor data that should be excluded from further analysis. All flux measurements were standardized to micromoles per square meter per second and subsequently merged into a single dataset for analysis.

The half-hourly NEE data were partitioned into GPP and R_{eco} using the standard flux-partitioning algorithms developed by the FLUXNET community (Reichstein et al., 2005). To correspond to the temporal resolution of the macro-climatic indices, all half-hourly variables—including LE, H, and various meteorological parameters—were aggregated to daily time steps.

2.3. The extraction of the macroclimatic and equatorial wave indices

R_{eco} was determined using a non-parametric Random Forest (RF; Breiman, 2001) algorithm with the nighttime partitioning method, based on the assumption that nighttime NEE equals R_{eco} when GPP is zero (Reichstein et al., 2005). The RF model was trained on nighttime air temperature data $R_{eco} = f(T_{air})$ and then applied to daytime temperature data to predict daytime R_{eco} . GPP was calculated using the equation $GPP = NEE_{obs} - R_{eco_predicted}$, with physical constraints being applied so that $R_{eco} \geq 0$ and $GPP \leq 0$. The RF method was chosen over traditional parametric equations for its greater ability to identify complex, non-linear relationships and saturation patterns driven by humidity fluctuations, thereby reducing the root-mean-square error (RMSE).

Because of significant gaps in the in situ measurements of incoming global radiation, we used a gap-filling method that relied on satellite-derived daily OLR as a proxy. A linear regression model was developed over overlapping observation periods (with an R^2 of approximately 0.28), enabling us to continuously estimate the extent to which surface shortwave radiation is attenuated by local convective cloud cover. To separate the effects of temporary weather events from those of the natural seasonal cycle, all daily variables were transformed into daily anomalies. This was done by determining a daily climatological baseline (that is, the multi-year average for each day of the year) and then subtracting this baseline from the actual observed daily values. The interannual climate background phase was determined using the Niño 3.4 Sea Surface Temperature (SST) index; the period from May 2015 to May 2016 was classified as the active El Niño (Wang et al., 2025).

2.4. The statistical analyses carried out on ecosystem decoupling

2.4.1. Superposed Epoch Analysis (also known as Composite Analysis)

To investigate the hypothesized decoupling of carbon and water fluxes in the wet tropical montane forest at Lore Lindu, EC measurements were integrated with a complete satellite-derived outgoing longwave radiation dataset, serving as a large-scale climatic index. Given that tropical forest canopies exhibit highly nonlinear and lagged responses to synoptic and intraseasonal weather anomalies, conventional linear regression methods are insufficient. The MJO was monitored using the daily Real-time Multivariate MJO (RMM) index (M. C. Wheeler & Hendon, 2004), which makes use of both its phase (1–8) and amplitude to indicate the presence of active intraseasonal convection over the Maritime Continent (in particular during Phases 3, 4, and 5). To detect the passage of high-frequency convectively coupled equatorial waves—namely, the KW and ERW—space-time wavenumber-frequency filtering was applied to daily global OLR data, following the original method of Wheeler & Kiladis (1999). This spectral filter isolates specific wavenumber-frequency bands, such as wavenumbers 1–14 for Kelvin waves,

following established atmospheric wave analysis standards. After global filtering, the dataset was spatially subset to extract the grid point corresponding to Lore Lindu (1.5° S, 120° E), yielding a localized time series for further analysis.

The KW were identified by filtering for signals travelling eastward with a zonal wavenumber between 1 and 14 and a period ranging from 2.5 to 30 days, while the ERW were identified by filtering for signals travelling westward with a zonal wavenumber between 1 and 10 and a period between 5 and 48 days. The global filtered OLR anomalies were then selected to correspond to the nearest grid point with coordinates matching those of the BSF tower. A wave was regarded as being active at the study site when the local OLR anomaly it caused fell below -1.0 standard deviation, which signified the passage of the wave's wet/convective phase.

To formally quantify the dynamic, lagged responses of carbon and water fluxes to the discrete passage of equatorial waves, we approached the Superposed Epoch Analysis (SEA) technique (Rammig et al., 2015; Rao et al., 2019). SEA isolates the true physiological signal from background ecological noise by aligning and averaging time-series data around predefined key events.

In this study, the key event day (t_0 or Lag 0) was designated as the peak convective passage of the KW or ERW over Lore Lindu, identified when the localized OLR anomaly reached its minimum threshold. For a defined set of N independent wave events, a temporal window was extracted for each event i , ranging from Lag -5 to Lag +5 days ($k \in [-5, +5]$). If $X_{i,k}$ represents the flux anomaly (e.g., GPP or NEE) for event i at lag k , the composite mean C_k for each specific lag value was calculated using the following equation:

$$C_k = \frac{1}{N} \sum_{i=1}^N X_{i,k} \quad (1)$$

where N is the total number of independent wave events observed ($n = 100$ for KW and $n = 60$ for ERW).

To ensure statistical robustness and to overcome the inherent autocorrelation in daily micro-meteorological data, the SEA framework evaluates the significance of C_k by comparing it with background variability (Rao et al., 2019). Furthermore, to investigate the modulating effect of the ENSO background state, the KW composite dataset (N_{KW}) was explicitly stratified into two discrete subpopulations: events occurring during the 2015–2016 El Niño drought and events occurring under normal or La Niña conditions.

2.4.2. Partial Correlation Matrix

To quantitatively verify the decoupling of carbon and water fluxes, a partial correlation analysis was conducted. Unlike the simple Pearson correlation, which can be greatly influenced by confounding multicollinear variables (for

example, a storm that causes both low light and high humidity), partial correlation assesses the intrinsic linear relationship between two variables while accounting for the effects of all other defined variables. The formula for the partial correlation between two variables (X) and (Y), controlling for a third variable (Z), is:

$$\rho_{XY.Z} = \frac{\rho_{XY} - \rho_{XZ}\rho_{YZ}}{\sqrt{(1 - \rho_{XZ}^2)(1 - \rho_{YZ}^2)}} \quad (2)$$

The partial correlation of (X) and (Y) given (Z) is denoted by $\rho_{XY.Z}$; ρ_{XY} represents the bivariate correlation between (X) and (Y); ρ_{XZ} is the bivariate correlation between (X) and (Z); and ρ_{YZ} is the bivariate correlation between (Y) and (Z). This formula gives the association between (X) and (Y) after the linear effects of (Z) have been removed from both (X) and (Y). The partial correlation coefficients (r_p) together with their corresponding p -values were obtained from the inverse covariance (precision) matrix of the master dataset. We examined the relationship between GPP/NEE anomalies, LE anomalies, and water status (LE-H) anomalies (June, 2022), while holding global radiation, MJO amplitude, KW anomalies, and ERW anomalies constant. An insignificant partial correlation between GPP and LE, together with a highly significant partial correlation between GPP and radiation, was taken as the primary statistical evidence that the canopy was light-limited rather than water-limited. That carbon assimilation was structurally decoupled from evapotranspiration dynamics.

3. RESULTS

3.1. Contrasting associations of GPP with latent heat flux and shortwave radiation

Partial correlation analysis revealed a weak and statistically non-significant association between daily GPP and LE anomalies (correlation coefficients (r_p) = 0.047, p = 0.102), whereas GPP was positively associated with global shortwave radiation anomalies (r_p = 0.264, p < 0.001). These contrasting relationships indicate that short-term variation in carbon assimilation was more closely associated with incoming radiation than with LE during the observation period (Figure 1).

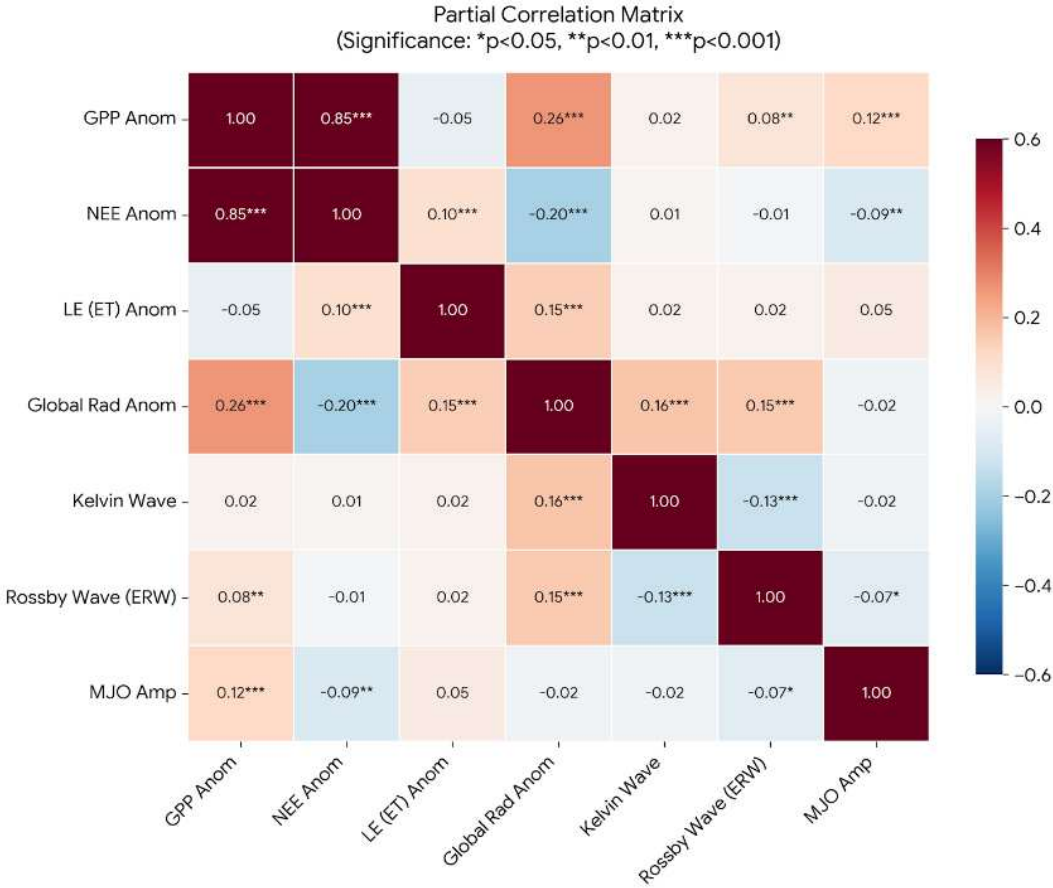


FIGURE 1: The partial correlation matrix for the daily carbon fluxes, water fluxes, and meteorological drivers at Lore Lindu National Park from 2013 to 2017. The matrix displays the intrinsic linear relationships between the anomalies of GPP, NEE, LE, global shortwave radiation, and the amplitudes of the MJO, KW, and ERW. The r_p were obtained using an inverse covariance (precision) matrix that accounts for the effects of all other variables simultaneously. Asterisks indicate statistical significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

3.2. Intraseasonal Variation and Equatorial Waves

The Superposed Epoch Analysis showed that the convective (wet) stages of the MJO—typically stages 3 and 4 over the Maritime Continent—had a significant suppressive effect on both GPP and NEE; on the other hand, carbon assimilation reached its peak during the subsiding, drier phases (that is, phases 7, 8, and 1).

Maximum light penetration into the canopy occurred during extended periods of cloud-free conditions. Similarly, the passage of ERW caused a sharp decrease in GPP on the day of peak convective activity (Lag 0), followed by a rapid physiological recovery by Lag +3 to +4 days (Figure 2).

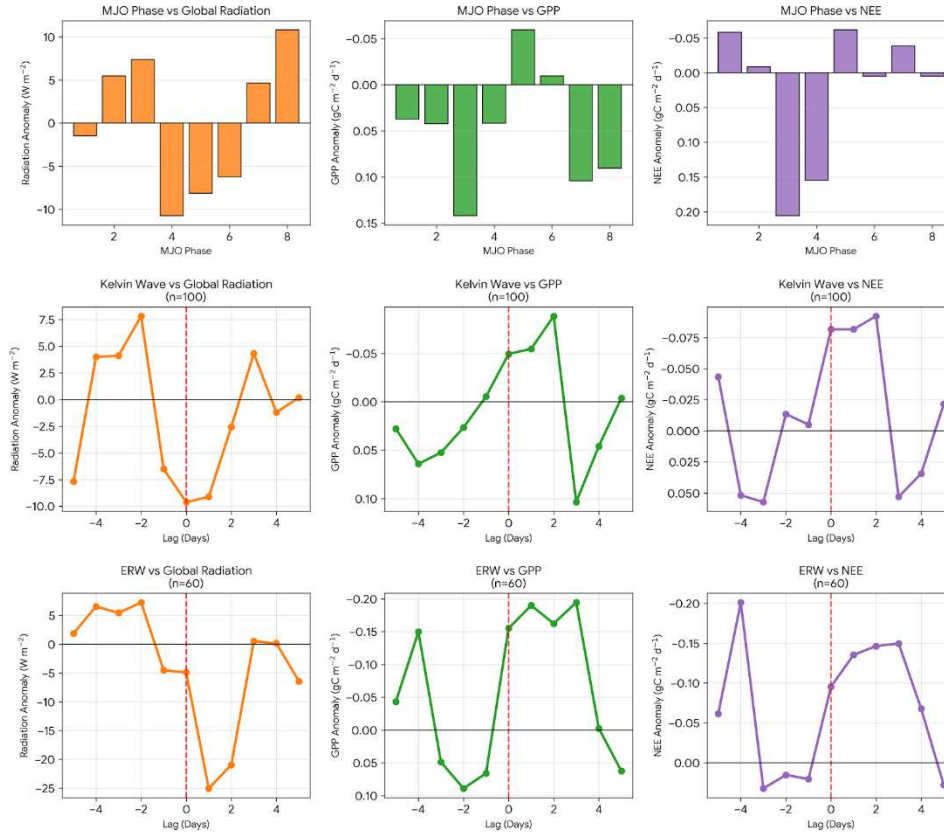


FIGURE 2: The combined responses of global radiation and carbon fluxes to multiscale tropical climate waves. The panels display the anomalies in incoming global radiation (in the left column, shown in orange), GPP (the middle column, shown in green), and NEE (the right column, shown in purple), with these responses modulated by the MJO (in the top row), KW (the middle row), and ERW (the bottom row). For the MJO, responses are grouped into its eight phases for cases with amplitudes greater than 1. The responses to KW (with $n = 100$) and ERW (with $n = 60$) are based on a Superposed Epoch Analysis (SEA) centred on the peak.

The active convective flow (Lag 0) is indicated by dashed red lines; the y-axes for GPP and NEE have been inverted, with upward trends indicating greater ecosystem carbon assimilation. At Lag 0, when the Kelvin Wave arrives, the solar radiation anomaly drops sharply into negative values, and the LE also falls. Even though there is a reduction in solar radiation, the Gross Primary Production on Days 0, +1, and +2 does in fact rise (that is, it absorbs more CO_2). To better understand how energy is distributed, we examined anomalies in the difference between latent and sensible heat fluxes (LE-H). During the convective phases of the MJO and at the point when both the Kelvin and Equatorial Rossby Waves reach their peak (Lag 0), Figure 3 displays a noticeable decrease in the LE-H anomalies, this decline occurring at the same time as the strong negative radiation anomalies shown in Figure 2.

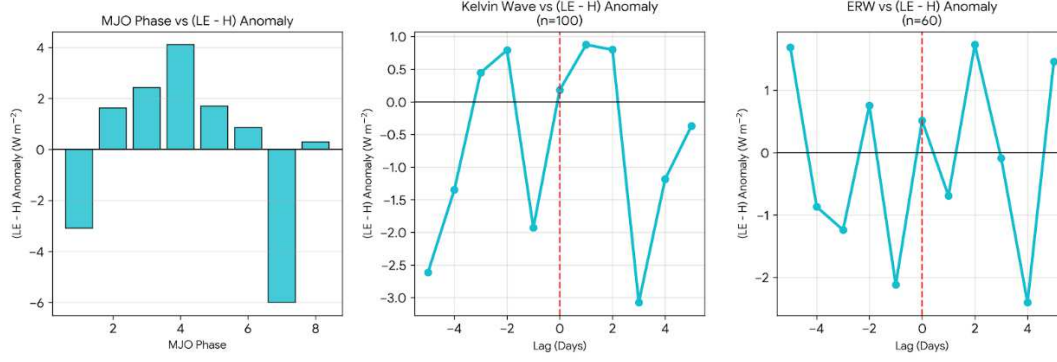


FIGURE 3: A superposed-epoch analysis (SEA) of anomalies in ecosystem energy partitioning (LE-H) associated with the passage of convectively coupled equatorial waves. The panels display the difference between anomalies in LE and H (cyan) for the eight phases of the MJO on the left, for KW in the middle ($n = 100$), and for ERW on the right ($n = 60$). In the cases of KW and ERW, Lag 0 (red dashed lines) corresponds to the day when the peak convective wave passes. A decrease in LE-H indicates a sharp reduction in the energy available for evapotranspiration.

3.3. ENSO-dependent carbon-flux responses to Kelvin Wave passage

Stratifying KW events by background ENSO state revealed contrasting GPP responses (Figure 4). During the 2015–2016 El Niño period ($n = 34$ events), positive GPP anomalies occurred around Lag 0 and Lag +1. In contrast, KW events occurring under normal and La Niña conditions ($n = 66$) were predominantly associated with negative GPP anomalies around peak wave passage. This pattern suggests that the ecosystem response to KW-associated convection depended on the background ENSO state.

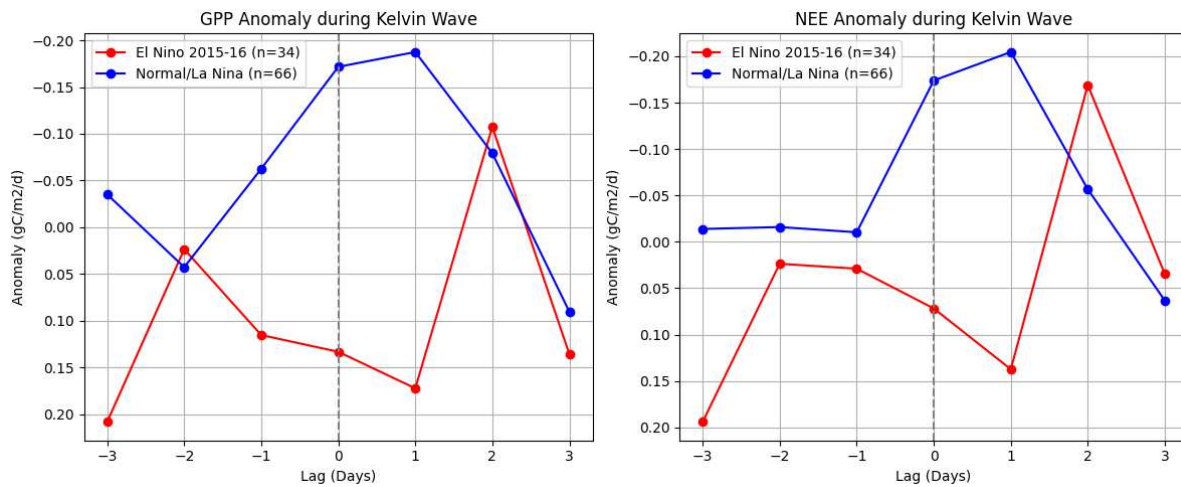


FIGURE 4: The divergent responses of canopy carbon flux to passages of a KW, depending on the background ENSO state. The Superposed Epoch Analysis compares the anomalies in GPP (left) and NEE (right) for KW events

that took place during the severe 2015–2016 El Niño drought (indicated by the red lines, $n = 34$) with those occurring under normal and La Niña conditions (the blue lines, $n = 66$). The lag of zero (gray dashed lines) corresponds to the peak of the active convective phase of the wave.

To statistically validate the divergent canopy responses observed during wave passage, we evaluated the Pearson correlation between the approaching-wave timeframe (Lag -2 to Lag +1) and the composite GPP anomalies. Under normal and La Niña conditions, GPP anomalies exhibited an exceptionally strong and statistically significant negative correlation with the approaching wave 0.9999 ($p = 0.001$), confirming a systematic suppression of photosynthesis. In contrast, during the 2015–2016 El Niño drought, the response trajectory diverged: rather than declining, the GPP anomaly increased, peaking positively towards the wave passage (from 0.085 at Lag -2 to 0.132 at Lag 0). This distinct statistical divergence demonstrates that background climatic conditions fundamentally modulate the ecosystem's deficient suppression to high-frequency equatorial waves, shifting the canopy from radiation-starved suppression to opportunistic carbon assimilation.

TABLE 1: Pearson correlation between the approaching wave timeframe (Lag -2 to Lag +1) and the composite GPP/NEE anomalies under El Niño and Normal/La Niña conditions.

	GPP	NEE
Actual Lag -3 to 0	El Nino: $r=0.285$, $p=0.7148$	El Nino: $r=0.300$, $p=0.7005$
	Normal: $r=-0.542$, $p=0.4577$	Normal: $r=-0.094$, $p=0.9057$
Actual Lag -2 to +1	El Nino: $r=-0.574$, $p=0.4258$	El Nino: $r=-0.781$, $p=0.2188$
	Normal: $r=-0.999$, $p=0.0015$	Normal: $r=-0.872$, $p=0.1279$

4. DISCUSSION

4.1. The limitation of light and the decoupling of the carbon-water fluxes

To determine whether water availability inherently constrains ecosystem fluxes, we evaluated the daily volumetric soil water content from the ERA5-Land dataset (Figure 5). Throughout the 2013–2017 observation period, soil moisture in the upper layers (0–28 cm) remained consistently high, averaging $0.38 \pm 0.04 \text{ m}^3/\text{m}^3$. Even during periods of reduced precipitation, soil water volume rarely dropped below thresholds that would induce severe physiological water stress. Consequently, carbon and water fluxes showed weak daily coupling, while GPP was significantly and positively associated with shortwave radiation anomalies ($r_p = 0.264$, $p < 0.001$). The persistence of a high baseline soil moisture, alongside strong radiation-driven flux responses, empirically supports

the premise that this tropical montane forest operates primarily as an energy-limited rather than water-limited ecosystem.

The permanent wilting point (PWP) threshold of $0.20 \text{ m}^3/\text{m}^3$ (Figure 5) was used as a conservative approximation representative of medium- to fine-textured tropical montane soils (e.g., loam to clay loam). This aligns with the default parameters for medium-textured soils in the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL) land surface model used by ERA5-Land, which assigns a PWP of approximately $0.171 \text{ m}^3/\text{m}^3$ (Balsamo et al., 2009). The 0.20 baseline visually demonstrates that even during the severe 2015–2016 El Niño, soil moisture rarely dropped below critical physiological limits for deep-rooted forest canopies.

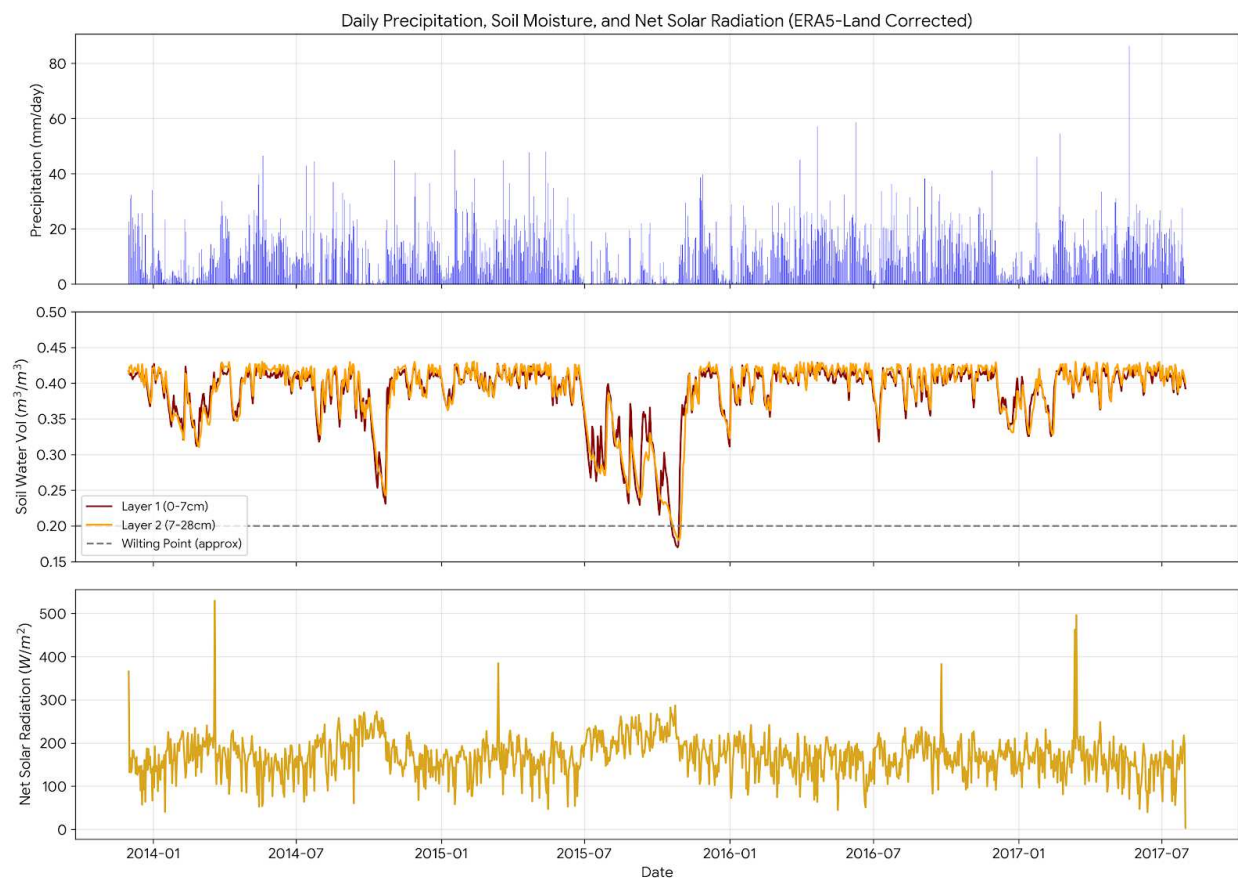


Figure 5: Temporal dynamics of daily precipitation, soil moisture, and net solar radiation at Lore Lindu National Park (2013–2017) derived from ERA5-Land reanalysis data. The panels display (top) daily total precipitation (mm/day, blue bars); (middle) volumetric soil water content (m^3/m^3) for Layer 1 (0–7 cm, dark red line) and Layer 2 (7–28 cm, orange line), and (bottom) daily average net surface solar radiation (W/m^2 , golden line). The dataset demonstrates that volumetric soil water consistently remained above the critical wilting point throughout the observation period, including during the severe 2015–2016 El Niño drought.

The partial-correlation results, together with the generally high surface-layer soil moisture, indicate that radiation was more strongly associated with short-term GPP variability than with LE or surface soil moisture during the observation period. This pattern is consistent with a strong influence of energy availability on short-term carbon assimilation at this wet tropical montane site, while not excluding episodic or deeper-root-zone water limitation that could not be resolved by the available data. This result supports and makes a fundamental contribution to the ideas put forward by Gotsch et al. (2015) and Gotsch et al. (2016). According to Gotsch et al. (2016), tropical montane cloud forests (TMCF) could be light-limited due to frequent fog and cloud cover; our study refines this hypothesis into a quantified, ecosystem-scale mechanism by showing that the convective phases of the MJO and ERW consistently reduce canopy photosynthesis through radiation starvation.

Furthermore, the energy-partitioning LE-H analysis provides evidence of periodic decoupling between carbon and water fluxes. In many agricultural regions and areas with seasonally limited water availability, a decrease in LE relative to H typically indicates increasing water stress and reduced evaporative cooling (June, 2022). In contrast, in the hyper-humid environment of Lore Lindu, the observed sharp reduction in LE-H is entirely attributable to radiation starvation. Extensive cloud cover associated with atmospheric disturbances restricts the energy available for evapotranspiration, illustrating that water flux dynamics and carbon assimilation are systematically decoupled from terrestrial water availability.

4.2. The resilience of an ecosystem compared with that at the leaf level

The sharp decrease in LE-H is entirely due to radiation starvation; the widespread cloud cover associated with atmospheric disturbances restricts the energy available to sustain evapotranspiration fluxes, indicating that the dynamics of water flux and carbon assimilation are systematically decoupled from the availability of terrestrial water.

At the ecosystem level, the decoupling of carbon and water fluxes differs markedly from the ecophysiological behaviours observed at the leaf and tree levels in recent studies. Brum et al. (2023) noted that when soil moisture is chronically deficient, trees exhibit strong isohydric regulation to avoid xylem embolism. Similarly, Eller et al. (2015) showed that leaf-wetting events greatly reduce transpiration. Our ecosystem-level results contradict the idea that conservative water-use behaviours observed at the tree level automatically imply that carbon uptake stops. Although Eller et al. (2015) attribute the reduction in fluxes solely to leaf-wetting and stomatal closure, our dataset attributes the overall decline in ecosystem GPP during the wave passage to radiation starvation.

On the other hand, even though studies like Gnanamoorthy et al. (2022) have placed a strong emphasis on ET and water flux as the main constraints upon ecosystem productivity, and while global assessments assume that large-scale drought events uniformly turn tropical forests into carbon sources (Worden et al., 2021), our results clearly contradict this broad generalization. The occurrence of a KW during the El Niño drought acts as a decoupling catalyst, allowing GPP to surge even while overall ET is suppressed, overriding severe soil moisture deficits (Brum et al., 2023).

4.3. Potential mechanisms underlying ENSO-dependent responses to Kelvin Waves

The contrasting GPP responses to KW passage under El Niño and non-El Niño conditions suggest that the ecological effect of a synoptic convective disturbance depends on the background atmospheric state. During El Niño, when radiation and atmospheric moisture demand can be elevated, transient increases in cloudiness associated with KW passage may temporarily alter the balance between radiation availability and atmospheric water demand. Such changes provide a plausible explanation for the positive GPP anomalies observed around the KW passage during the 2015–2016 event.

One possible mechanism is a temporary reduction in Vapor Pressure Deficit (VPD) associated with increased cloudiness. Changes in the direct-to-diffuse radiation ratio could also influence canopy-scale photosynthesis. However, because diffuse PAR and stomatal conductance were not measured directly in this study, these pathways remain mechanistic hypotheses rather than demonstrated processes. Future observations combining eddy-covariance fluxes with VPD, direct and diffuse radiation, and canopy physiological measurements would allow these mechanisms to be tested explicitly.

4.4. Methodological improvements and limitations

During the drought associated with El Niño, KW acts as a catalyst for decoupling, enabling GPP to rise even as total ET is suppressed, thereby overcoming severe soil moisture deficits (Brum et al., 2023). The high-frequency synoptic analysis that we have carried out offers a significant mechanistic improvement on the macroscale regional El Niño observations published by Olchev et al. (2015) and Gushchina et al. (2019). As Gushchina et al. (2019) noted, there was a dramatic rise in solar radiation and temperatures during the 2015–2016 El Niño, whereas Olchev et al. (2015) found a similar seasonal increase in gross primary production due to reduced cloud cover.

The peak levels of radiation documented by Gushchina et al. (2019) eventually cause the canopy to suffer from severe VPD stress, leading to hydraulic-safety-induced stomatal closure. More significantly still, these results contradict those of Gotsch et al. (2015), who noted the extreme vulnerability of montane ecosystems to atmospheric moisture deficits during the dry season. Our analysis over time shows that temporary cloud cover caused by equatorial waves can quickly reduce VPD and transform intense direct sunlight into diffuse PAR that penetrates the canopy. Environmental control in these forests, therefore, involves a highly dynamic oscillation between light limitation and relief from atmospheric drought. The greatest bursts of carbon assimilation during the drought occur not under clear skies but during the passage of transient KW systems, thereby preventing the forest from undergoing midday stomatal closure.

One of the main advantages of this study is the way it integrates its methods. Earlier ecological studies have mostly relied on general monthly climatic indices to explain variations in flux. The researchers identified the local, high-frequency effects of travelling equatorial waves by combining in situ high-frequency eddy covariance data with careful space-time wavenumber-frequency filtering.

We recognise that using OLR as a proxy to fill in the missing in-situ shortwave radiation data does lead to a certain amount of estimation uncertainty. Yet in the field of equatorial meteorology, OLR is a highly reliable, physically verified proxy for both deep convection and optical cloud thickness. Moreover, although the 4-year period of observation (2013–2017) is relatively short when it comes to making long-term climatological inferences, it does include one of the most severe El Niño events of the century and thus provides a rare natural experiment. In the future, global vegetation models need to be updated to include the high-frequency 'rescue effects' of equatorial waves, since failing to account for these synoptic decoupling mechanisms will lead to a systematic overestimation of carbon losses in tropical montane forests.

5. CONCLUSION

This study demonstrates that high-frequency equatorial atmospheric variability is associated with measurable changes in carbon and energy fluxes in a Wallacean tropical montane forest. Daily GPP anomalies were weakly associated with latent heat flux but more strongly related to incoming shortwave radiation, indicating an important role of energy availability in regulating short-term carbon assimilation at this wet montane site.

Convective phases associated with the MJO and ERW were generally accompanied by reduced radiation and lower carbon assimilation. Kelvin Wave responses, however, differed according to the background ENSO state. During the 2015–2016 El Niño, positive GPP anomalies occurred around peak KW passage, whereas KW events under normal and La Niña conditions were predominantly associated with negative GPP anomalies. This contrast indicates that

ecosystem responses to synoptic atmospheric disturbances cannot be interpreted independently of the prevailing large-scale climate state.

These findings highlight a temporal scale of atmosphere–ecosystem interaction that is not fully represented by monthly or seasonal climate indices. Incorporating synoptic atmospheric variability alongside seasonal climate anomalies may therefore improve understanding of tropical forest carbon-flux responses to climate extremes. Longer observational records across multiple tropical montane sites, together with direct measurements of atmospheric moisture demand and diffuse radiation, will be needed to determine the generality and mechanisms of the responses identified here.

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Declarations

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