Assessing the sensitivity of MODIS EVI to rainfall and radiation extremes in the Amazon rainforest

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Abstract. Clarifying the response of vegetation to environmental changes is essential for better understating the susceptibility of the Amazon forest to extreme events. Vegetation indices derived from satellite imagery have often been used to assess changes in forest canopy caused by climate variability. However, recent studies indicate that some vegetation indices are strongly affected by satellite data artefacts and may not provide a reliable indicator of changes in canopy characteristics. In this context, it is currently unclear if vegetation indices are sensitive to subtle changes in the Amazon forest canopy. This study analyses 12 years of MODIS enhanced vegetation index (EVI) in order to evaluate its response to changes in rainfall and solar radiation. We show that, after removing cloud and aerosol contamination, and correcting BRDF effects, radiation and rainfall extremes show no influence on EVI anomalies. However, EVI seasonal patterns are still evident after accounting for sun-sensor geometry effects.

Keywords: Rainfall, Radiation, MODIS, EVI.

1. Introduction

The impacts of climate variability on the Amazon forest are still under debate. In particular, understanding the effects of climate extremes on the Amazon ecosystem remains a controversial topic (Samanta et al., 2012; Aragão et al., 2014). Recent studies have shown that long periods of water-stress have the potential of triggering the release of massive amounts of carbon to the atmosphere (Lewis et al., 2011) by causing widespread tree mortality (Phillips et al., 2010).

Remote sensing has been broadly considered an essential tool for monitoring the Amazon ecosystem (Anderson et al., 2010; Silva et al., 2013). For instance, vegetation indices (VI) obtained from satellite observations are often used as a proxy for assessing vegetation functioning and net primary production (e.g. Myneni et al., 2007). Hence, changes in VI patterns are considered as an indicator of the forest response to external environmental factors, such as water availability and solar radiation (Bradley et al., 2011; Brando et al., 2010).

Using enhanced vegetation index (EVI) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS), Huete et al. (2006) showed an increase in EVI during the dry season, contradicting model predictions that water limitation would lead to declines in forest greenness. Similarly, Saleska et al. (2007) reported that EVI data indicated an excessive greening of the Amazon forest during a strong drought in 2005. Nevertheless, using an EVI dataset with improved cloud and aerosol removal, Samanta et al. (2010) found no correlation between drought severity and greenness in intact Amazon forests during the 2005 drought.

Similar studies analyzed the drought in 2010 and reported a severe and persistent decline in vegetation greenness in 51% of all drought-stricken forests (Xu et al., 2011).

In most cases, discussions aiming to understand these heterogeneities in EVI patterns have focused on the hypothesis that in the Amazon forest radiation supersede water limitation inducing enhancement of EVI values during dry or drought conditions. However, the hypothesis that the EVI patterns in Amazon forest are driven by radiation has recently been undermined as Morton et al. (2014) showed that greening did not take place during the dry season. Confirming evidences reported by Moura et al. (2012) and Galvão et al. (2011), Morton et al. (2014) demonstrated that artefacts associated with MODIS sun-sensor geometry are the primary cause for the greening observed during the dry season.

Hence, it is currently unclear whether changes in vegetation functioning caused by climate variability can be captured using satellite EVI. Therefore, uncertainties in terrestrial ecosystem models based on VIs are high, and the reliability of model estimates of vegetation productivity under question, as the sensitivity of models to artefacts in remote sensing data still need to be formally evaluated.

In this study, we performed a sensitivity analysis to quantify the response of MODIS EVI to radiation and rainfall extremes throughout the year.

2. Methodology

To comprehensively assess EVI sensitivity to radiation and rainfall we performed a set of analyses at multiple spatial and temporal scales (Figure 1). We use two levels of EVI data, based on their quality and level of correction performed, as described below.

The first EVI dataset was compiled using the blue, red and NIR reflectance from the MCD43B4 product. The MCD43B4 provides bidirectional reflectance distribution function (BRDF) model adjusted nadir view reflectance data for 16-day periods at 1-km spatial resolution. The solar zenith angle corresponds to the angle at local solar noon. This dataset is hereafter denominated EVI_{NBAR} (Nadir BRDF Adjusted Reflectance).

The second EVI dataset was compiled using the MCD43B1 product, which contains MODIS BRDF model weights used to derive the NBAR product. However, for this later dataset, the sun zenith angle was fixed to 30 degrees for all months of the year. We refer to this dataset as EVI_{SAR} (Sun angle Adjusted Reflectance).

Monthly values of surface downward shortwave radiation flux were obtained from the Clouds and the Earth's Radiant Energy System (CERES) SYN1deg product. Monthly rainfall values were obtained from the Tropical Rainfall Measuring Mission (TRMM). The phase angle (i.e. the angle between the directions of sun illumination and sensor view) was calculated using the solar zenith angle, view zenith angle and relative azimuth angle provided in the MOD13A2 product.

We assessed the sensitivity of monthly EVI anomalies to changes in radiation and rainfall within the entire extent of the Amazon basin. Monthly standardized anomalies, for all datasets, were calculated using as baseline the period between 2001 and 2012. The sensitivity analyses consisted in grouping EVI anomaly pixels within bins of radiation anomalies, rainfall anomalies or phase angle. The distributions of EVI anomalies were then constructed within each bin and the bins median were computed. For radiation and rainfall anomalies, the bin width used was 0.5 σ, ranging from -2.5 σ to 2.5 σ.

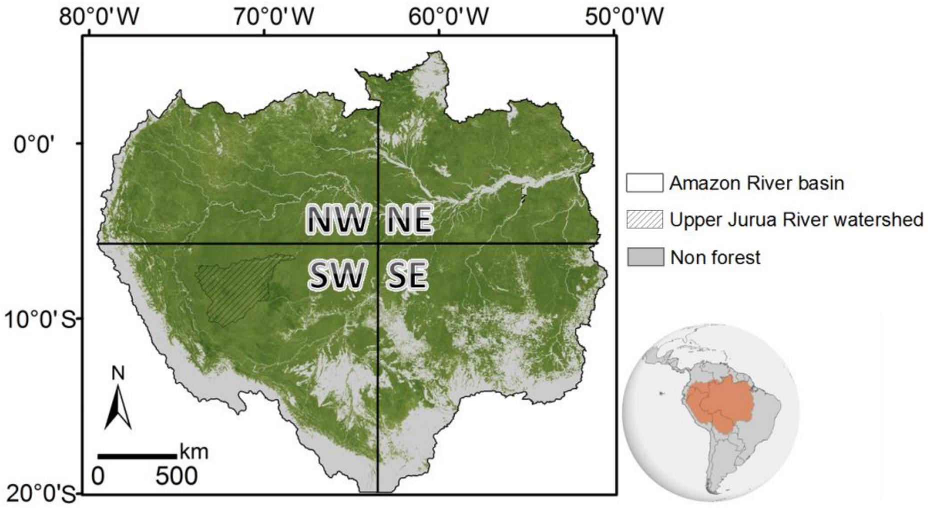

Figure 1. Study area consisted in the entire Amazon River basin, which was divided in four quadrants (Maeda et al., 2014).

3. Results and Discussion

The relationships between EVI and radiation flux anomalies for the entire Amazon basin are presented in Figure 2. No significant relationships are observed, in any season of the year. Hence, we find no evidences that variations in incoming solar radiation have influence on EVI$_{\mathrm{SAR}}$ anomalies in the Amazon basin. Similar results are also observed in the relationship between the EVI and rainfall anomalies (Figure 2). These results show that the decrease in water input during meteorological droughts has no impact on the Amazon forest EVI values. Although these evidences challenge previous claims that EVI anomalies are affected by droughts (e.g. Brando et al., 2010; Saleska et al., 2007) it cannot discard the hypothesis that the photosynthetic capacity of the forest is water-limited, given the possibility that EVI may not be sensitive enough to capture sudden changes in canopy structure and/or chemical composition caused by water stress.

The response of EVI anomalies to radiation anomalies shows similar results throughout different geographical regions of the Amazon basin. The sensitivity of EVI$_{\mathrm{SAR}}$ to variations in radiation anomalies, analyzed in four quadrants of the Amazon basin, is presented in Figure 3. Although a slightly larger variance in EVI$_{\mathrm{SAR}}$ anomalies is observed in the SE quadrant of the basin, no evident trends are observed between medians of EVI$_{\mathrm{SAR}}$ anomalies and radiation anomaly flux bins.

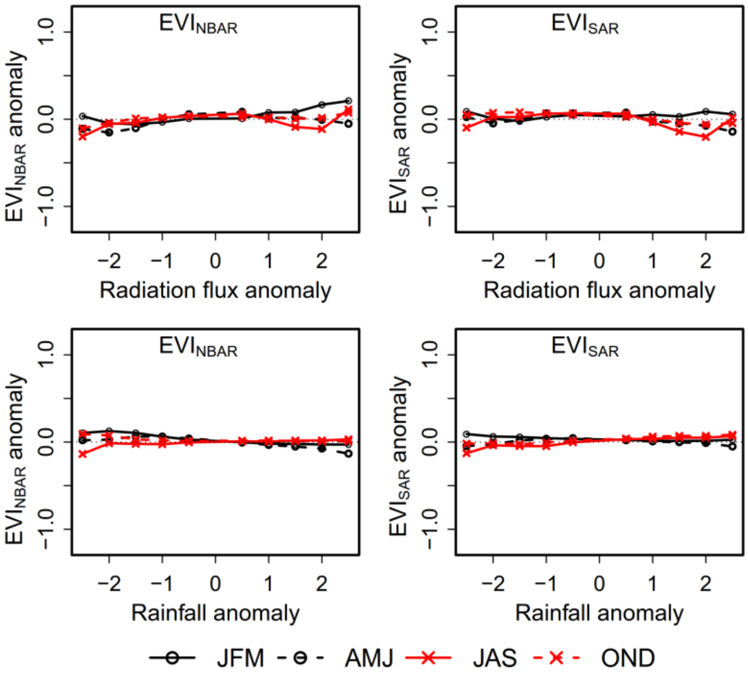

Figure 2. Relationships of EVI and short wave radiation flux anomalies, for quarters of the year, using the EVI_{NBAR} and EVI_{SAR} datasets. The lines indicate the median of EVI anomaly values in each radiation anomaly bin of 0.5 σ in width.

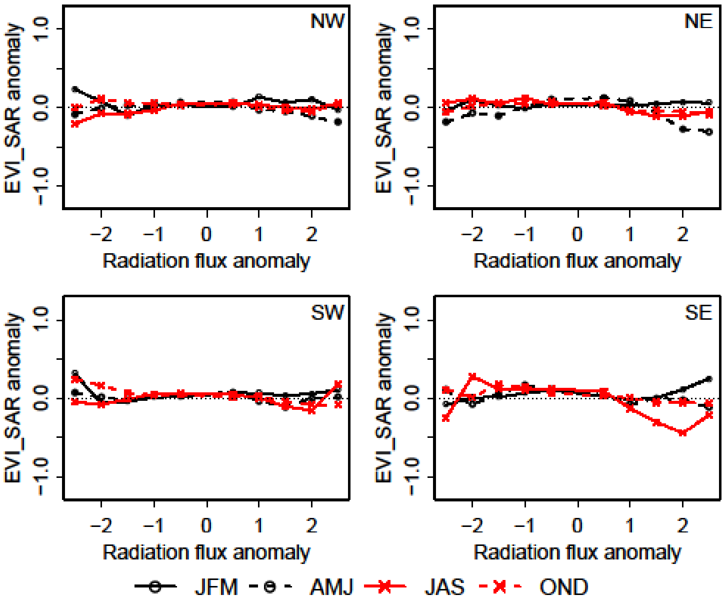

Figure 3. Relationships of EVI_{SAR} and short wave radiation flux anomalies for quarters of the year, divided in four geographical regions: North-West (NW), North-East (NE), South-West (SW) and South-East (SE). The lines indicate the median of EVI anomaly values in each radiation anomaly bin of 0.5 σ in width (Maeda et al., 2014).

To evaluate whether or not rainfall and solar radiation affect EVI seasonal patterns we evaluate monthly long-term averages (2001–2012) of EVI_{NBAR}, EVI_{SAR}, radiation, rainfall and phase angle for the upper Jurua River basin (Figure 3). This assessment was performed in a smaller and homogeneous area to avoid misinterpretations associated with spatial variations in climate and vegetation. Only pixels with at least 5 years of valid data were considered. Our results show that, even after different levels of BRDF correction, EVI$_{NBAR}$ and EVI$_{SAR}$ still reveal clear seasonal patterns. This result contrasts with Morton et al. (2014), who showed that greening patterns during the dry season could not be observed after BRDF correction. The discrepancy could be explained by the use of different BRDF correction methods or may represent genuine seasonal vegetation changes.

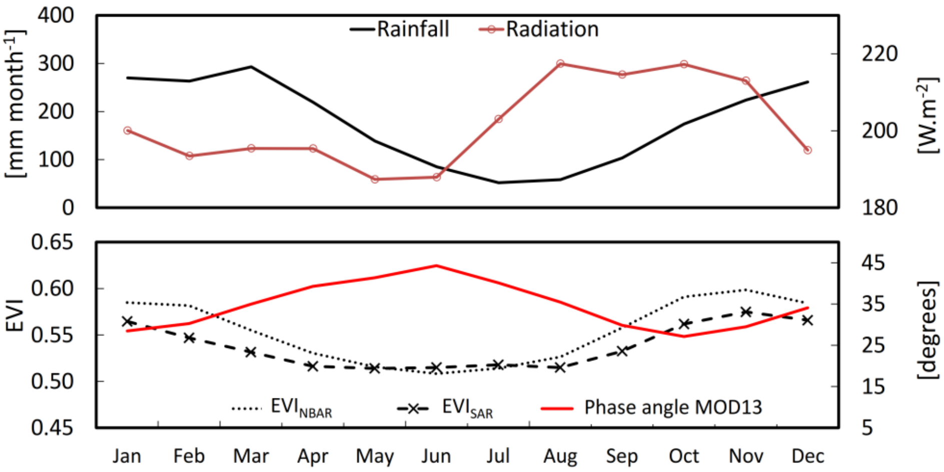

Figure 4. Long-term (2001–2012) monthly averages of radiation and rainfall; and long-term (2001–2012) monthly averages of EVI$_{NBAR}$, EVI$_{SAR}$, and scattering angle obtained for the upper Jurua River basin.

Interestingly, the only difference between the EVI$_{NBAR}$ and the EVI$_{SAR}$ datasets is the monthly average sun zenith angle considered in the BRDF model. While in the EVI$_{NBAR}$ sun zenith angle corresponds to the angle at local solar noon, in the EVI$_{SAR}$ the angle is fixed to 30 degrees. The use of a constant sun zenith angle causes an evident smoothing in the seasonal variation of EVI$_{SAR}$, indicating that sun-sensor geometry is in part responsible for intra-annual patterns (Figure 3). Furthermore, we show that even after BRDF correction carried out in the EVIN$_{BAR}$ and EVI$_{SAR}$, the seasonal pattern in these datasets still have a significant (p-value<0.001) correlation with monthly average phase angle (obtained from the MOD13 product). Hence, it is plausible that the BRDF model behind the EVI$_{NBAR}$ and EVI$_{SAR}$, cannot fully remove artefacts associated with sun-sensor geometry, although genuine vegetation trend cannot be discarded. In agreement with Galvão et al. (2011) we observed that EVI$_{SAR}$ is linearly correlated with BRDF corrected NIR reflectance (Figure 5). On the other hand, red and blue bands show no correlation with EVI$_{SAR}$, leading to the conclusion that the remaining seasonal patterns are mainly driven by changes in NIR reflectance, which is not considered a good indicator of photosynthetic activity.

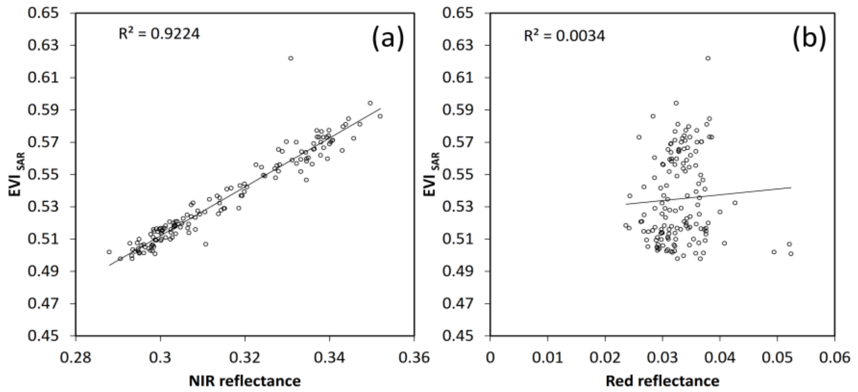

Figure 5. Relationship between EVI_{SAR}, and, (a) NIR and (b) red reflectance in the upper Jurua watershed (monthly values from 2001 to 2012) (Maeda et al., 2014).

We also show that long-term monthly EVI_{SAR} averages are not significantly correlated with incoming radiation flux (Figure 3). Monthly rainfall averages, on the other hand, show a significant correlation with EVI_{SAR} (p-value<0.05). However, this correlation does not necessarily represent causality, given that a significant relationship between EVI_{SAR} and rainfall is not observed when analyzing geographical areas with different rainfall patterns (Figure 7). This statement is reinforced by the lack of EVI_{SAR} sensitivity to rainfall anomalies, showed in Figure 2.

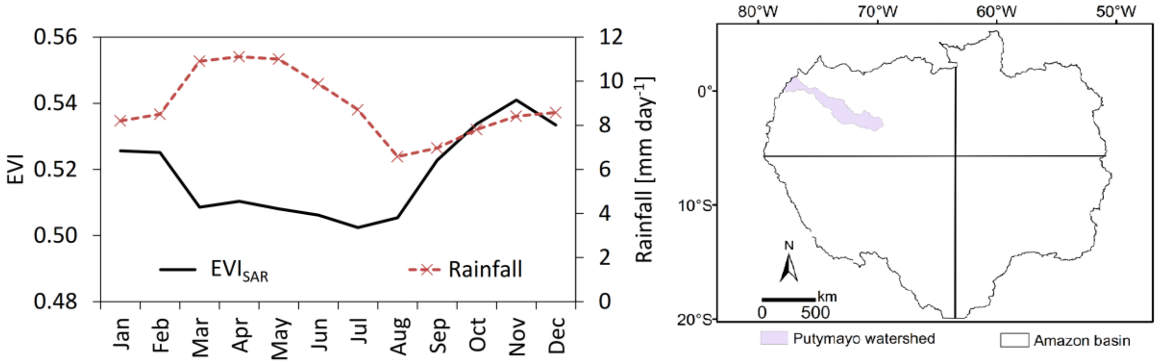

Figure 6. Monthly long-term averages (2001–2012) of EVI_{SAR} and rainfall for the Putymayo river watershed (Maeda et al., 2014).

4. Conclusions

Our results show evidences that, after removing artefacts caused by clouds, aerosols and BRDF effects, radiation and rainfall extremes exert no influence on EVI anomalies. Furthermore, radiation and rainfall show no evident influence on long-term EVI patterns in intact equatorial forests. In agreement with previous findings, our results confirm that the annual EVI seasonality is in part explained by variation in sun-sensor geometry. However, we show that, after BRDF correction, seasonal patterns are still present in intact evergreen forests, contradicting previous claims that seasonal changes in greening patterns cannot be observed after accounting for sun-sensor geometry artefacts.

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