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Abstract

A novel technique that links vegetation properties and ET fluxes with a microwave “emissivity difference vegetation index” (EDVI) has been developed and applied to the Amazon region. These EDVI values can be derived from a combination of satellite microwave measurements with visible and infrared observations. This technique is applicable both day and night times under all-weather conditions which is particularly important for remote sensing since under cloudy conditions classic optical techniques are not applicable. For the Amazon basin, EDVI captures vegetation variation from dense vegetation (rain-forest) to short and/or sparse vegetation (savanna) under all-weather conditions. Good relations between microwave based EDVI and optical indexes of NDVI and EVI are found for various vegetation conditions. More importantly, EDVI shows no sign of saturation even for the tropical rain forest, while NDVI (and EVI to a lesser extent) is clearly saturated. Over the Amazon region in a normal dry season day, EDVI can provide the vegetation information over 98% of the land surface while the optical vegetation indexes can be retrieved only for a small fraction (14%) of the region.

1. Introduction

The terrestrial vegetation and ecological systems play important roles in global change and climate variations. An accurate depiction of evapotranspiration (ET) and photosynthesis processes is essential in the understanding of the response and influence of the vegetation system to water, energy, and carbon cycles of the climate. Since clouds have controlling effects on terrestrial carbon uptake [Min and Wang 2008], it is crucial to monitor vegetation-atmosphere interactions under all weather conditions.

Existing satellite remote sensing techniques for ET, photosynthesis, and vegetation state estimations are generally based on measurements at visible (VIS) and near-infrared (NIR) wavelengths [Nemani and Running 1989; Nishida et al. 2003; Running and Kimball 2005; Mu et al. 2007; Glenn et al. 2007; references therein], such as normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). These spectral measurements are directly related to the absorbed fraction of photosynthetically active radiation (PAR) and have certain correlations with moisture and carbon exchanges of atmosphere and land surface. Another advantage of these indexes is their higher spatial resolutions compared to those at other wavelengths, which is critical in account for the heterogeneity of land surface. The limitations of the measurements are their low temporal resolution caused by high sensitivity to clouds and aerosols (unable to provide information under cloudy conditions) and the saturation at intermediate values of leaf area index (LAI) [Asra et al. 1984; Sellers 1985; Myneni et al. 1995; Gutman 1999; Granger 2000]. NDVI may represent total vegetation water of leaves when it is not satuated [Hong et al. 2007]. Because of the rapid change of vegetations during spring onset and fall senescence, these multi-day composite indexes cannot accurately capture the transitions of vegetation states during growing seasons. In some regions where cloud covers are high, for example in the Amazon Basin, these indexes are inadequate in providing information on the structure and function of terrestrial ecosystems, particularly in rain season, while vegetation systems generally have enhanced ET and carbon uptake under cloudy conditions [Min 2005; Min and Wang 2008]. There are considerable gaps in understanding feedback mechanisms associated with evaporation processes of land surfaces. The wide spectra of spatial and temporal scales of climate system and inherent heterogeneity of the biosphere also require improved remote sensing techniques to study and monitor surface/canopy states, atmospheric and environmental change processes, and the effect of variations in vegetation on atmospheric dynamics and thermodynamics.

There is a long history to use passive microwave measurements for monitoring vegetation and soil properties. Many researches related microwave polarization difference temperature of 37 GHz (MPDT) to soil moisture, surface roughness, canopy structure and vegetation content [Choudhury and Tucker, 1987; Becker and Choudhury, 1988; Kerr and Njoku, 1990; and Paloscia and Pampaloni, 1992], as MPDT decreases with increasing vegetation. Justice et al [1989] found that MPDT is more sensitive to short vegetation (grass) than to dense vegetation (trees and shrubs). Calvet et al [1994] simulated the sensitivity of multiple channel microwave brightness temperature and normalized polarization differences (at 6.6, 10.7, 18 and 37 GHz) to biomass and air temperatures in the boundary layer. They found the biomass effect is better discriminated at lower frequencies. Background soil emission signals can make significant contributions to those vegetation indexes and let the physical explanations difficult. Recently, Shi et al [2008] proposed a new microwave vegetation index (MVIs) for short vegetation covers, based on the finding that bare soil emissions at two adjacent frequencies of AMSR-E are highly correlated and can be expressed as a liner function. As pointed out by Prigent et al. [2001], atmospheric effects, especially cloud cover, is responsible for a large part of the polarization difference and brightness temperatures, casting doubt on the interpretation of simple indexes solely in terms of surface properties.

To overcome the above limitations, we developed a novel technique that links vegetation properties and ET fluxes with an “emissivity difference vegetation index” (EDVI) [Min and Lin 2006a; b; Li et al., 2009]. EDVI is derived from a combination of satellite microwave measurements with visible and infrared observations through accurately atmospheric correction. This technique was demonstrated applicable under all-weather conditions for monitoring vegetation biomass and ecosystem exchange processes in Harvard forest. The characteristics of vegetation in Amazon might differ from those of Harvard forest. As discussed by Min and Lin (2006a,b), EDVI is mainly related to the canopy properties of vegetation water content between two effective emission layers. Although the absolute values for a given VWC in the crown layer may be different in Harvard forest and Amazon, the general dependency of VWC should be similar. In order to demonstrate the capability of EDVI technique over large spatial domain for regional and global applications, the technique should be tested in various climate conditions.

The Amazon Basin contains almost one-half of the world's undisturbed tropical evergreen forest as well as large areas of tropical savanna. The forests account for about 10% of the world's terrestrial primary productivity and the carbon stored in land ecosystems. Furthermore, the Amazon region generally has significant cloudiness although it varies greatly between the wet and dry seasons. As moderate cloudy skies substantially enhance ET and carbon uptake, it is crucial to understand vegetation-atmosphere feedback under all weather conditions [Min 2005; Min and Wang, 2008]. Due to the excessive cloudiness in the region, the classic vegetation indexes from optical sensors may bias or even fail to provide information of vegetation structure and distribution. In this study we applied this technique to the Tropics to illustrate its applicability for various vegetation and weather conditions. We retrieved the EDVI index over the Amazon Basin by mainly combining AMSR-E and MODIS measurements from Aqua for the year 2004.

2. Method and data sets

Physical properties of vegetation, such as plant water content, vegetation coverage, canopy structure, vegetation phenology, and physical temperature, are major factors in determining satellite measured radiances [Wigneron et al. 1993; Njoku 1999; Wigneron et al. 2003 and reference therein]. Passive microwave observations have different sensitivities for the dynamic ranges of vegetation structure and biomass from those of visible and infrared measurements, and are less affected by aerosols and clouds [Choudhury 1995]. Microwave land surface emissivity (MLSE) can be derived from satellite measurements during both day and night times under all-sky (non-precipitating) conditions [Lin and Minnis 2000]. Thus, a synergism of microwave, infrared, and visible measurements offers great potential to monitor surface and vegetation properties on a continuous basis.

There is a semi-empirical relationship between the optical depth at microwave wavelengths and vegetation water content, which varies systematically with both wavelength and canopy structure [Jackson and Schmugge 1991]. The microwave surface emission above a canopy is an integration of the microwave radiation from the whole canopy vertical profile and the soil weighted by its transmission. The emissivity observed at longer wavelengths with a weaker attenuation by the canopy generally represents an effectively thicker layer than those observed at shorter wavelengths with stronger attenuation. Thus, we introduce the microwave land surface emissivity difference between two wavelengths to indicate vegetation water content and other vegetation properties of the canopy with a minimal influence of the soil emission underneath vegetation canopy [Min and Lin, 2006a, b]. Analogous to NDVI, the EDVI is defined as:

$$EDVI_P = \frac{MLSE_P^A - MLSE_P^B}{0.5(MLSE_P^A + MLSE_P^B)} . \qquad (1)$$

where *p* represents a polarization at vertical or horizontal direction, and A and B indicate the two wavelengths of microwave measurements. Based on our studies, we chose a pair of channels at about 19 and 37 GHz from current satellite passive microwave sensors as the basic set to investigate their potential for detecting vegetation physiology changes and estimating land-atmosphere exchange. For Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer (AMSR-E), the pair is from measurements at 19.4 and 37.0 GHz and at 18.7 and 36.5 GHz, respectively. The $MLSE_p^{19}$ represents the thicker effective emission layer deeper into the canopy while $MLSE_p^{37}$ represents the thinner one. Thus, EDVI is related to the canopy properties of vegetation water content and structure of two effective emission layers. The studies of Min and Lin [2006a; b] found that the EDVI is sensitive to leaf development through vegetation water content of the crown layer of the forest canopy, and demonstrated that the spring onset and growing season duration can be determined accurately from the time series of satellite estimated EDVI within uncertainties of approximately 3 and 7 days for spring onset and growing season duration, respectively, compared to in-situ observations. The leaf growing stage can also be monitored by a normalized EDVI.

All datasets used in this study are summarized in Figure 1. We retrieved MLSE values of 18.7 and 36.5 GHz from AMSR-E Level 2A Global Swath spatially-resampled brightness temperatures, AE_L2A, using a combined technique [Min and Lin 2006a]. These MLSE values are estimated based on an atmospheric microwave radiative transfer (MWRT) model [Lin et al. 1998], which accurately accounts for the atmospheric absorption and emission of gases and clouds, especially the temperature and pressure dependences of these radiative properties [Lin et al. 2001]. The scattering of upwelling microwave radiation is primarily due to precipitation-sized hydrometeors present above the emitting layer (Lin and Rossow 1997; Vivekanandan et al. 1990; Wilheit et al. 1982). To avoid the complexity of microwave scattering and the dependence of observed radiances on precipitating hydrometeors, we only processed non-precipitating pixels identified by AMSR-E product of rain rate/type (AE_Rain). We further filtered out the pixels that

Tb85V were less than 285 K to minimize the scattering effects on our retrievals. The information of surface types, i.e. ocean, land, coast and sea ice, from AE_Rain product are also used to determine validity of pixelz for MLSE retrievals: only pixels identified as “land” are included. The major inputs of the model are effective land surface skin temperature, column water vapor (CWV), cloud water amount, surface air temperature and pressure. The NCEP reanalysis data is used to estimate CWV and surface air temperature values. Cloud water amount is adopted from MODIS cloud products (MYD06L2), which are retrieved from combined visible and infrared measurements. Specifically, cloud fraction, cloud phase, cloud top temperature, and cloud water and ice paths are used and projected into AMSR-E spatial grids in the retrievals. The vertical distributions of atmospheric temperature, pressure and gas abundance are constructed based on climatological profiles [McClatchy et al. 1972] and interpolated to conform to the surface temperature and pressure as well as CWV values derived from NCEP reanalysis data. As indicated by the study of Min and Lin [2006a, b], the horizontal component of the EDVI is generally more sensitive to a broader range of canopy properties, such as VWC, canopy leaf/stem structure, and orientation, with a larger dynamic range. The crosstalk among these canopy properties may reduce the correlation of the horizontally polarized EDVI with the specific variable evapotranspiration fraction (EF), i.e, evapotranspiration. As shown by Min and Lin [2006a], the vertical component of the EDVI has a higher correlation with vegetation state and evapotranspiration than the horizontal component. Thus, we used the vertical component of EDVI in the following discussion.

In order to validate and evaluate our retrievals, MODIS land surface reflectance (MYD09GHK) was used to derive instantaneous NDVI and EVI under clear-sky conditions. Together with the MODIS standard product of 16-day NDVI and EVI composites (MYD13A1), we projected NDVI and EVI values into the AMSR-E spatial grids for the comparison. We also used AMSR-E retrieved surface VWC and soil moisture (AE_land) for the evaluation [Njoku, 1999; 2007].

3. Results

Figure 2 shows retrieved MLSEs at 19 and 37 GHz and derived EDVI based on an Aqua data on August 30, 2004. In the $10^{\circ} \times 30^{\circ}$ domain of this case, over 98% of the land surface pixels were valid for MLSE retrievals. In other words, microwave based MLSE and EDVI can provide the vegetation information over 98% of the land surface over the Amazon region. MLSE is indicative of moisture conditions of combined canopy and underneath soil. There is a soil moisture and vegetation gradient from north to south, with low MLSEs at the Amazon basin. Inferred EDVI, which represents vegetation conditions, also clearly shows a gradient from north to south, corresponding to the dense vegetation of rain-forest in the northern Amazon Basin to the savanna in the south. Several high MLSE areas with very low EDVIs are savanna land. In the south-east edge of the image, low EDVIs but relatively low MLSEs indicate sparse vegetation with somewhat moist soils.

Evaluation and validation of retrieved products are keys to the success of a retrieval algorithm. We utilized this case as a basis to assess the uncertainty of our comprehensive retrievals. There are four major error sources that could impact on retrieved EDVIs, including the cloud liquid water path (LWP) retrieved from MODIS, the column water vapor (CWV) estimated from NCEP reanalysis, the land surface skin temperatures (LST) estimated from NCEP reanalysis, and the brightness temperatures (Tb) at 19 and 37 GHz channels observed by AMSR-E. We randomly perturbed each parameter within its maximum uncertainty, based on its measurement or model uncertainty assessment, and compared the perturbed retrievals with the normal retrievals. As shown in Figure 3, given maxmum uncertainties of $\pm$15% in LWP, $\pm$10% in CWV, $\pm$2 K in LST, and $\pm$1 K in microwave Tb, respectively, the evaluated standard deviations of EDVI range from 1.48E-4 to 4.88E-4, i.e., about 1.5% of the averaged EDVI.

To validate our EDVI retrieval, we compared it with optical vegetation indexes of NDVI and EVI as well as VWC retrieved from microwave [Njoku, 2007]. Since NDVI and EVI can only be retrieved under clear-sky condition, we compared those indexes in the clear-sky subset of the same Aqua orbit data on August 30, 2004, shown in Figure 4. In this 10^o x 30^o domain, the percentage of clear-sky pixels in this normal dry season day is less than 14%. This illustrates that only a small fraction of the land can be monitored by the classic vegetation indexes in the Amazon region. However, over the same domain microwave based EDVI can provide the vegetation information over 98% of the land (Figure 2c).

As shown in Figures 4c and 4d, NDVI (and EVI as well) varies substantially from 0.25 to 0.9, indicating substantial variability of vegetation in the domain, corresponding to the vegetation differences in the north and south. EDVI shows a consistent spatial gradient with NDVI. We further divided the domain into two sectors (see Figure 4a), according to spatial occurrences and vegetation conditions. For all clear-sky pixels, EDVI correlates well with NDVI and EVI in each sector (Figure 5a and 5b). The slopes between EDVI and NDVI in both sectors are consistent, with statistically significant correlation coefficients of 0.44 and 0.62 for dense vegetation area A and sparse and short vegetation area B, respectively. Slightly better statistic characteristics are evident for EDVI and EVI, due to less saturation of EVI. Overall correlation coefficient in the entire domain is 0.54. Retrieved VWC from microwave measurements has slightly better statistics with NDVI and EVI in the sparse and short vegetation region (area B) than that of EDVI. However, there are almost no correlations between VWC and NDVI (and EVI) in the dense vegetation region (area A). The correlation coefficients between EDVI and VWC are 0.05 and 0.52 in the areas of A and B, respectively. Retrieved VWC may represent integrated VWC for the entire canopy, including branches and trunks [Njoku 1999], while EDVI (and NDVI) represent the upper-most portion of vegetation [Min and Lin 2006b]. It may be one reason for the poor correlations of VWC with other indexes in the dense vegetation region. It is worth noting that although branches and trunks contain most water in the tree, they play a little direct role in the leaf evapotranspiration and photosynthesis processes. Retrieved VWC in the dense vegetation does not represent the vegetation state in terms of atmosphere-land interaction. Nonetheless, these statistics indicate EDVI is applicable to a variety of vegetation conditions for atmosphere-land interactions, much better than VWC in dense vegetation.

Furthermore, as shown in Figure 6, the histograms of EDVI inside both sectors are close to a Gaussian distribution. The maximum occurrences of EDVI for sectors A and B are at values of about 0.12 and 0.08, respectively. They show no sign of saturation of EDVI even for the densest vegetation in the world, the rainforest of the Amazon Basin. It is worth noting that although the simple two-layer model of Min and Lin (2006a) shows EDVI saturates at about the VWC value of 0.7 kg/m^2, it may not reflect real world since the model does not account for multiple scattering effects and only has the first order scattering influences (single scattering). With considerations of full multiple scattering, the increase of EDVI with VWC is going to be slower than what we simulated (Fig.2b in Min and Lin 2006a), and the saturation point of EDVI on VWC should be much higher. On the other hand, the VWC used in the current study is a standard product of AMSR_E, representing the vegetation water content in the entire column (including trucks and branches), however, the EDVI is sensitive to the VWC in the crown layer of the canopy not the entire column of the canopy. From Figure 6b, a similar conclusion can be drawn for microwave based retrievals of VWC, which also show similar distributions to the EDVI histograms. In contrast, as shown in Figure 6c, the histograms of NDVI illustrate bi-mode distributions. NDVI is clearly saturated with distribution skewed to a high value of 0.9. Having similar characteristics to NDVI, EVI exhibits much less problem of saturation than NDVI.

Since optical indexes of NDVI and EVI are not retrievable under cloudy conditions, we further compared instantaneous all-weather EDVI against a 16-day composite NDVI and EVI, shown in Figure 7. In the figure, we also compared EDVI with VWC. The spatial distribution of instantaneous EDVIs for cloudy pixels corresponds well with the 16-day composites of NDVI and EVI, illustrating EDVI can capture vegetation variation under all-weather conditions.

In order to compare more quantitatively among these indexes, we further divided the region into three sectors based on vegetation characteristics, shown in Figure 7a. The sector C is a transition area between dense vegetation area A and relatively short and/or sparse vegetation area (savanna) B. The relationships between EDVI and composite NDVI (EVI as well) for cloudy pixels of ARMS-E are weaker than those from clear-sky instantaneous comparisons, as shown in Figure 8, because of temporal mismatch and changes of vegetation as a result of the presence of clouds. These relationships get stronger and stronger from dense vegetation to sparse vegetation, due in part to the saturation of optical indexes and sensitivity differences among different vegetation indexes. Note that the relationships between VWC and NDVI (and EVI) are weaker than those between EDVI and NDVI (and EVI), except for sparse vegetation area. This is consistent with the finding under clear-sky conditions.

A recent study has shown a large seasonal swing in leaf area for Amazon rainforests, which may be critical to the initiation of the transition from dry to wet season and seasonal carbon balance between photosynethetic gains and respiratory losses in tropical forests [Myneni et al. 2007]. It could have substantial hydrological and biogeochemical significances. As Myneni et al. [2007] pointed out, it is crucial to minimize the impact of clouds on optical vegetation indexes to monitor seasonal variation of vegetation since there is significant cloudiness in the Amazon region. In contrast to classic vegetation indexes of NDVI and EVI, the EDVI is insensitive to clouds and can be retrieved under both clear-sky and cloudy conditions. Because of the severity of NDVI saturation, we used EVI for the following discussion.

Figure 9 shows the time series of retrieved EDVI and EVI at one LBA (Large-scale Biosphere-Atmosphere Experiment) site of Km67, which is a primary forest. In order to increase temporal samples for EVI, we derived the EVI from reflectances of 10 lowest values (500 m resolution of MODIS) within a footprint of AMSR-E (27x16 km^2), if MODIS cloud mask identifies these MODIS pixels as clear-sky pixels. For doing so, we allowed EVI to be retrieved under the broken cloud conditions even when the cloud cover in the AMSR-E footprint was up to 99%. For the comparison, we ignored the vegetation variability within the AMSR-E footprint. Even though, the EVI can only be derived by about 27% of all AMSR-E pixels of Aqua overpasses. If we further restrained cloud cover to less than 50% over the AMSR pixels, the retrievable samples of EVI are limited to about 16%, mostly during the dry season. There are some differences of retrieved EVIs with different cloud cover constraints (99% vs. 50%), illustrating the inhomogeneous vegetation within the AMSR-E footprint. It is clear, though, that the temporal variations of EDVI (dark solid curve) are consistent with the smoothed variations of instantaneous EVI retrievals with a cloud cover constraint of 99% (light solid curve) at the site, similar to the spatial statistical analysis. Both EDVI and EVI decrease from the wet season to the early dry season and then increase in the late dry season. However, if simply using the 16-day composite EVI data for the Km67 site directly from the MODIS standard product without further screening cloud contamination (dashed curve), the 16-day composite EVI increased slightly from the wet season to the dry season. The different seasonality of short-time scale averages with that of the 16-day composites manifests the issue of cloud impacts on classic optical vegetation indexes and demonstrates the advantage of all-weather measurements of microwave based EDVI. With high temporal resolution, EDVI can monitor vegetation changes even down to the synoptic (a few days) or smaller scales [Li et al 2009], which is critically important for terrestrial hydrological, ecological, and biogeochemical cycling as well as climate modeling. Furthermore, as discussed in Min and Lin [2006a] and Li et al. [2009], long term seasonal trend of EDVI is linked to variances of canopy resistance due to the interrelationship among leaf development, environmental condition and microwave radiation. Short term changes of EDVI caused by synoptic scale weather variations can be used to parameterize the response of vegetation resistance to the quick changes of environmental factors including water vapor deficit, water potential and others. Thus, retrieved EDVI can also be used to estimate evapotranspiration (ET) from the first principle of the surface energy balance model [Li et al. 2009].

4. Summary and discussion

Characterization of ET and carbon uptake processes is essential in understanding the responses of climate and terrestrial ecological systems to climate change and variation, which needs advanced remote sensing tools to represent vegetation states. Due to the limitations of classic optical indexes, we used our newly developed microwave technique [Min and Lin 2006a; b] to link the “emissivity difference vegetation index” (EDVI) to vegetation properties over the Amazon basin. The EDVI, retrieved from a combination of satellite microwave, visible and infrared measurements, provides an accurate measure of vegetation state under all-weather conditions, where classic optical indexes are unavailable.

At a normal dry season day in the Amazon region, EDVI can provide the vegetation information over 98% of the land surface while the classic vegetation indexes can be obtainable only for a small fraction (14%) of land surface. For a particular footprint of microwave measurements in the Amazon Basin, with the least constraints of cloudy conditions, the frequency of retrievable classic vegetation indexes is only 1/3 of the microwave based EDVI. As illustrated through the intercomparison, EDVI captures vegetation variation from dense vegetation (rain-forest) to short and/or sparse vegetation (savanna) under all-weather conditions. Good relationships between microwave based EDVI and optical indexes of NDVI and EVI are found for various vegetation conditions. More importantly, EDVI shows no sign of saturation even for the tropical rain forest in the Amazon Basin, while NDVI (and EVI to a lesser extent) is clearly saturated. Comparison of microwave based VWC with those indexes indicated that VWC has high correlations with vegetation indexes for sparse vegetation and has no correlation for dense vegetation. Different vegetation indexes may be responsive to different dynamic ranges of vegetation structure and biomass under various sky conditions.

Since the land surface functions as a heterogeneous boundary between the atmosphere and biosphere, the physical, biological and chemical processes related to carbon, energy and water cycles are strongly spatio-temporal scales dependent. This dependence requires observational capability with spatial resolutions from point (surface site or footprint of optical sensor), local (satellite microwave footprint ~30 km), and regional to global scales, and with temporal resolutions from minutes for site observations, hours for multiple satellite measurements, to daily and monthly averages for regional and global composites. Thus, it is extremely useful to generate a unique high spatial and temporal vegetation index by combining high temporal resolution microwave based EDVI with high spatial resolution optical indexes. The synergism product may shed a light on better monitoring and understanding of the exchange processes of land surface and atmosphere.

As a new microwave-related vegetation index, the interpretations of EDVI deserve more detailed studies. The multiple scattering from trees may play an important role in determining the upward microwave signals. And sub-pixel contamination due to open water and wetlands may also introduce additional uncertainties in the EDVI retrievals.

Captions:

Figure 1. Summary of all datasets used in EDVI retrieving and in the inter-comparison of this study

Figure 2. Retrieved MLSEs at 19 and 37 GHz and derived EDVI over the Amazon Basin on August 30, 2004.

Figure 3. Comparison between perturbed and normal EDVI with four major error sources.

Figure 4. Comparison between three different vegetation indices under clear sky at the Amazon on Aug 30 , 2004: (a) The microwave emissivity difference vegetation index (EDVI); (b) The vegetation water content (VWC) derived from AMSR-E; (c) The normalized difference vegetation index (NDVI); (d) The enhanced vegetation index (EVI).

Figure 5. Comparison between EDVI, VWC, NDVI, and EVI in the north and south sectors under clear-sky conditions on Aug. 30, 2004.

Figure 6. Histograms of EDVI, VWC, NDVI, and EVI for both A and B sectors.

Figure 7. Comparison between three different vegetation indices under all-weather conditions at the Amazon on Aug 30, 2004: (a) instantaneous EDVI; (b) instantaneous VWC; (c) 16-day composite NDVI; and (d) 16-day composite EVI.

Figure 8. Comparison between EDVI, VWC and composite NDVI and EVI in three sectors under all-weather conditions on Aug. 30, 2004.

Figure 9 . Time series of EDVI and EVI at an LBA Km67 site. Solid circles represent EDVI; Open circles and squares represent EVI with upper limit cloud coverage 99% and 50%, respectively. Solid triangles represent 16-day composite EVI. Black and gray solid curves represent smoothed EDVI and EVI, respectively.

Reference

Asrar, G. E., M. Fuchs, E. T. Kanemasu, J. L. Hatfield, “Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat, ”*Agron. J.*, vol. 76, pp. 300-306, 1984.

Becker , F. & Choudhury, B. J., “Relative sensitivity of normalized difference vegetation index (NDVI) and microwave polarization difference index (MPDI) for vegetation and desertification monitoring.” *Remote Sensing of Environment*, 24, pp. 297-311,1988.

Calvet, J. C., J. P. Wigneron, E. Mougin, Y. H. Kerr, J. L. S. Brito, “Plant water content and temperature of the Amazon forest from satellite microwave radiometry.” *IEEE Trans. Geosic. Rem. Sens.* 32(2): pp. 397-408, 1994.

Choudhury, B. J., Tucker, C. J., Golus, R. E. & Newcomb, W. W., “Monitoring vegetation using Nimbus-7 scanning multichannel microwave radiometer’s data.” *International Journal of Remote Sensing*, 8(3), pp533-538, 2007

Choudhury, B. J., Y.H. Kerr, E.G., Njoku and P. Pampaloni (editors), *Passive microwave remote sensing of land-atmosphere interaction*, Utrecht, The Netherlands, 1995.

Glenn, E., P., A. R. Huete, P. L. Nagler, K. K. Hirschboeck, and B. Paul, “Integrating Remote Sensing and Ground Methods to Estimate Evapotranspiration,” *Critical Reviews in Plant Sciences*, vol. 26, pp. 139-168, 2007.

Granger, R. J., “Satellite-derived estimates of evaportranspiration in the Gediz basin,” *J. Hydrometeorol.*, vol. 229, pp. 70-76, 2000.

Gutman, G., “On the use of long-term global data of land reflectances and vegetation indices derived from the advanced very high resolution radiometer” *J. Geophys. Res.*, vol. 104, pp. 6241-6255, 1999.

Hong, S., V. Lakshmi, and E.E. Small,“Relationship between Vegetation Biophysical Properties and Surface Temperature Using Multisensor Satellite Data,” *J. Climate,* vol. 20, pp. 5593–5606, 2007.

Jackson, T. J., and T. J., Schmugge, “Vegetation effects on the microwave emission of soils,” *Remote Sensing of Environment*, vol. 36, pp. 203–212, 1991.

Kerr, Y. H. & Njoku, E. G., “A semiempirical model for interpreting microwave emission from semiarid land surfaces as seen from space.” *IEEE Transactions on Geoscience and Remote Sensing*, 28, pp. 384– 393, 1990.

Justice, C. O., Townshend, J. R. G., Choudhury, B. J., “Comparision of AVHRR and SMMR data for monitoring vegetation phenology on a continental scale.” *International Journal of Remote Sensing*, 10(10), pp.1607-1632, 1989.

Lin, B., and W.B. Rossow, “Precipitation water path and rainfall rate estimates over oceans using special sensor microwave imager and International Satellite Cloud Climatology Project data,” *J. Geophys. Res.*, 102, pp. 9359-9374, 1997.

Li, R., Q. Min, and B. Lin, “Estimation of evapotranspiration in a mid-latitude forest using the Microwave Emissivity Difference Vegetation Index (EDVI)”, *Remote Sensing of Environment*, 113, pp. 2011-2018, doi:10.1016/j.rse.2009.05.007, 2009

Lin, B., B. Wielicki, P. Minnis, and W. B. Rossow, “Estimation of water cloud properties from satellite microwave, infrared, and visible measurements in oceanic environments. I: Microwave brightness temperature simulations,” *J. Geophys. Res.*, vol. 103, pp. 3873-3886 1998.

Lin and Minnis 2000, “Temporal variations of land surface microwave emissivities over the ARM southern great plains site”, J. App. Meteor., 39, 1103-1116, 2000.

Lin B., P. Minnis, A. Fan, J. Curry and H. Gerber, “Comparison of cloud liquid water paths derived from in situ and microwave radiometer data taken during the SHEBA/FIREACE,” *Geophysical Research Letters.,* vol. **28,** pp. 975–978, 2001

McClathey, R. A., Fenn, R. W., Selby, J. E. A.., Voltz F. E., and Garing, J. S., “Optical properties of the atmospherem,” Air Force Cambridge Research Laboratories, AFCRL-72-0497. Environmental Research Papers, 411, 1972.

Min, Q., “Impacts of aerosols and clouds on CO2 uptake over Harvard Forest,” J. Geophys. Res, vol. 110, D06203, doi:10.1029/2004JD004858, 2005.

Min, Q. and B. Lin, “Remote sensing of evapotranspiration and carbon uptake at Harvard Forest,” 2006: Remote Sensing of Environment, vol. 100 , pp. 379 – 387, 2006a.

Min, Q. and B. Lin, “Determination of spring onset and growing season duration using satellite measurements,” Remote Sensing of Environment, vol. 104, pp. 96-102, 2006b.

Min Q., S. Wang, “Clouds modulate terrestrial carbon uptake in a midlatitude hardwood forest,” *Geophys. Res. Lett.,* vol. 35, L02406, doi:10.1029/2007GL032398., 2008.

Mu Q., M. Zhao, F.A. Heinsch, M. Liu, H. Tian and S.W. Running, “Evaluating water stress controls on primary production in biogeochemical and remote sensing based models,” *Journal of Geophysical Research,* vol. 112, p. G01012, 2007.

Myneni, R. B., F. B. Hall, P. J. Sellers, A. L. Marshak, “The interpretation of spectral vegetation indices,” IEEE Trans. GeoSci. Remote Sens. Vol. 33, pp. 481-486, 1995.

Myneni et al., 2007: “Large seasonal changes in leaf area of amazon rainforests,” Proc. Natl. Acad. Sci., vol. 104, pp. 4820-4823, doi:10.1073/pnas.0611338104.

Nemani RR, Running SW, “Testing a theoretical climate-soil-leaf area hydrological equilibrium of forests using satellite data and ecosystem simulation,” *Agric. Forest Meteorol.*, vol. 44, pp. 245–260, 1989.

Nishida, K., R. R. Nemani, S. W. Running, and J. M. Glassy, “An operational remote sensing algorithm of land surface evaporation,” J. Geophy. Res., 108(D9), vol. 427, doi:10.1029/2002JD002062, 2003.

Njoku E. G., AMSR Land Surface Parameters, **“**Surface Soil Moisture, Land Surface Temperature, Vegetation Water Content,”ATBD of AMSR-E Science Team, NASA EOS Project, 1999.

Njoku, E., AMSR-E/Aqua L2B Surface Soil Moisture, Ancillary Parms, & QC EASE-Grids V002, Boulder, Colorado USA: National Snow and Ice Data Center. Digital media. 2007 updated daily.

Prigent, C., F. Aires, W. B. Rossow, E. Matthews, "Joint characterization of vegetation by satellite observations from visible to microwave wavelength: A sensitivity analysis." *J. Geophys. Res.* 106: pp. 2373-86, 2000.

Paloscia, S. & Pampaloni, P., "Microwave vegetation indexes for detecting biomass and water conditions of agricultural crops." *Remote Sensing of Environment*, 40, 15-26, 1992.

Running, S.W., and J.S. Kimball, *Satellite-based analysis of ecological controls for land-surface evaporation resistance. Encyclopedia of Hydrological Sciences*. Vol. 5., M.G. Anderson and J.J. McDonnell (Eds.), John Wiley & Sons Ltd. 2005.

Sellers, P. J., "Canopy reflectance, photosynthesis, and transpiration," Intl. J. Remote Sens. Vol. 6, pp. 1335-1372, 1985.

Shi J., T. Jackson, J. Tao, J. Du, R. Bindlish, L. Lu, and S. Chen, "Microwave vegetation indices for short vegetation covers from satellite passive microwave sensor AMSR-E", *Remote Sensing of Environment*, 112, pp. 4285-4300, 2008.

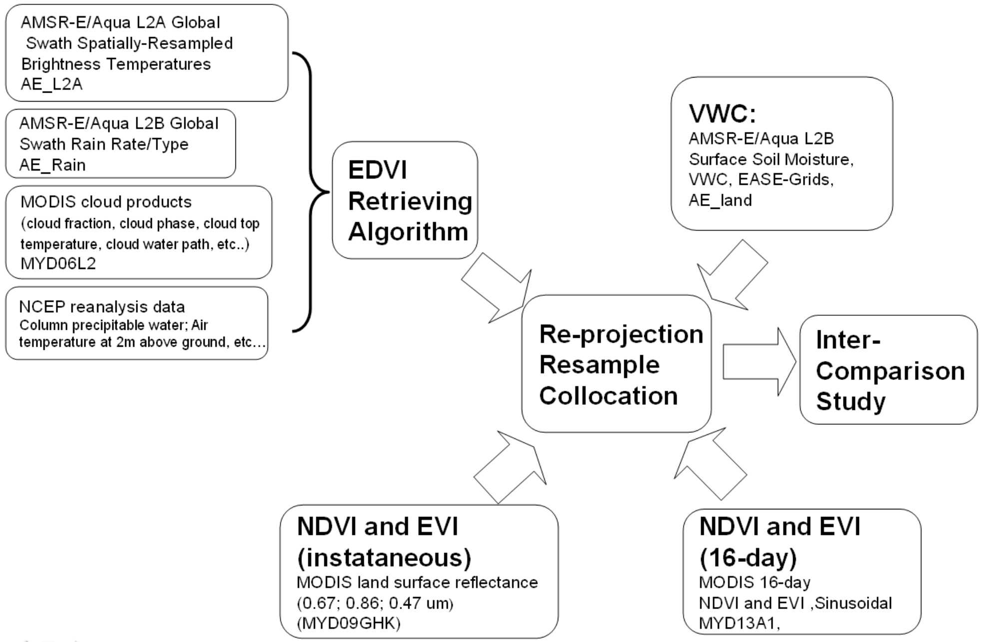
Vivekanandan, J., J. Turk, G.L. Stephens and V.N. Bringi, "Microwave radiative transfer studies using combined multiparameter radar and radiometer measurements during COHMEX," *J. Appl. Met.*, vol. 29, pp. 561-585, 1990.

Wigneron, J.-P., J.-C. Calvet,, Y.H. Kerr, A. Chanzy, and A. Lopes, “Microwave emission of vegetation: sensitivity to leaf characteristics,” IEEE Trans. Geosci. Remote Sensing, vol. 31, pp. 716-726, 1993.

Wigneron, J.-P., J.-C. Calvet, T. Pellarin, A.A. Van de Griend, M. Berger, P. Ferrazzoli, “Retrieving near-surface soil moisture from microwave radiometric observations: current status and future plans,” Remote Sensing of Environment, vol. 85, pp. 489–506, 2003.

Wilheit, T.T., A.T.C. Chang, J.L. King, E.B. Rodgers, R.A. Nieman, B.M. Krupp, A.S. Milman, J.S. Stratigos, and H. Siddalingaiah, “Microwave Radiometric Observations Near 19.35, 92 and 183 GHz of Precipitation in Tropical Storm Cora,” *J. Appl. Meteor.*, vol. 21, pp. 1137–1145. 1982.

Figures:


AMSR-E/Aqua L2A Global
Swath Spatially-Resampled
Brightness Temperatures
AE_L2A
AMSR-E/Aqua L2B Global
Swath Rain Rate/Type
AE_Rain
MODIS cloud products
(cloud fraction, cloud phase, cloud top temperature, cloud water path, etc..)
MYD06L2
NCEP reanalysis data
Column precipitable water; Air temperature at 2m above ground, etc…
EDVI Retrieving Algorithm
VWC:
AMSR-E/Aqua L2B Surface Soil Moisture, VWC, EASE-Grids, AE_land
Re-projection Resample Collocation
Inter-Comparison Study
NDVI and EVI (instataneous)
MODIS land surface reflectance (0.67; 0.86; 0.47 um) (MYD09GHK)
NDVI and EVI (16-day)
MODIS 16-day NDVI and EVI ,Sinusoidal MYD13A1,

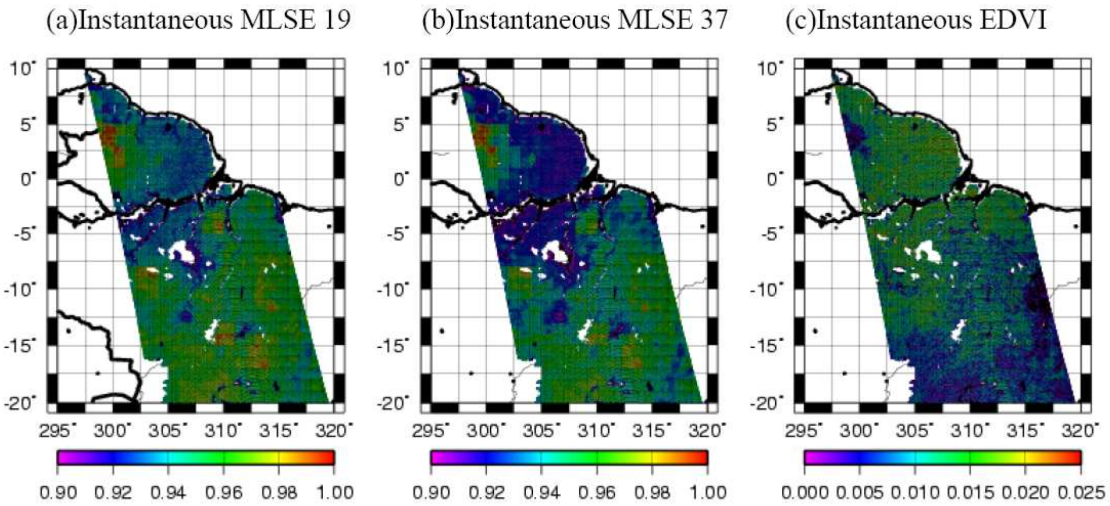

(a)Instantaneous MLSE 19
(b)Instantaneous MLSE 37
(c)Instantaneous EDVI
10°
5°
0°
-5°
-10°
-15°
-20°
295°
300°
305°
310°
315°
320°
0.90
0.92
0.94
0.96
0.98
1.00
0.000
0.005
0.010
0.015
0.020
0.025

Figure 2

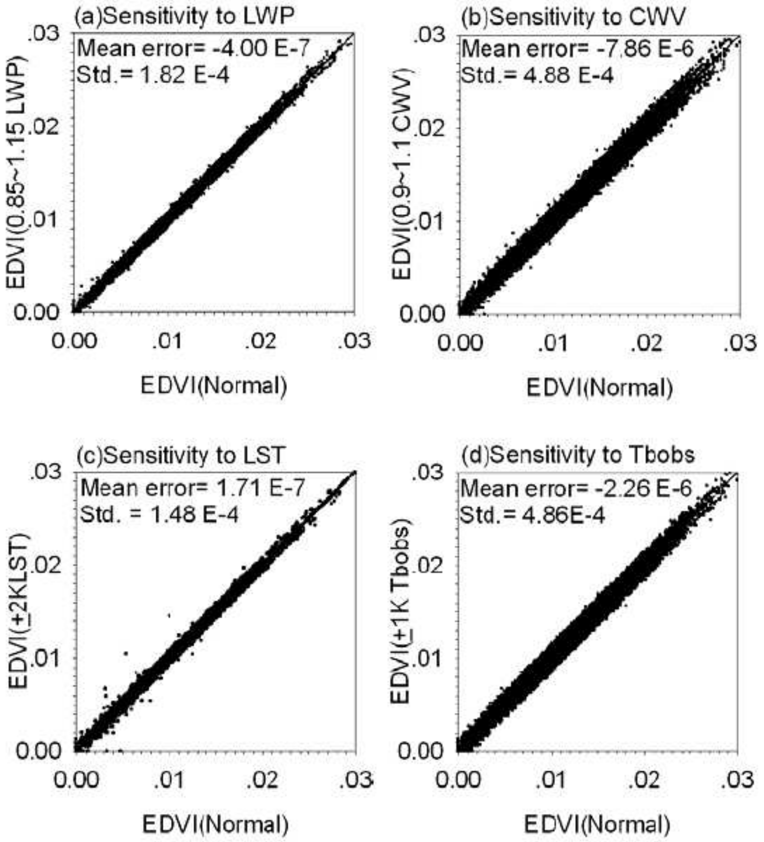
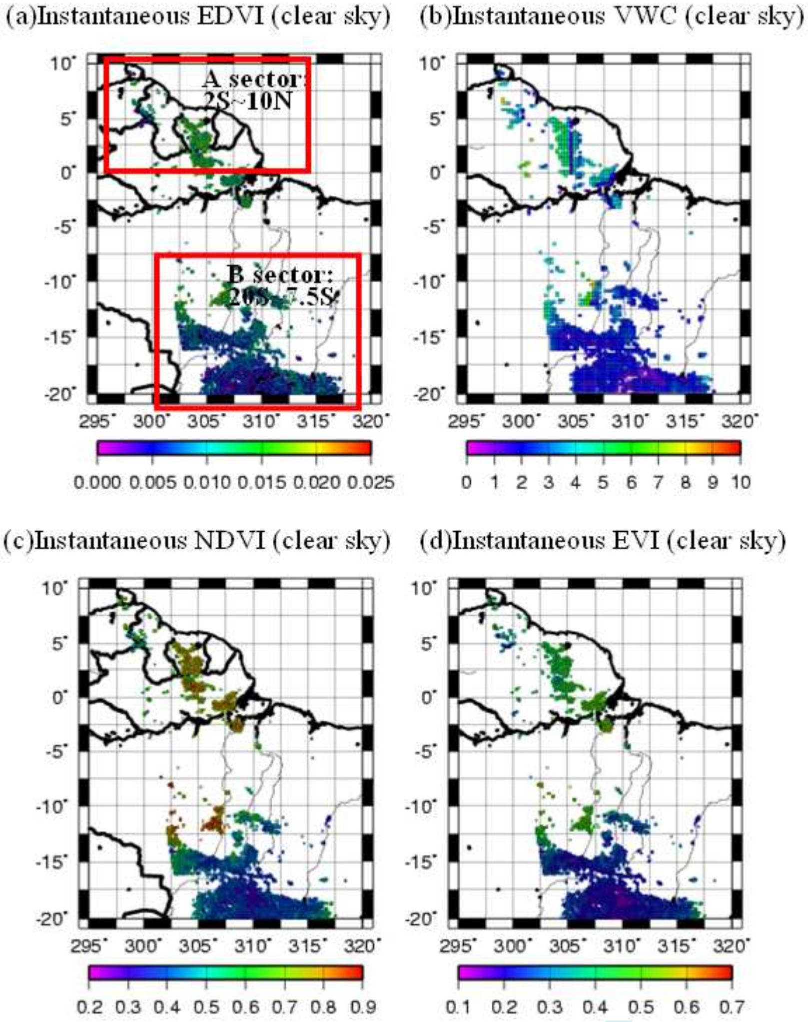

(a)Sensitivity to LWP
Mean error= -4.00 E-7
Std.= 1.82 E-4
EDVI(0.85~1.15 LWP)
EDVI(Normal)
(b)Sensitivity to CWV
Mean error= -7.86 E-6
Std.= 4.88 E-4
EDVI(0.9~1.1 CWV)
EDVI(Normal)
(c)Sensitivity to LST
Mean error= 1.71 E-7
Std. = 1.48 E-4
EDVI(±2KLST)
EDVI(Normal)
(d)Sensitivity to Tbobs
Mean error= -2.26 E-6
Std.= 4.86E-4
EDVI(±1K Tbobs)
EDVI(Normal)
0.00
.01
.02
.03

Figure 3


(a)Instantaneous EDVI (clear sky) (b)Instantaneous VWC (clear sky)

(c)Instantaneous NDVI (clear sky) (d)Instantaneous EVI (clear sky)

Figure 4

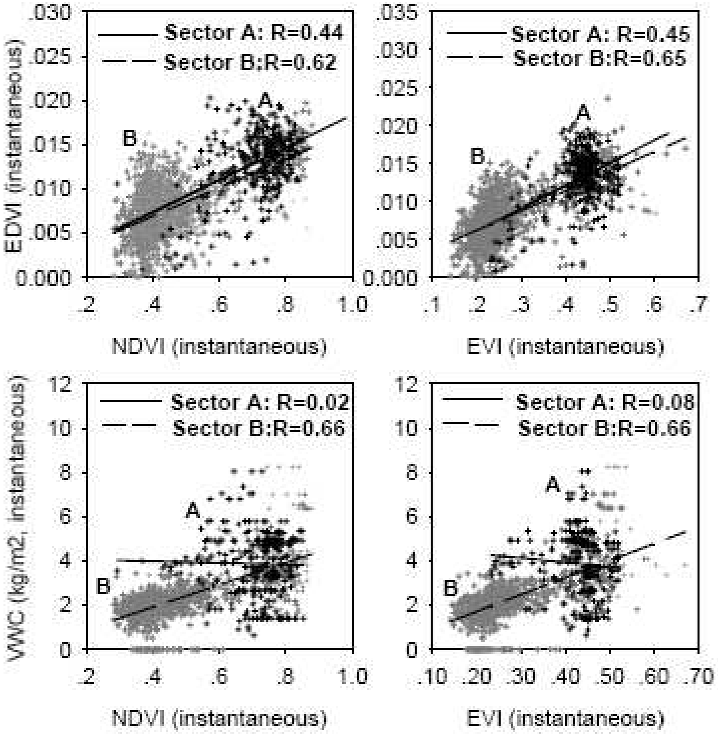


Figure 5

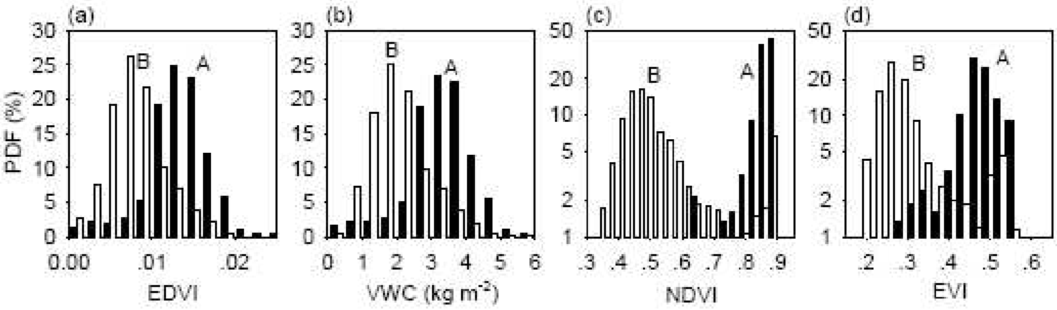


Figure 6

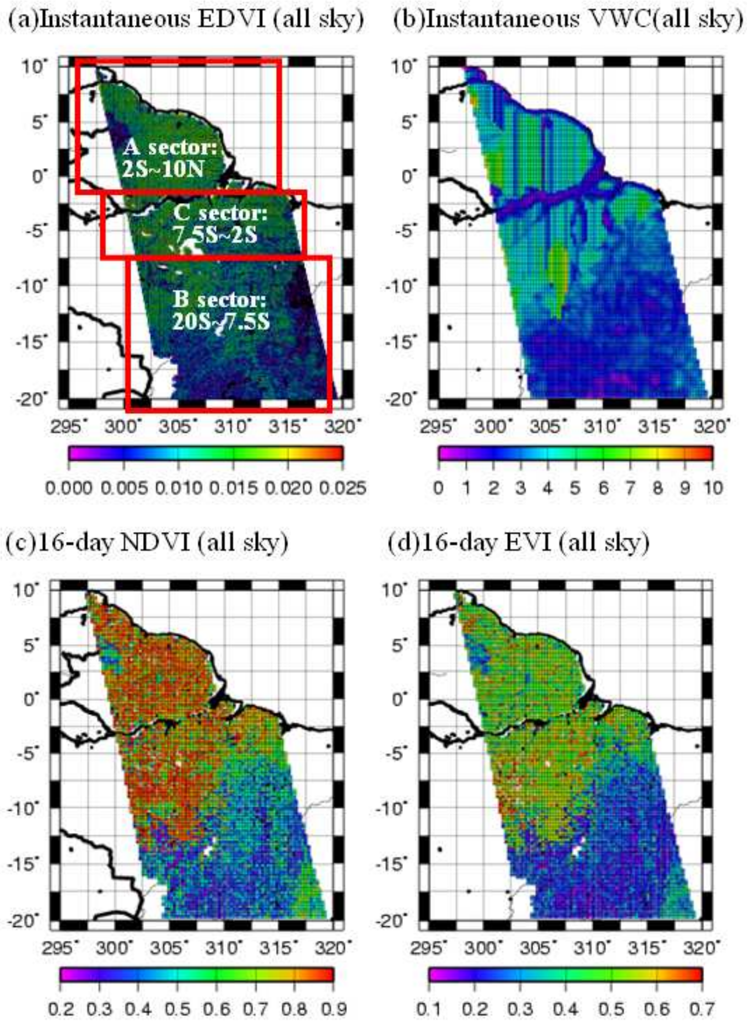

(a)Instantaneous EDVI (all sky)
(b)Instantaneous VWC(all sky)
A sector:
2S~10N
C sector:
7.5S~2S
B sector:
20S~7.5S
10°
5°
0°
-5°
-10°
-15°
-20°
295° 300° 305° 310° 315° 320°
0.000 0.005 0.010 0.015 0.020 0.025
0 1 2 3 4 5 6 7 8 9 10
(c)16-day NDVI (all sky)
(d)16-day EVI (all sky)
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0.1 0.2 0.3 0.4 0.5 0.6 0.7

Figure 7

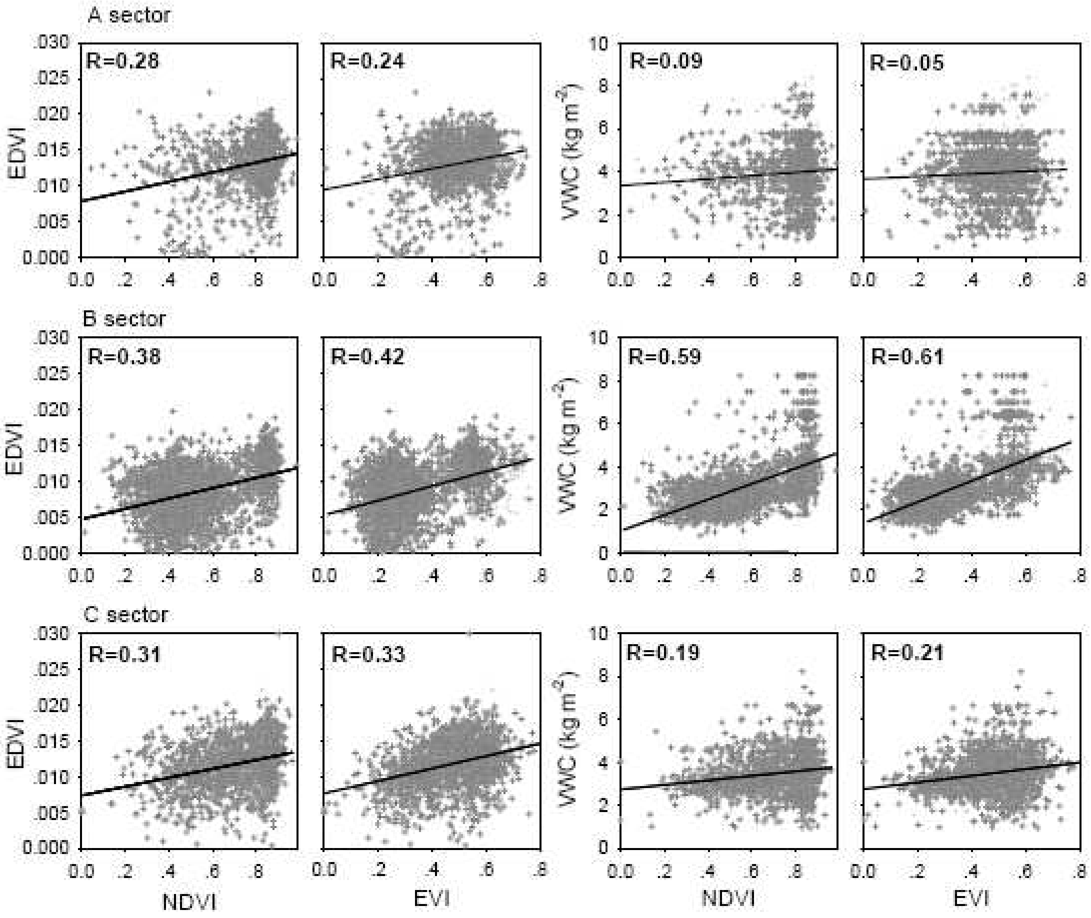

A sector
B sector
C sector
R=0.28
R=0.24
R=0.09
R=0.05
R=0.38
R=0.42
R=0.59
R=0.61
R=0.31
R=0.33
R=0.19
R=0.21
EDVI
VWC (kg m^{-2})
.030
.025
.020
.015
.010
.005
0.000
10
8
6
4
2
0
0.0
.2
.4
.6
.8
NDVI
EVI

Figure 8

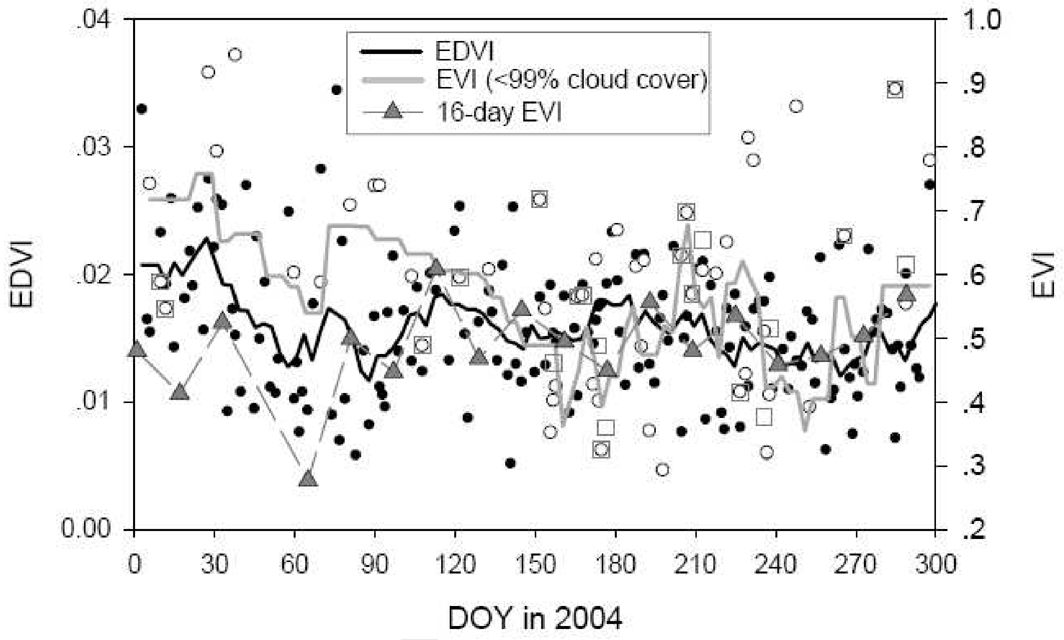

EDVI
EVI (<99% cloud cover)
16-day EVI
EDVI
EVI
.04
.03
.02
.01
0.00
1.0
.9
.8
.7
.6
.5
.4
.3
.2
0
30
60
90
120
150
180
210
240
270
300
DOY in 2004

Figure 9

We thank the reviewer for very thorough and constructive comment. Those comments and suggestions help us a lot to improve the quality of the paper. Below are our responses to those comments. The response (in *Italic*) follows each comment.

Reviewer: 1
Comments to the Author
General comments

In this study, passive microwave observations are used to analyze the hydrological state of the vegetation, to complement the visible and near-infrared measurements that are limited by the cloud cover and saturation problems.

The relationship between microwave-related indices and vegetation is not new and has been documented in the past (e.g., Tucker et al., IJRS, 1989; Justice et al., IJR, 1989; Prigent et al., JGR, 2001). Similar conclusions were drawn related to cloud sensitivity and saturation effects by the previous studies.

From the title of the study, the reader expects that the authors will attempt to quantify some vegetation parameters. Unfortunately, this paper does not provide more than previously published.

Answer:
The use of microwave signals to monitor soil moisture and vegetation property has a long history. However, how to choose an optimal microwave-related vegetation index is far from over. What we proposed here is a new index, completely different from previous microwave-related indices. For example, the microwave polarization difference temperature (MPDT) was defined as Tb37V-Tb37H. The MPDT index generally decreases with increasing vegetation in the FOV. As reported by Justice et al (1989), MPDT can only monitor seasonal variations in grassland with strong seasonality, but does not successively capture the seasonal variations for trees and shrubs. In other words, for dense vegetation covers, a new microwave vegetation index is need. As demonstrated by Min and Lin (2006a,b), the EDVI has a good capability to monitor the seasonal variations in dense vegetation (i.e. the Harvard Forest). It is sensible to test its performance in Amazon rainforest. The results in this paper are encouraging and the new index brings new information into the literature.

Another difference between our EDVI and previous microwave indices is that the EDVI is based on surface emissivity retrieved after carefully removing impacts of clouds, water vapor, and other atmospheric factors (atmosphere correction). Most indices directly use microwave brightness temperatures. Therefore, the EDVI is less influenced by clouds and capable for all weather applications

We added a paragraph in the introduction to briefly review previous studies about microwave-related vegetation indices:

“There is a long history to use passive microwave measurements for monitoring vegetation and soil properties. Many researches related microwave polarization difference temperature of 37 GHz (MPDT) to soil moisture, surface roughness, canopy structure and vegetation content [Choudhury and Tucker, 1987; Becker and Choudhury, 1988; Kerr and Njoku, 1990; and Paloscia and Pampaloni, 1992], as MPDT decreases with increasing vegetation. Justice et al [1989] found that MPDT is more sensitive to short vegetation (grass) than to dense vegetation (trees and shrubs). Calvet et al [1994] simulated the sensitivity of multiple channel microwave brightness temperature and normalized polarization differences (at 6.6, 10.7, 18 and 37 GHz) to biomass and air temperatures in the boundary layer. They found the biomass effect is better discriminated at lower frequencies. Background soil emission signals can make significant contributions to those vegetation indexes and let the physical explanations difficult. Recently, Shi et al [2008] proposed a new microwave vegetation index (MVIs) for short vegetation covers, based on the finding that bare soil emissions at two adjacent frequencies of AMSR-E are highly correlated and can be expressed as a liner function. As pointed out by Prigent et al. [2001], atmospheric effects, especially cloud cover, is responsible for a large part of the polarization difference and brightness temperatures, casting doubt on the interpretation of simple indexes solely in terms of surface properties.”

The authors talk about what could be done with these indices (vegetation state, ET…) but do not provide any evaluation or prove of it.

The results are discussed very superficially over a limited area and a short period of time, and the conclusions cannot be easily generalized.

One variable that is key in the study, the water vegetation content (VWC) derived from the microwave observations, is not at all described. The general conclusions let the reader think that the vegetation state has been carefully quantified, which is clearly not the case.

The paper is well written and structured, but it does not bring any new insights. As a consequence, the study should be extended to a longer time period and larger zone, with an attempt to quantify the hydrological state of the vegetation, before it can be published.

Answer:
The EDVI index was first proposed by Min and Lin (2006a). We showed potential application of EDVI for estimating ET and CO2 fluxes. Min and Lin (2006b) further demonstrated its application in monitoring seasonal variations in mid-latitude forest. Recently, Li, Min and Lin (2009) developed a retrieval algorithm that directly uses EDVI to quantitatively retrieve ET. The goal of current study is to test and to assess the performance of EDVI in Amazon rainforest. To retrieve ET and/or CO2 using EDVI in regional scale (Amazon) is our next step.

In the introduction of this revision, we stated:
“To overcome the above limitations, we developed a novel technique that links vegetation properties and ET fluxes with an “emissivity difference vegetation index” (EDVI) [Min and Lin 2006a; b; Li et al., 2009]. EDVI is derived from a combination of satellite microwave

measurements with visible and infrared observations through accurately atmospheric correction. This technique is applicable under all-weather conditions for monitoring vegetation biomass and ecosystem exchange processes. In order to demonstrate the capability of EDVI technique over large spatial domain for regional and global applications, the technique should be tested in various climate conditions.

The Amazon Basin contains almost one-half of the world's undisturbed tropical evergreen forest as well as large areas of tropical savanna. The forests account for about 10% of the world's terrestrial primary productivity and the carbon stored in land ecosystems. Furthermore, the Amazon region generally has significant cloudiness although it varies greatly between the wet and dry seasons. As moderate cloudy skies substantially enhance ET and carbon uptake, it is crucial to understand vegetation-atmosphere feedback under all weather conditions [Min 2005; Min and Wang, 2008]. Due to the excessive cloudiness in the region, the classic vegetation indexes from optical sensors may bias or even fail to provide information of vegetation structure and distribution. In this study we applied this technique to the Tropics to illustrate its applicability for various vegetation and weather conditions. We retrieved the EDVI index over the Amazon Basin by mainly combining AMSR-E and MODIS measurements from Aqua for the year 2004."

As shown in the paper, extensive intercomparisons between EDVI and NDVI (EVI and VWC) are discussed over a quite large domain of $10^{\circ} \times 30^{\circ}$ *with a ten-month long dataset. We fully understand the desire of the reviewer for a longer time period and larger zone. This paper just illustrates the capability of EDVI for vegetation states. Actually, we are developing a 6-year long dataset over entire Amazon region, using the same methodology.*

The VWC is a standard product of AMSR, AE_land. The detailed description of the algorithm and the dataset can be found in Njoku (1999, 2007).

More detailed comments

p. 6. The link between the EDVI and the VWC is very vague. There is no explanation how the VWC is estimated and at no point in the text it is evaluated. 'The EDVI is related to the canopy properties of VWC and structure of the two effective emission layer'. How is it derived? Where is it proved?

Answer:
As discussed above, the VWC is a standard product of AMSR_E. Extensive evaluation has been conducted by the AMSR-E team (Njoku, 2007). The relationship between EDVI and vegetation water content was discussed in Min and Lin (2006a,b).

p.7. The vertical component of the EDVI has a higher correlation with vegetation state…'. Why is it so? H polarization is usually more sensitive to the surface properties. Could it be because the atmosphere has also more impact of the H polarization?

Answer:

In page 9 of this revision, we added this statement:

"As indicated by the study of Min and Lin [2006a, b], the horizontal component of the EDVI is generally more sensitive to a broader range of canopy properties, such as VWC, canopy leaf/stem structure, and orientation, with a larger dynamic range. The crosstalk among these canopy properties may reduce the correlation of the horizontally polarized EDVI with the specific variable evapotranspiration fraction (EF), i.e, evapotranspiration. As shown by Min and Lin [2006a], the vertical component of the EDVI has a higher correlation with vegetation state and evapotranspiration than the horizontal component. Thus, we used the vertical component of EDVI in the following discussion."

p.9. 'There is moisture gradient from north to south'. Moisture or vegetation? Or both? How are the two components separated?

Answer:

As stated in the paper, MLSE is indicative of moisture conditions of combined canopy and underneath soil. The two components can not be separated by MLSE. We modify the sentence as "There is clearly soil moisture and vegetation gradient from north to south …"

p. 10. Could you indicate the reference point for the sensitivity analysis? For the CWV for instance, it is very different if the reference point is 0.05kg/m2 or if it is 0.5kg/m2….

Answer:

There is no fixed reference point in the sensitivity analysis. We randomly perturbed each parameter within its maximum uncertainty based on its uncertainty assessment, and compared the perturbed retrievals with the normal retrievals. These bias are set to be ±15% in LWP, ±10% in CWV, ±2 K in LST, and ±1 K in microwave Tb, based on possible measurement uncertainty. The sensitive analysis evaluates the difference of retrievals between "true" and "perturbed" parameters to assess the retrieval errors.

p.10. The numbers 98% and 14% respectively for microwave observations and VIS/IR observations are derived from one orbit only over 10°x30°. These numbers are presented as if they were representative of general conditions. This is clearly not the case.

Answer:

In the Amazon basin, cloud cover is excessive even during the dry season. August 30, 2004, a normal dry season day, was randomly selected. Certainly to be more representative, we will assess this using our ongoing 6-year long dataset.

In this revision, we clarified this in page 11::

"... we compared those indexes in the clear-sky subset of the same Aqua orbit data on August 30, 2004, shown in Figure 4. In this 10^{o} x 30^{o} domain, the percentage of clear-sky pixels in this normal dry season day is less than 14%....However, over the same domain microwave based EDVI can provide the vegetation information over 98% of the land (Figure 2c).*”*

p. 15. Missing reference. Li et al.

Answer:

Yes, we already added it into the reference list.

We thank the reviewer for very thorough and constructive comment. Those comments and suggestions help us a lot to improve the quality of the paper. Below are our responses to those comments. The response (in *Italic*) follows each comment.

Reviewer: 2
Comments to the Author

The authors attempt to show that a microwave emissivity vegetation index (EDVI) developed in previous papers by Min et al. (2006a,b) does not saturate in dense vegetation and offers significant potential to monitor vegetation canopies in the Amazon above that which is provided by optical IR observations (NDVI and EVI). The authors translate previous results from the Harvard forest and project these to the Amazon with little consideration of how characteristics of vegetation in the Amazon might differ from those of Harvard forest. The theoretical underpinnings of EDVI given in Min (2006a) to justify the use of EDVI for temperate forests do not seem to translate directly to the Amazon.

Simulations from Min (2006a) show that EDVI apparently saturates at VWC of 0.7 kg m-2 and in the present manuscript where VWC is on the order of 1-6 kg m-2 (or more) the authors argue that the index does not saturate.
Furthermore, Min (2006a) used a radiative transfer model that neglects multiple-scattering, a mechanism that likely produces much of the results observed with the EDVI and is likely to dominate the EDVI response in the Amazon at the frequencies considered.

Additionally, sub-pixel open water and wetlands are temporally dynamic and extensive in the Amazon region and poses significant problems for microwave radiometry of the land surface, especially channel gradient approaches such as the one presented in this manuscript, by masking the emission of the land fraction within the pixel. The problem of open water was not mentioned in this manuscript. It should be mentioned and its effects considered in the analysis.

Unclear physical justification could be bolstered by strong empirical evidence, but such evidence was also absent from this manuscript. Comparisons were only made to NDVI and EVI which apparently saturate.

The authors present no other independent in situ or additional ancillary information with which to test their saturation hypothesis. The authors compare only one day of data (Aug. 30, 2004) for the bulk of their findings.

The manuscript lacks attention to detail in methods and also in the data analysis.

Language is generally imprecise and the authors seem to make several claims that are not substantiated by the data they present (see detailed comments). The manuscript also largely ignores relevant microwave radiometry work previously done in the Amazon region by others. Previous investigations by Calvet et al. (1994) and Prigent et al. (2001) should be mentioned:

Calvet, J. C., J. P. Wigneron, E. Mougin, Y. H. Kerr, J. L. S. Brito. Plant water content and temperature of the Amazon forest from satellite microwave radiometry. 1994. IEEE Trans. Geosic. Rem. Sens. 32(2): 397-408.

Prigent, C., F. Aires, W. B. Rossow, E. Matthews. 2000. Joint characterization of vegetation by satellite observations from visible to microwave wavelength: A sensitivity analysis. J. Geophys. Res. 106: 2373-86.

Additionally the manuscript has some organizational problems. Most of the first portion of the Results section, up to about pg 10 ln 37, belongs in the Methods or the Discussion sections. The results section should only include results, not discussion of findings or justification of methods, etc.

Answer:
First, as shown in Figure 6 in the revision (Figure 5 in the previous version), the histograms of EDVI inside both sectors are close to a Gaussian distribution. The maximum occurrences of EDVI for sectors A and B are at values of about 0.12 and 0.08, respectively. It indicates that there are no signs of saturation of EDVI even for the densest vegetation in the world, the rainforest of the Amazon Basin. We did analyze 10-month long data, which draw the same conclusion.

It is true that characteristics of vegetation in Amazon might differ from those of Harvard forest. As discussed by Min and Lin (2006a,b), EDVI is mainly related to the canopy properties of vegetation water content between two effective emission layers. The absolute values for a given VWC in the crown layer may be different in Harvard forest and Amazon, the general dependency of VWC should be similar.

We also included this discussion in page 5 of this revision:

"This technique was demonstrated applicable under all-weather conditions for monitoring vegetation biomass and ecosystem exchange processes in Harvard forest. The characteristics of vegetation in Amazon might differ from those of Harvard forest. As discussed by Min and Lin (2006a,b), EDVI is mainly related to the canopy properties of vegetation water content between two effective emission layers. Although the absolute values for a given VWC in the crown layer may be different in Harvard forest and Amazon, the general dependency of VWC should be similar."

Because EDVI is defined as the microwave emissivity difference between two wavelengths, which minimizes the influence of the soil emission underneath vegetation canopy and is sensitive to VWC and other vegetation properties between two emission layers in different effective thickness. Min and Lin (2006a,b) further proposed a simple two-layer model that considers the crown layer of the forest to be a homogenous absorbing and scattering medium above an emission layer of the soil-trunk. The important point is that the EDVI is sensitive to the VWC in the crown layer of the canopy not the entire column of the canopy. Most water of a tree is contained in the truck. The

VWC in the crown layer is relatively small but photosynthetically important.

Although the simple two-layer model of Min and Lin (2006a) shows EDVI saturates at about the value of 0.7 kg/m^2*, it may not reflect real world since the model does not account for multiple scattering effects and only has the 1*st *order scattering influences (single scattering). With considerations of full multiple scattering, the increase of EDVI with VWC is going to be slower than what we simulated (Fig.2b in Min and Lin 2006a), and the saturation point of EDVI on VWC should be much higher. More importantly, the VWC used in the current study is a standard product of AMSR_E, represnting the vegetation water content in the entire column (including trucks). So the values of VWC are quite large (1-6 kg m-2). That is one of reason that VWC from AMSR_E does not correlate to NDVI and EDI well in the dense vegetation region. In the revision, we clearly state how the VWC retrieved and what the VWC represents for.*

In page 13 of this revision, we included this discussion:

"Furthermore, as shown in Figure 6, the histograms of EDVI inside both sectors are close to a Gaussian distribution. The maximum occurrences of EDVI for sectors A and B are at values of about 0.12 and 0.08, respectively. They show no sign of saturation of EDVI even for the densest vegetation in the world, the rainforest of the Amazon Basin. It is worth noting that although the simple two-layer model of Min and Lin (2006a) shows EDVI saturates at about the VWC value of 0.7 kg/m^2*, it may not reflect real world since the model does not account for multiple scattering effects and only has the first order scattering influences (single scattering). With considerations of full multiple scattering, the increase of EDVI with VWC is going to be slower than what we simulated (Fig.2b in Min and Lin 2006a), and the saturation point of EDVI on VWC should be much higher. On the other hand, the VWC used in the current study is a standard product of AMSR_E, representing the vegetation water content in the entire column (including trucks and branches), however, the EDVI is sensitive to the VWC in the crown layer of the canopy not the entire column of the canopy. From Figure 6b, a similar conclusion can be drawn for microwave based retrievals of VWC, which also show similar distributions to the EDVI histograms. In contrast, as shown in Figure 6c, the histograms of NDVI illustrate bi-mode distributions. NDVI is clearly saturated with distribution skewed to a high value of 0.9. Having similar characteristics to NDVI, EVI exhibits much less problem of saturation than NDVI. "*

Sub-pixel inhomogeneity, particularly open water and wetland, does pose significant problems for microwave radiometry of the land surface. We used the emissivity difference between two frequencies. The impacts of soil moisture open water are reduced. However, it is still a big issue.

In the conclusion section of this revision, we stated:
"As a new microwave-related vegetation index, the interpretations of EDVI deserve more detailed studies. The multiple scattering from trees may play an important role in determining the upward microwave signals. And sub-pixel contamination due to open water and wetlands may also introduce additional uncertainties in the EDVI retrievals."

We will combine high spatial resolution optical indices with high temporal EDVI. For doing so, information of vegetation fraction (and open water fraction) provided by optical indices will help us to minimize the sub-pixel inhomogeneity problem. We added discussion into the revision.

The EDVI index was first proposed by Min and Lin (2006a). We showed potential application of EDVI for estimating ET and CO2 fluxes. Min and Lin (2006b) further demonstrated its application in monitoring seasonal variations in mid-latitude forest. Recently, Li, Min and Lin (2009) developed a retrieval algorithm that directly uses EDVI to quantitatively retrieve ET. The goal of current study is to test and to assess the performance of EDVI in Amazon rainforest. We added a figure (Figure 1 in the revision) and related discussion about what data and how to retrieve and compare the EDVI using visible, infrared, and microwave measurements. We modified manuscript following reviewer's suggestion.

We also added a paragraph in the introduction part to briefly review previous studies (including Calvet et al 1994 and Prigent et al 2000) of using microwave measurements to monitor vegetation properties.
In page 4-5 in this revision, we stated:
"There is a long history to use passive microwave measurements for monitoring vegetation and soil properties. Many researches related microwave polarization difference temperature of 37 GHz (MPDT) to soil moisture, surface roughness, canopy structure and vegetation content [Choudhury and Tucker, 1987; Becker and Choudhury, 1988; Kerr and Njoku, 1990; and Paloscia and Pampaloni, 1992], as MPDT decreases with increasing vegetation. Justice et al [1989] found that MPDT is more sensitive to short vegetation (grass) than to dense vegetation (trees and shrubs). Calvet et al [1994] simulated the sensitivity of multiple channel microwave brightness temperature and normalized polarization differences (at 6.6, 10.7, 18 and 37 GHz) to biomass and air temperatures in the boundary layer. They found the biomass effect is better discriminated at lower frequencies. Background soil emission signals can make significant contributions to those vegetation indexes and let the physical explanations difficult. Recently, Shi et al [2008] proposed a new microwave vegetation index (MVIs) for short vegetation covers, based on the finding that bare soil emissions at two adjacent frequencies of AMSR-E are highly correlated and can be expressed as a liner function. As pointed out by Prigent et al. [2001], atmospheric effects, especially cloud cover, is responsible for a large part of the polarization difference and brightness temperatures, casting doubt on the interpretation of simple indexes solely in terms of surface properties."

Detailed Comments:

Pg 2 ln 25: "…spare vegetation…"

Does the author mean "sparse vegetation?" This apparent mistake occurs numerous times throughout the manuscript. Also, labeling savannahs as "sparse" vegetation seems a bit misleading, considering that savannahs can be quite productive, especially during the rainy season. Perhaps the author can think of a more accurate term.

Answer:

We use "short and sparse vegetation" for savannahs in our revision.

Pg 3 ln 55: "NDVI may represent vegetation water content (VWC) of leaves but only for low NDVI cases." Please be more precise by giving a number.

Answer:

NDVI is directly linked to the leaf chlorophyll absorption, which has some relationship with vegetation water content. NDVI will saturate at LAI of about 3.0. We changed the sentence to "NDVI may represent total vegetation water of leaves when it is not saturated [Hong et al. 2007]."

Pg 4 ln 4: "Because of the rapid change of vegetations during spring onset and fall senescence, these indexes cannot accurately capture the transitions of vegetation states during growing seasons."

The indices are unable to capture spring onset and fall senesce because vegetation is changing rapidly? It seems that if the indices saturate for high biomass conditions that they would be better able to capture vegetation changes under spring and fall transitions when canopy biomass is reduced than under mid-growing season conditions when biomass is near maximum levels. Please explain.

Answer:

Because NDVI and other optical indices can not be retrieved under cloudy conditions, most available datasets of NDVI are 16-day composite or at least 8-day composite. The spring and fall transitions are about 20 days or so. It is difficulty to use such composite dataset to monitor such variation accurately, particularly to detect spring onset. We changed the sentence to "Because of the rapid change of vegetations during spring onset and fall senescence, these multi-day composite indexes cannot accurately capture the transitions of vegetation states during growing seasons."

Pg 5 ln 34: "Current assessment of the global water and energy cycles are limited by a lack of quantitative information on the variety, distribution, and temporal variability of vegetation with important physiological and ecological function at regional and global scales. To overcome the above limitations…"

Are the authors really going to solve all these problems in one paper with one technique? This problem statement should be more narrowly focused and the authors should be more realistic about what their technique can and cannot accomplish.

Answer:

The statement is our goal, and we try to develop an approach to achieve it. We modified this part in our revision.

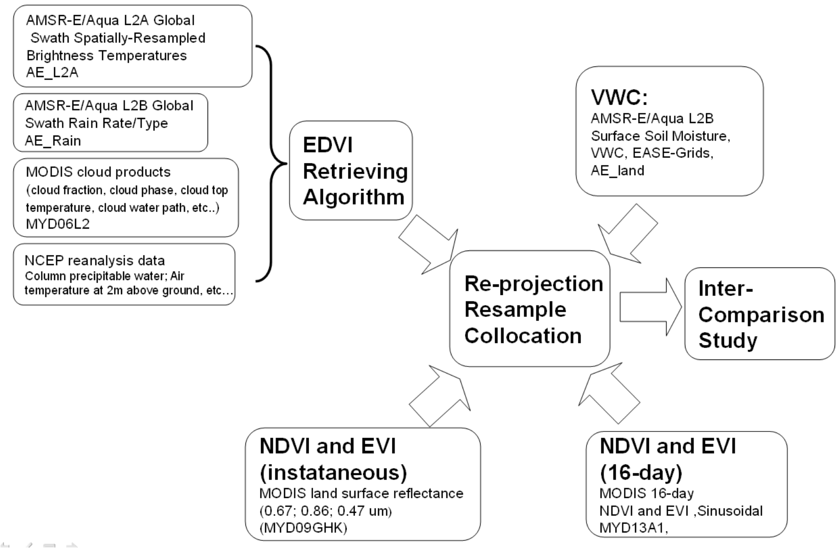
Pg 4 ln 46: "…that is derived from a combination of satellite microwave measurements with visible and infrared observations. This technique is applicable under all-weather conditions for monitoring vegetation biomass and ecosystem exchange processes…"

The authors justify their technique by stating that optical-IR remote-sensing is limited by clouds and now say that their technique employs optical-IR data. This seems like a contradiction and the authors should explain this discrepancy. The techniques described in the manuscript use model re-analysis in addition to satellite data, which were not mentioned.

Answer:

The visible and infrared observations from MODIS provide no information of vegetation under cloudy conditions. However, they do provide key information of clouds. We use this information to determine the contribution of clouds to the AMSR-E observed Tb, and then to get the net contribution from land surface. Also, we use AMSR-E rain rate retrievals to screen raining or non-raining pixels. Only non-raining cloud samples are included in current algorithm. NCEP re-analysis data are used to provide information of the air to atmosphere corrections. More detailed descriptions of what and how we use satellite and re-analysis datasets in the study are added in the revision with a new figure (Figure 1).

The added figure 1



Pg 4 ln 53: "In order to demonstrate the capability of EDVI technique…"

Is the authors' goal to demonstrate the technique or to test it? If the authors are doing science, their goal should be to "test" the technique rather than "demonstrate" it.

Answer:

We changed the word of "demonstrate" to "test", following the reviewer's suggestion.

Pg 6 ln 6: "The emissivity observed at longer wavelengths with a weaker attenuation by the canopy generally represents an effectively thicker layer than those observed at shorter and stronger attenuation wavelengths."

This statement is misleading given the previous sentences about optical depth. A greater optical depth means stronger attenuation by definition but a shallower penetration/emission depth. The authors should make the distinction between penetration/emission depth and optical depth more clear.

Answer:
We changed it to "The emissivity observed at longer wavelengths with a weaker attenuation by the canopy generally represents an effectively thicker penetration/emission layer than those observed at shorter wavelengths with stronger attenuation."

Pg 6 ln 18: "…a minimal influence of the soil emission underneath vegetation canopy…"

Why does this index have a minimal influence on soil emission? It seems like the validity of this statement depends on the attenuation of the canopy for the specific wavelengths and polarizations that are used.

Answer:
The EDVI is defined as emissivity difference between two wavelengths, some contribution of soil emission is subtracted out. It is true that a strong attenuation of the canopy is needed to fully remove soil emission, which depends on wavelength and polarization.

Pg 6 ln 29: "Based on our studies, we chose a pair of channels at about 19 and 37 GHz…"

Why were these channels chosen? The authors should be more specific and give some reasons why this particular channel pair is better than other possible channel pairs. That MLSEP19 and MLSEP37 represent relatively thicker and thinner emission layers can be said about any pair of channels because canopy attenuation generally increases with frequency.

Answer:
AMSR-E has 4 frequencies beside the two we used. The 6.9 GHz channel has severe RFI contamination. The 23.8 GHz channel is too sensitive to water vapor. The 89.0 GHz channel is too sensitive to cloud ice. The 10.7 GHz chaanel is a good one with a different attenuation. We are currently working on using three channels to get some information of vegetation vertical structure.

Pg 7 ln 31: "…surface measurements of temperature and pressure…"

What surface measurements of temperature and pressure were used? The authors previously state that they use NCEP reanalysis surface air temperatures. These are re-analysis data, not measurements. Are the authors using surface measurements from another source? If so, how are these interpolated to a regional domain?

Answer: We changed it to "… the surface temperature and pressure as well as CWV values derived from NCEP reanalysis data"

Pg 7 ln 55: "…the vertical component of the EDVI has a higher correlation with vegetation state and evaporation than the horizontal component..."

Min and Lin (2006a, b) studied the Harvard Forest. How can the authors be sure that better results will be obtained for v-polarization in the Amazon based on results for a temperate mid-latitude forest without further testing or reasoning?

Answer:

In page 9 of this revision, we added this statement:

"As indicated by the study of Min and Lin [2006a, b], the horizontal component of the EDVI is generally more sensitive to a broader range of canopy properties, such as VWC, canopy leaf/stem structure, and orientation, with a larger dynamic range. The crosstalk among these canopy properties may reduce the correlation of the horizontally polarized EDVI with the specific variable evapotranspiration fraction (EF), i.e, evapotranspiration. As shown by Min and Lin [2006a], the vertical component of the EDVI has a higher correlation with vegetation state and evapotranspiration than the horizontal component. Thus, we used the vertical component of EDVI in the following discussion."

Pg 7 ln 13: "…we retrieved MLSE values from AMSR-E Level 2A Global Swath spatially-resampled brightness temperatures, AE_L2A, for all microwave frequencies and polarizations using a combined technique."

The authors previously stated that MLSE was defined as MLSEP19 and MLSEP37 and these are the only results that are shown in the manuscript. What happened to the results computed from all the other frequencies and polarizations? Why do the authors mention that these were computed if they were not used? What do the authors mean by "combined technique?"

Answer:
We changed it "We retrieved MLSE values of 18.7 and 36.5 GHz from AMSR-E …" The "combined technique" means combine microwave, visible and infrared signals together to retrieve EDVI.

Pg 8 ln 15: "Together with the MODIS standard product of 16-day NDVI and EVI composites (MYD13A1), we projected NDVI and EVI values into the AMSR-E spatial grids for the comparison."

Are the EDVI data on a daily timescale or were they aggregated to 16-day to compare with

MODIS? What overpasses were used, ascending, descending or both?

Answer:
We used the daytime observations from AMSR-E when quasi-simultaneous observations from MODIS are also available. For all comparison, we did not aggregate EDVI data.

Pg 8 ln 32: “The Amazon Basin…(entire paragraph)”

This paragraph should be omitted. It does not belong in the Results section or really anywhere in the manuscript.

Answer:
We moved some of this paragraph into the introduction section.

Pg 8 ln 53 to Pg 9 ln 13: “The scattering of upwelling…to minimize scattering effects on our retrievals.”

This entire section does not belong in the Results section. It belongs in the Methods section.

Answer:
We re-organized this part into the method section

Pg 9 ln 20: “MLSE is indicative of moisture conditions of combined canopy and underneath soil. There is a moisture gradient from north to south, with low MLSEs at the Amazon basin.”

Where’s the evidence for these statements? The authors previously said that MLSE is not sensitive to the underlying soil (Pg 6 ln 18), but now they say that it is? What kind of a moisture gradient is present (e.g. atmospheric moisture, canopy moisture, soil moisture, open water)?

Answer:
In P6 ln 18, we mentioned “the microwave land surface emissivity difference between two wavelengths…” not the MLSE.

We changed the “There is a moisture gradient from north to south” to “There is soil moisture and vegetation gradient from north to south” .

Pg 9 ln 51: “…land surface skin temperatures (LST) estimated from NCEP…”

The Methods state that NCEP air temperatures were used. Are NCEP air temperatures and LST both used?

Answer: Yes.

Pg 10 ln 6: "…given uncertainties of…"

The authors need some discussion of where they obtained numbers for input uncertainty and proof that they are reasonable. It would be helpful to at least have some citations.

Answer: Those uncertainties (i.e. ±15% in LWP, ±10% in CWV, ±2 K in LST, and ±1 K in microwave Tb) are selected mainly based on common measurements and/or model uncertainty assessments.

Pg 10 ln 10: "…the evaluated standard deviations range from land surface skin temperatures (LST) about 1.5 % of EDVI."

The authors only look at each error source individually, which does not give a realistic estimate of the overall error. The authors should consider the total amount of error in EDVI when all error sources are present at once.

Answer:

If assuming those parameters are independent, the total amount of error can be assessed simple mean square root of each individual parameter, So we only discussed individual parameter.

Pg 10 ln 49: "We further divided the domain into two sectors (see Figure 3a), according to spatial occurrences and vegetation conditions."

It is unclear to which "spatial occurrences" the author is referring. Does the author mean to say, "…spatial occurrences of vegetation types…?" Why did the authors choose to compare between two broad sectors? It seems that it would be more informative to compare against one of the widely available land cover classifications. Furthermore, this statement belongs in the 'Methods' section.

Answer: It means the spatial distribution of clear sky where NDVI and EVI are available.

Pg 11 ln 41 – Pg 11 ln 41: (Entire paragraph)

Why did the authors choose to compare instantaneous NDVI, EVI, and EDVI for only one day (Aug. 30, 2004)? How would these relationships look if a different day were chosen? It seems that it would be more informative to compare over a long time period to gain an understanding of the probability distribution and stability of this relationship over time.

Answer: The idea here is to firstly compare them via a case study (contains EDVI retrievals as much as ~58,000 in this case) in which detail cloud properties , raining status and meteorology conditions can be carefully checked in order to verify the performance of our retrieving algorithm. In the $10^{o} \times 30^{o}$ domain of this case, retrievals are made in different vegetation densities, under clear sky, water cloudy sky, ice cloudy sky with different cloud parameters and atmosphere status. It is reasonable to expect the results representative for other different days, as we showed in an ten-month statistic study.

Pg 11 ln 11 to ln 41: "Retrieved VWC from microwave measurements has slightly better statistics with NDVI and EVI in the sparse vegetation region (area B) than that of EDVI… Nonetheless, these statistics indicate EDVI is applicable to a variety of vegetation conditions and may even be much better than VWC for atmosphere-land interactions."

The relations shown in Fig 4 have a great amount of scatter and numerous outliers. Correlation statistics are very sensitive to outliers. It looks if the zero values and high value outliers were omitted from VWC in Figs 4c, d, then VWC would have a substantially higher correlation than EDVI for Sector B. The data seem to suggest that the additional utility of EDVI over VWC is limited to high biomass locations, contrary to the authors' conclusion.

Answer:
For area B, EDVI and VWC are comparable. As reviewer noticed, EDVI is better than VWC in the dense vegetation.

To clarify our statement, we revised the sentence as "Nonetheless, these statistics indicate EDVI is applicable to a variety of vegetation conditions for atmosphere-land interactions, Nonetheless, these statistics indicate EDVI is applicable to a variety of vegetation conditions for atmosphere-land interactions, much better than VWC in dense vegetation."

Pg 11 ln 31: "It is worth noting that although branches and trunks contain most of the water, they play a little role in the evapotranspiration and photosynthesis processes."

In fact, branches and trunks play a fundamental role in evapotranspiration and photosynthesis because without them the tree would be able to neither support itself, nor transport water between roots and leaves. Also, what do the author's mean by "most of the water?" Do they mean per unit dry weight, or the total weight of the water? Could the authors please use more precise language?

Answer:
Reviewer is right that branches and trunks play a fundamental role in evapotranspiration and photosynthesis because without them the tree would be able to neither support itself, nor transport water between roots and leaves. What we mean is the direct evapotranspiration and photosynthesis processes in leaves. We mean vegetation water in the canopy.

We changed into "It is worth noting that although branches and trunks contain most water in the tree, they play a little direct role in the leaf evapotranspiration and photosynthesis processes."

Pg 11 ln 46: "Furthermore, as shown in Figure 5, the histograms of EDVI inside both sectors are close to a Gaussian distribution… They show no sign of saturation of EDVI even for the densest vegetation in the world, the rainforest of the Amazon Basin."

How does showing that the EDVI follows a Gaussian distribution within both sectors show that EDVI does not saturate? For example: I could generate Gaussian random numbers and add them to a constant. The result would follow a Gaussian distribution, but the signal is still simply the constant. How can the authors be sure that that Gaussian variability is not just noise about a constant? Furthermore, the authors do not have any data on the distribution of vegetation density/biomass/VWC for the study area. How can they be sure that the distribution of vegetation density doesn't also have a skewed distribution that peaks at a high value? Such a distribution of vegetation is plausible because competition for light, space and other resources places an ultimate limit on plant density. See additional comment for Figure 5.

Answer:
From other indices we know that in each section the vegetation is different. And we do not have direct information about vegetation distribution. However, the distribution of EDVI is not skewed to a high value as shown in NDVI. We think that it is indicative that EDVI is not saturated whether or not the true distribution is a skewed .distribution.

Pg 12 ln 46: "These relationships get stronger and stronger from dense vegetation to spare vegetation, due in part to the saturation of optical indexes and sensitivity differences among different vegetation indexes."

This statement is false based on the information provided in Figure 7. The highest correlations are for Sector B, not for Sector A, as the statement implies.

Answer:
The sector of 7.5S~2S should be sector "C" rather than B. We already correct it in our revision.

It is necessary to clarify that A the sector with dense vegetation and B the relative short and/or sparse vegetation, and C the transition area.

The correlation between NDVI (EVI) and EDVI is highest in B sector, this is consistent with our statement.

Pg 14 ln 18: "Both EDVI and EVI decrease from the wet season to the early dry season and then increase in the late dry season. It demonstrates that EDVI captures seasonal variations of vegetation."

It is not clear to what seasonal variations the authors are referring. Whatever seasonal variation may exist in fig 8 is visually obscured by short term variability. The authors should use a timeseries statistic to show seasonal variations, if in fact such variations are detectable for this dataset.

Answer: we deleted the statement considering the short duration.

Figure 1: The checkered boarders are visually overpowering. The authors might consider making these narrower

Answer: We changed it.

Figure 5: EDVI can have very low or zero values for sector A. What is the significance of these low values if sector A is “the densest vegetation in the world” and NDVI does not even drop below 0.6? These low values were not mentioned in the manuscript. I suspect that these are caused by contamination of the microwave signal by open water. It seems that open water could cause eqn (1) to give negative values because Ev19 < Ev37 for pure water.

Answer: The very low values of EDVI in sector A is actually belongs to the area of about 2.5N-5.0N; 59.0W-61.5W (Figure 2c). In this area, very sparse vegetation are covered (Please check it using Google Earth). This feature demonstrated the validity of EDVI.

Figure 8: The symbols used in this figure and the associated explanations by the caption are confusing. The caption says that the solid circles are EDVI, while the figure legend says that the solid line, which does not pass through the solid circles, is also EDVI. Is the solid line some kind of a filter or moving average applied to the dots? Please expand the legend to include all the symbols and make sure that the legend and caption are in agreement.

Answer: Yes, solid curve are smoothed EDVI. We already fixed it in the revision.