

PT-JPL EVAPOTRANSPIRATION

REMOTE SENSING DEVELOPMENTS AT NASA'S JET PROPULSION LABORATORY

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WATER & CARBON CYCLES GROUP

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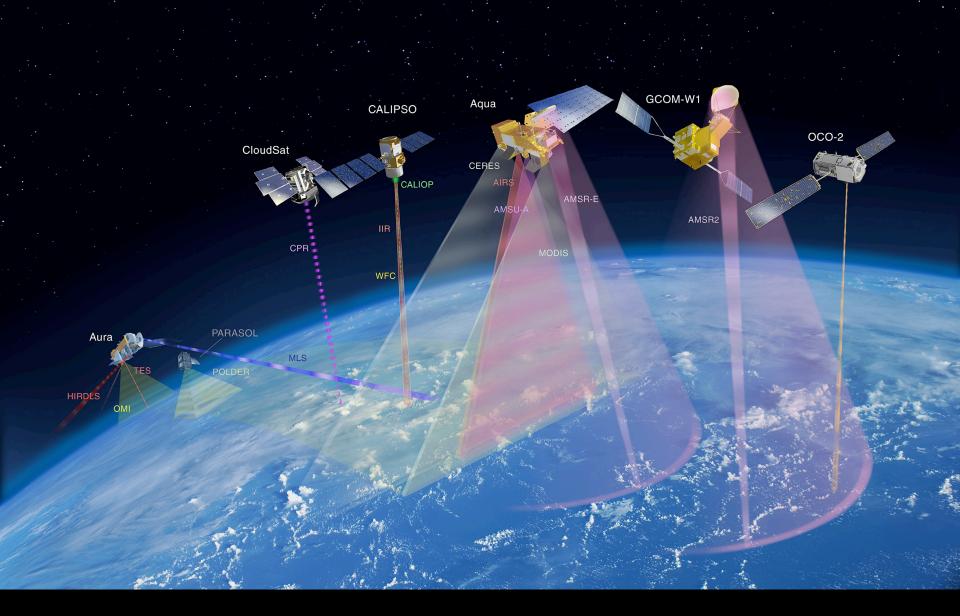
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Pasadena, California











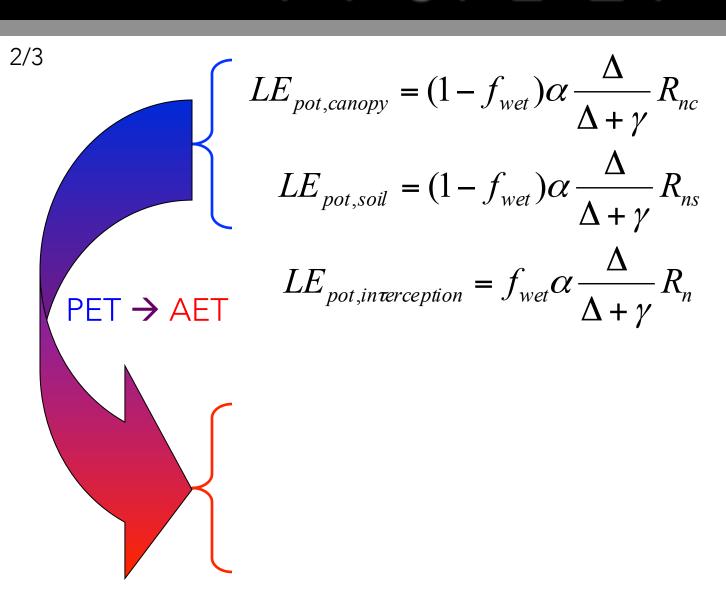
JPL EVAPOTRANSPIRATION (PT-JPL)

Global estimates of the **land–atmosphere water flux** based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites

<u>JB Fisher</u>, KP Tu, <u>DD Baldocchi</u> - Remote Sensing of Environment, **2008** - Elsevier Numerous models of evapotranspiration have been published that range in data-driven complexity, but global estimates require a model that does not depend on intensive field measurements. The Priestley–Taylor model is relatively simple, and has proven to be ... Cited by 164 Related articles All 11 versions Cite Save

1/3

$$LE_{pot} = \alpha \frac{\Delta}{\Delta + \gamma} R_n$$
 Priestley & Taylor (1972)



3/3

$$\begin{split} LE_c &= (1 - f_{wet}) \frac{f_g f_T f_M}{\Delta} \alpha \frac{\Delta}{\Delta + \gamma} R_{nc} \\ LE_s &= (f_{wet} + \frac{f_{SM}}{SM} (1 - f_{wet})) \alpha \frac{\Delta}{\Delta + \gamma} (R_{ns} - G) \end{split}$$

1.0

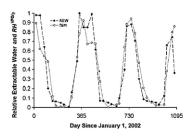


Fig. 1. Comparison of monthly f_{SM} to normalized volumetric water content (VWC), or relative extractable water - REW=(VWC-VWC_{min})/(VWC_{max}-VWC_{min}) – at an oak-assump site

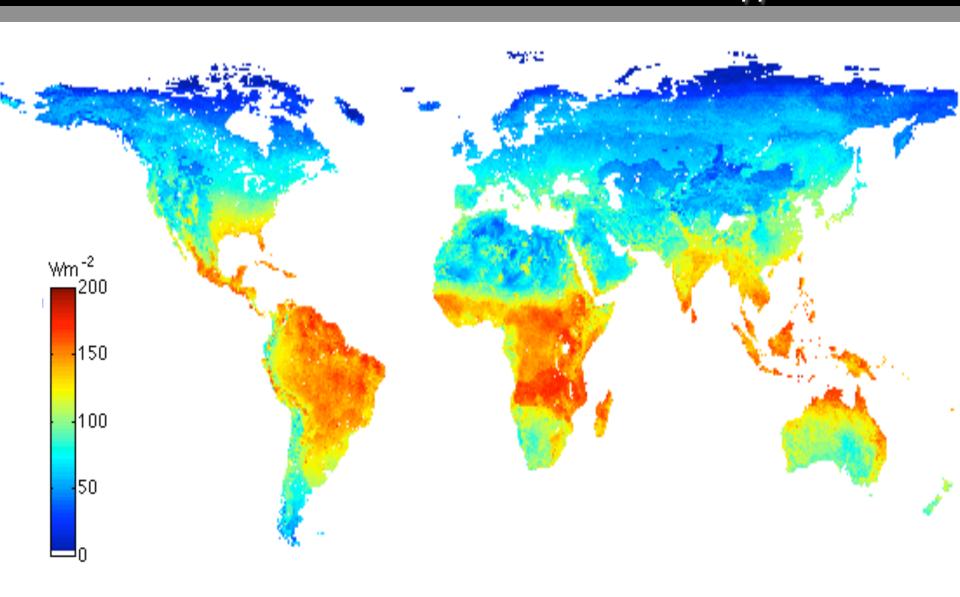
$$LE = LE_s + LE_c + LE_i$$

Net Radiation	MODIS CERES SRB ISCCP	
Air Temperature	MODIS AIRS	MODIS
Relative Humidity	MODIS AIRS	
Vegetation fraction	MODIS Landsat	MODERATE RESOLUTION IMAGING SPECTRO-RADIOMETER As imaging indiometer employing a dissipated, score insies and collecting gotors, and a set of indiplicatel designed insies of collecting gotors, and a set of indiplicatel designed in a good of the set of t

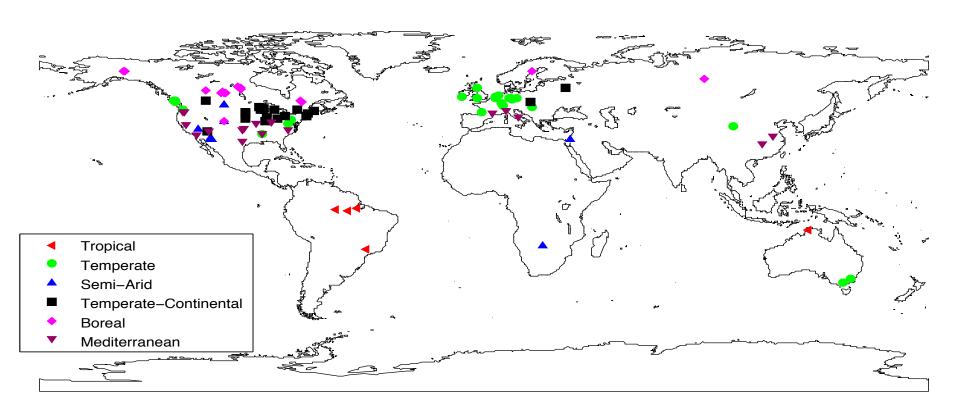
$$R_n = (1 - albedo) * SW_{dn} + LW_{dn} - LW_{up}$$

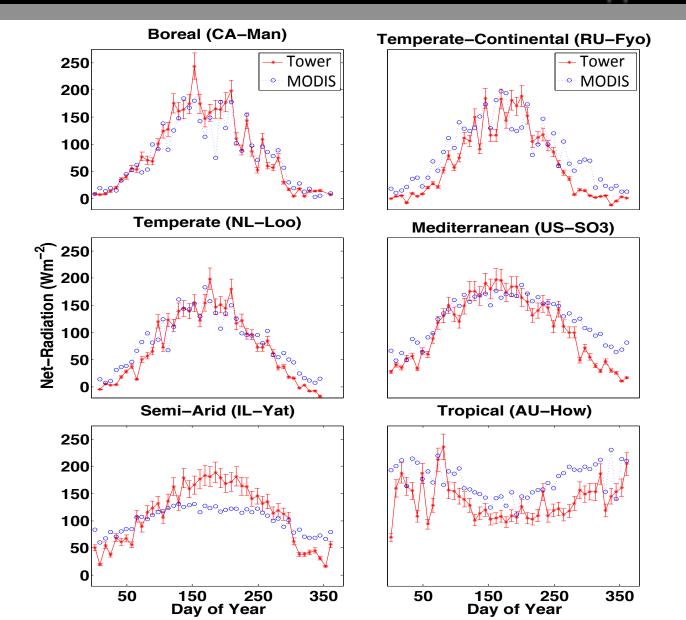
• We combined 11 variables from 6 different MODIS products daily over the MODIS era to estimate the components of R_n .

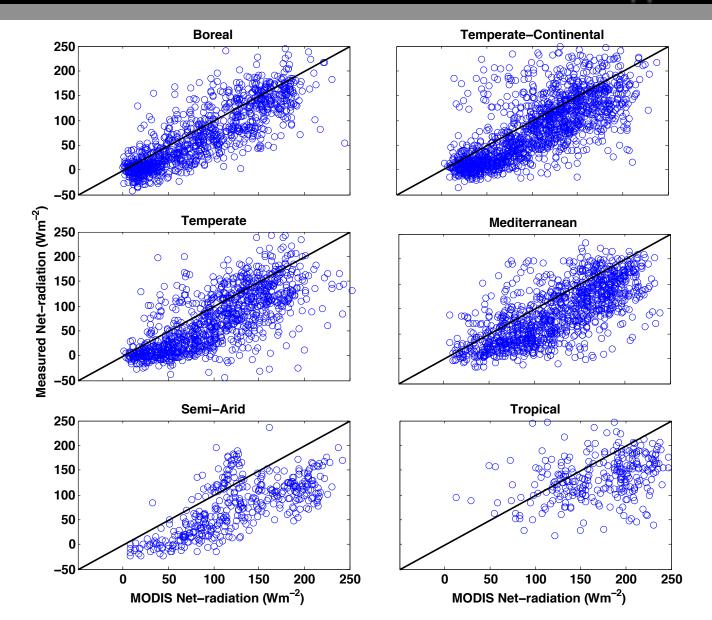
Component of R_n	MODIS products and method	
Albedo	Albedo from MCD43 (500 m, 8-day), land cover from MCD12 (500 m, annual)	
Incoming Shortwave (SW _{dn})	Cloud optical thickness, cloud top altitude, and solar zenith angle from MOD06 (5 km, daily); aerosol optical thickness at 550 nm from MOD04 (10 km, daily); Input MODIS data to a radiative transfer model (Kobayashi et al., 2008)	
Incoming Longwave (LW _{dn})	Near surface air temperature and vapor pressure from MOD07 (5 km, daily); estimate emissivity from vapor pressure and temperature	
Outgoing Longwave (LW _{up})	Land surface temperature and emissivity from MOD11 (1 km, daily); estimate broadband emissivity	

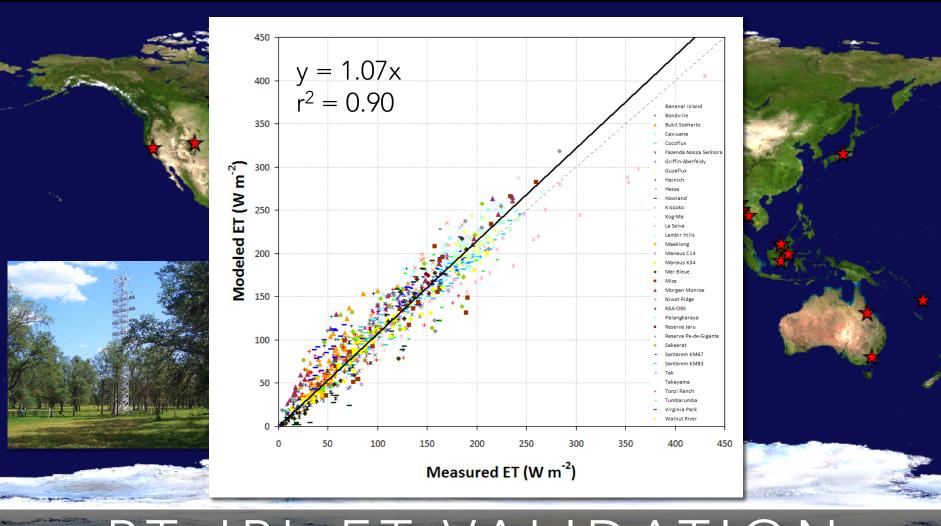


Validation at 126 sites across FLUXNET and SURFRAD.



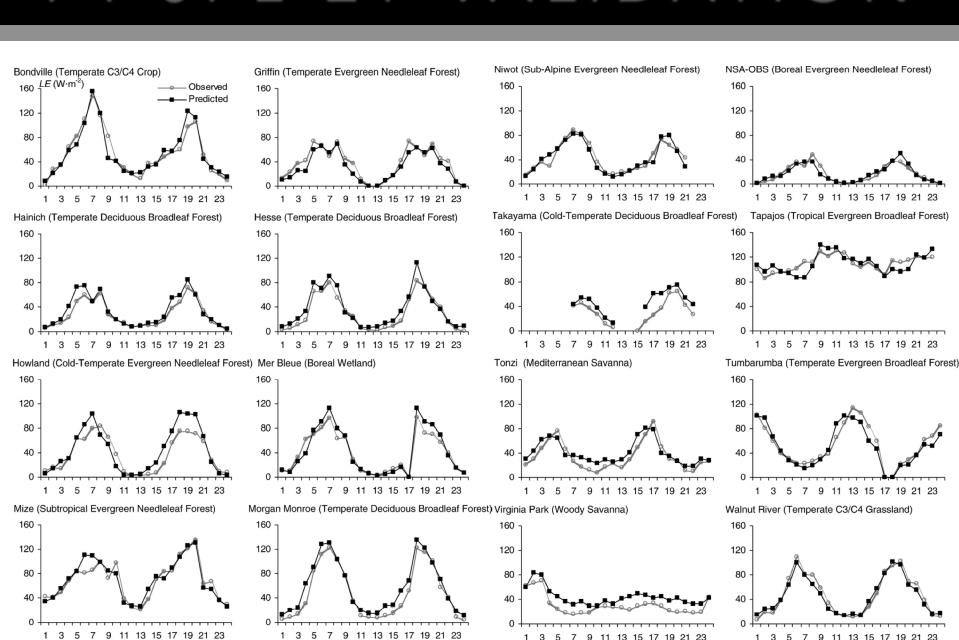




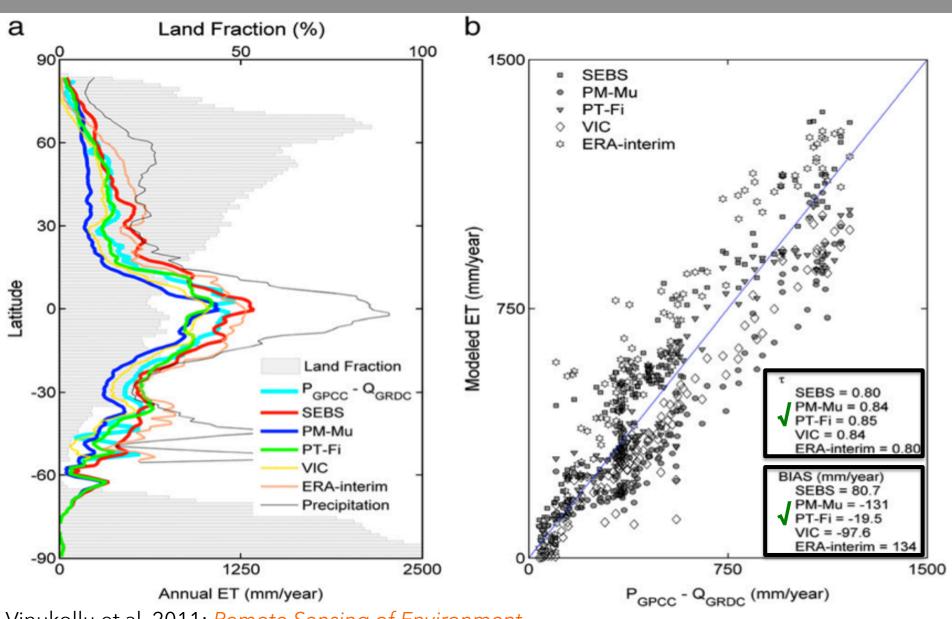


PT-JPL ET VALIDATION

PT-JPL ET VALIDATION

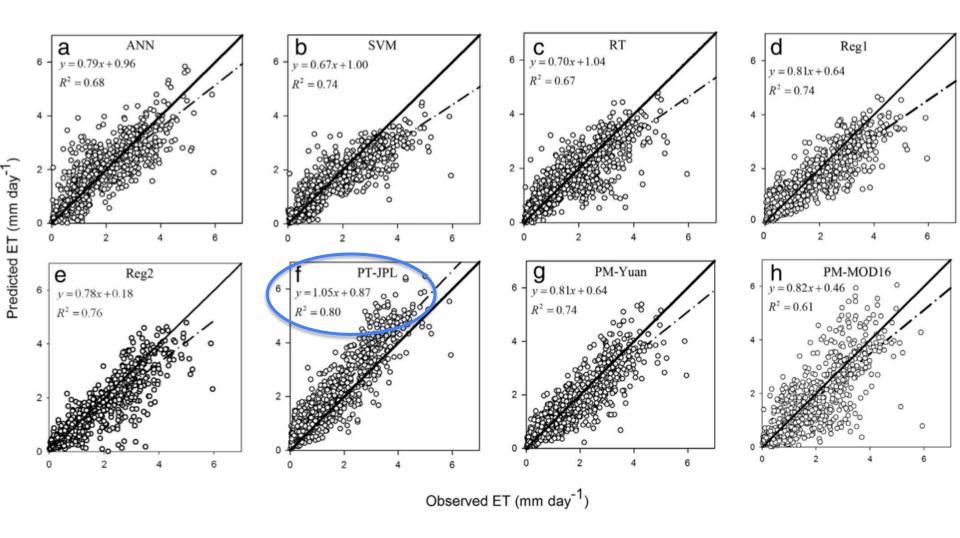


INDEPENDENT EVALUATION (GEWEX/PRINCETON)



Vinukollu et al. 2011: Remote Sensing of Environment

INDEPENDENT EVALUATION (BEIJING)



Chen et al. 2014: Remote Sensing of Environment

INDEPENDENT EVALUATION (GEWEX/AUSTRALIA)

Agricultural and Forest Meteorology 187 (2014) 46-61



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Multi-site evaluation of terrestrial evaporation models using FLUXNET data

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- b Water Desalination and Reuse Centre, King Abdullah University of Science and Technology (KAUST), Jeddah, Saudi Arabia
- c ARC Centre of Excellence for Climate Systems Science, University of NSW, Sydney, Australia
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 Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA

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Keywords: Multi-model intercomparisor Latent heat flux Energy balance Penman-Monteith Advection-aridity Priestley-Taylor

ABSTRACT

We evaluated the performance of four commonly applied land surface evaporation models using a high-quality dataset of selected FLUXNET towers. The models that were examined include an energy balance approach (Surface Energy Balance System; SEBS), a combination-type technique (single-source Penman-Monteith; PM), a complementary method (advection-aridity; AA) and a radiation based approach (modified Priestley-Taylor; PT-JPL). Twenty FLUXNET towers were selected based upon satisfying stringent forcing data requirements and representing a wide range of biomes. These towers encompassed a number of grassland, cropland, shrubland, evergreen needleleaf forest and deciduous broadleaf forest sites. Based on the mean value of the Nash-Sutcliffe efficiency (NSE) and the root mean squared difference (RMSD), the order of overall performance of the models from best to worst were ensemble mean of models (0.61, 64), PT-JPL (0.59, 66), SEBS (0.42, 84), PM (0.26, 105) and AA (0.18, 105) [statistics stated as (NSE, RMSD in W m⁻²)]. Although PT-JPL uses a relatively simple and largely empirical formulation of the evaporative process, the technique showed improved performance compared to PM, possibly due to its partitioning of total evaporation (canopy transpiration, soil evaporation, wet canopy evaporation) and lower uncertainties in the required forcing data. The SEBS model showed low performance over tall and heterogeneous canopies, which was likely a consequence of the effects of the roughness sub-layer parameterization employed in this scheme. However, SEBS performed well overall. Relative to PT-JPL and SEBS, the PM and AA showed low performance over the majority of sites, due to their sensitivity to the parameterization of resistances. Importantly, it should be noted that no single model was consistently best across all biomes. Indeed, this outcome highlights the need for further evaluation of each model's structure and parameterizations to identify sensitivities and their appropriate application to different surface types and conditions. It is expected that the results of this study can be used to inform decisions regarding model choice for water resources and agricultural management, as well as providing insight into model selection for global flux monitoring efforts.

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1. Introduction

Reliable estimates of evaporation (E) are required for the accurate representation of mass and energy exchanges at the land surface. In hydrological and water resource studies, an evaporation model is required to characterize the exchange of moisture between the surface and the overlying atmosphere. Not surprisingly, the choice of model can have considerable impact on water

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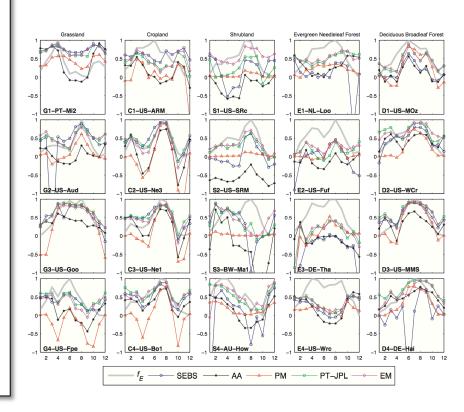
E-mail addresses: a.ershadi@studnet.unsw.edu.au (A. Ershadi), matthew.mccabe@kaust.edu.sa (M.F. McCabe), jason.evans@unsw.edu.au (J.P. Evans), nchaney@princeton.edu (N.W. Chaney), efwood@princeton.edu (F.F. Wood)

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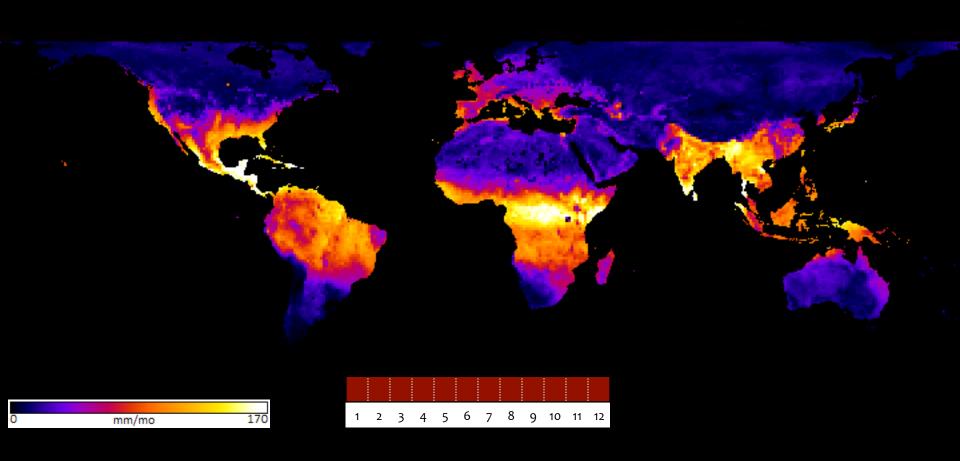
resource planning and decision support across a range of temporal and spatial scales. Improved understanding of the influence of model choice on flux estimation is required in order to better characterize the fidelity of these simulations, particularly in light of an increasing number of regional and global scale efforts to produce land surface heat flux data products (Jiménez et al., 2011; Mueller et al., 2013).

A number of models have been developed for the estimation of either the reference, potential or actual values of evaporation (see reviews of Kalma et al., 2008 and Wang and Dickinson, 2012). The reference evaporation is defined as the evaporation from a hypothetical, well-watered 'reference' crop (Allen, 2000), while potential evaporation is the maximum evaporation for a given surface if moisture is not limiting (Penman, 1948; Irmak and Haman, 2003). Estimation of the reference and potential evaporation is

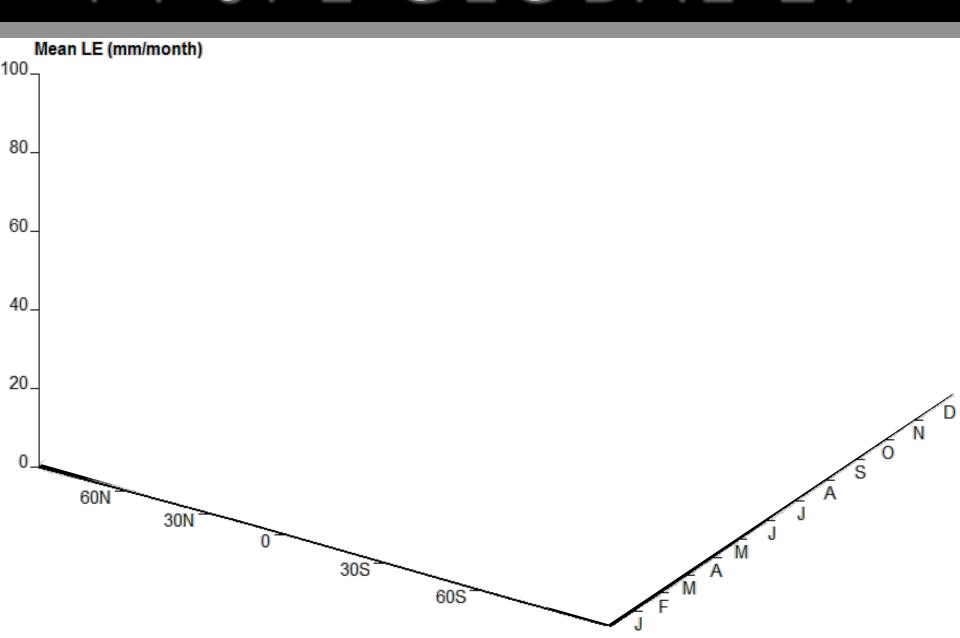
PT-JPL was the best performing ET retrieval algorithm.



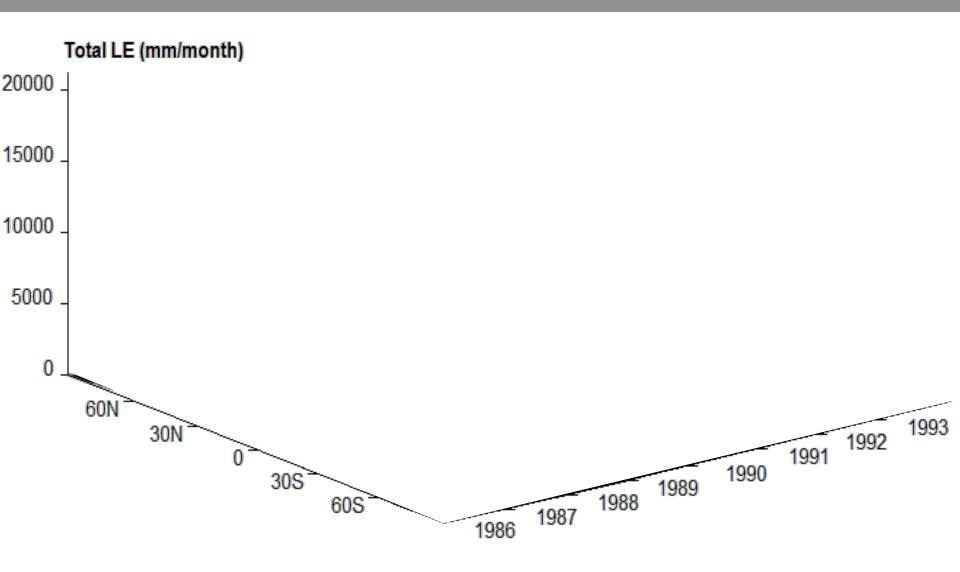
PT-JPL GLOBAL ET

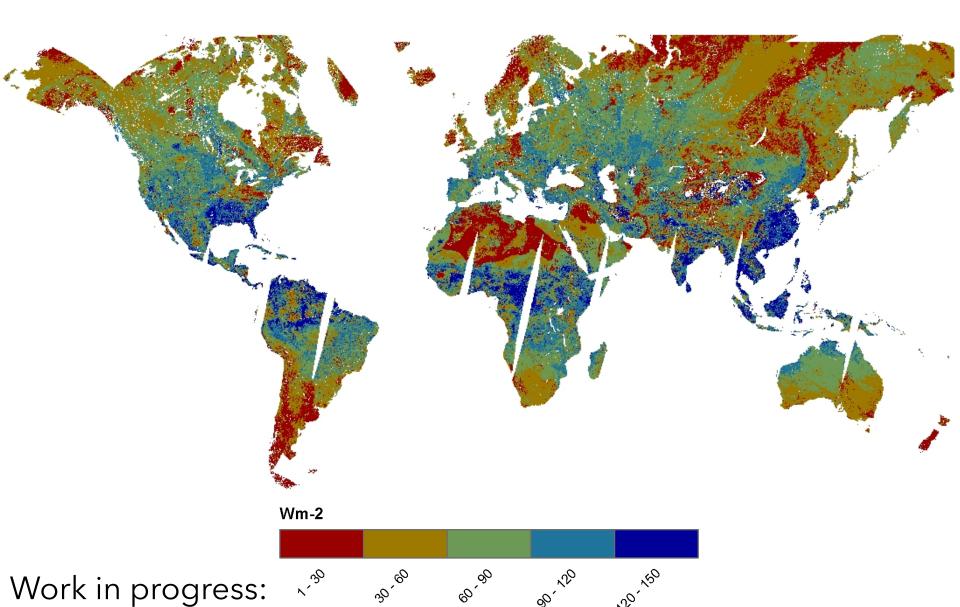


PT-JPL GLOBAL ET



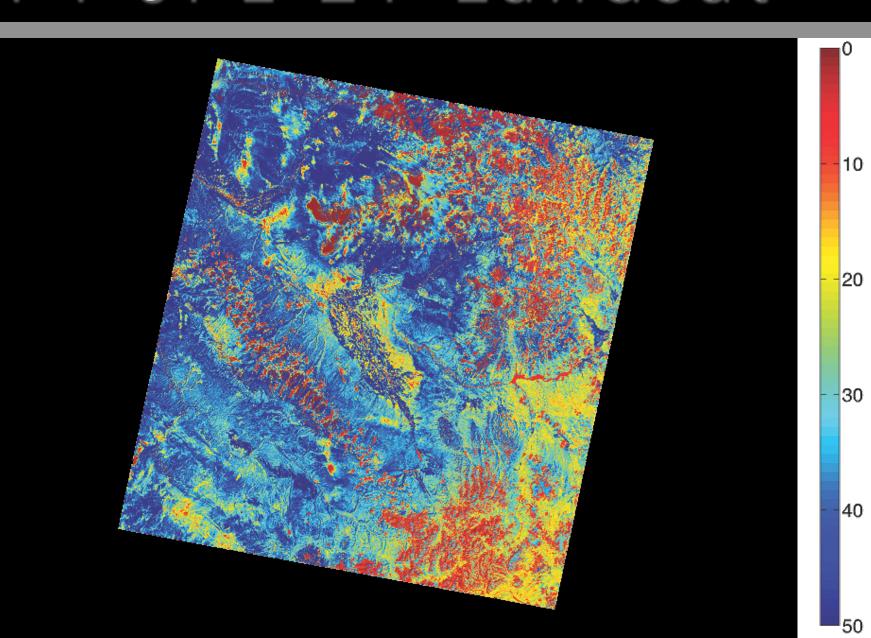
PT-JPL GLOBAL ET



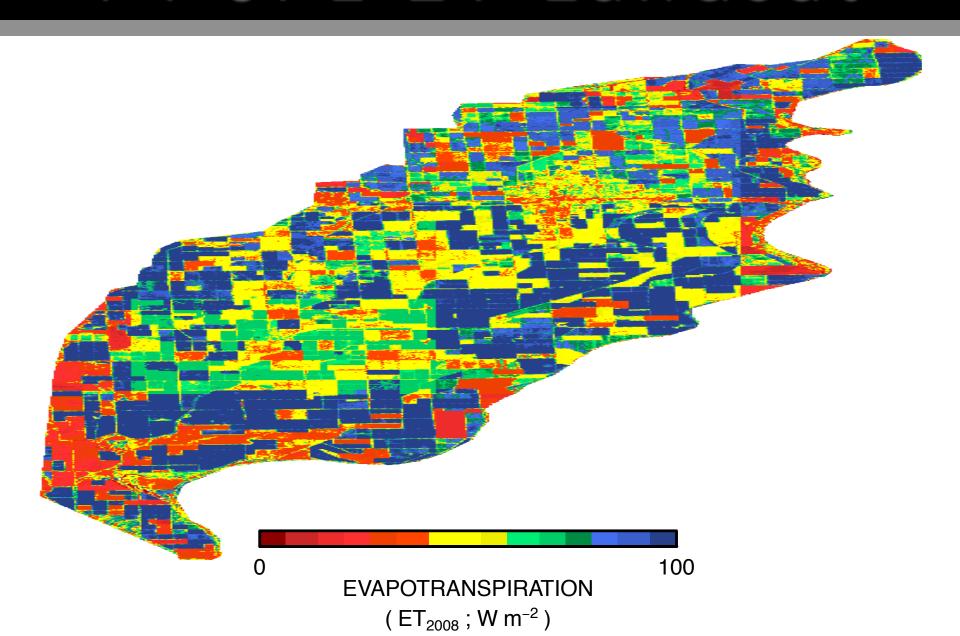


- Global, 1 km, daily, MODIS-era (10+ years)
- PT-JPL, PM-MOD16, SEBS, PMBL

PT-JPL ET Landsat



PT-JPL ET Landsat



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Actual evapotranspiration in drylands derived from in-situ and satellite data: Assessing biophysical constraints

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- b International Research Institute for Climate & Society, The Earth Institute, Columbia University, Lamont Campus, 61 Route 9W, Palisades, NY 10964-8000, USA
- ^c Géosciences Environnement Toulouse (UMR 5563 UPS-CNRS-IRD) Observatoire Midi-Pyrénées (OMP), Université de Toulouse, 18 Avenue Edouard Belin 31401 Toulouse Cedex 9, France de Desertification and Geoecology Dept. Estación Experimental de Zonas Áridas (EEZA), Consejo Superior de Investigaciones Científicas, Crtra. de Sacramento s/n La Cañada de San Urbano, E-04120 Almería, Spain

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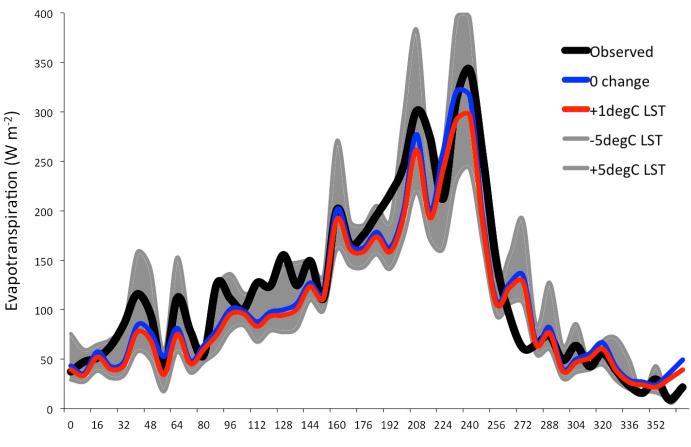
ABSTRACT

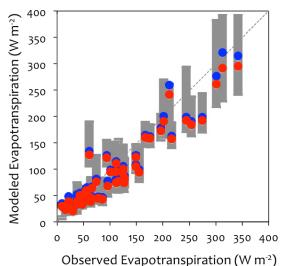
Improving regional estimates of actual evapotranspiration (λE) in water-limited regions located at climatic transition zones is critical. This study assesses an λE model (PT-JPL model) based on downscaling potential evapotranspiration according to multiple stresses at daily time-scale in two of these regions using MSG-SEVIRI (surface temperature and albedo) and MODIS products (NDVI, LAI and f_{PAR}). An open woody savanna in the Sahel (Mali) and a Mediterranean grassland (Spain) were selected as test sites with Eddy Covariance data used for evaluation. The PT-JPL model was modified to run at a daily time step and the outputs from eight algorithms differing in the input variables and also in the formulation of the biophysical constraints (stresses) were compared with the λE from the Eddy Covariance. Model outputs were also compared with other modeling studies at similar global dryland ecosystems.

The novelty of this paper is the computation of a key model parameter, the soil moisture constraint, relying on the concept of apparent thermal inertia (f_{SM-ATI}) computed with surface temperature and albedo observations. Our results showed that f_{SM-ATI} from both in-situ and satellite data produced satisfactory results for λE at the Sahelian savanna, comparable to parameterizations using field-measured Soil Water Content (SWC) with r^2 greater than 0.80. In the Mediterranean grasslands however, with much lower daily λE values, model results were not as good as in the Sahel ($r^2 = 0.57 - 0.31$) but still better than reported values from more complex models applied at the site such as the Two Source Model (TSM) or the Penman–Monteith Leuning model (PML).

PT-JPL-daily model with a soil moisture constraint based on apparent thermal inertia, f_{SM-ATI} offers great potential for regionalization as no field-calibrations are required and water vapor deficit estimates, required in the original

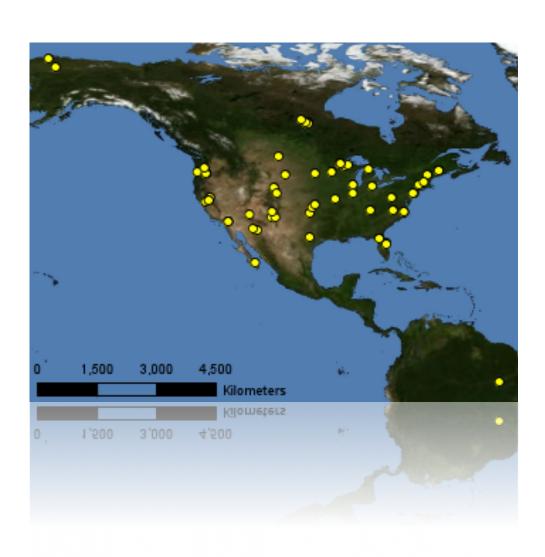






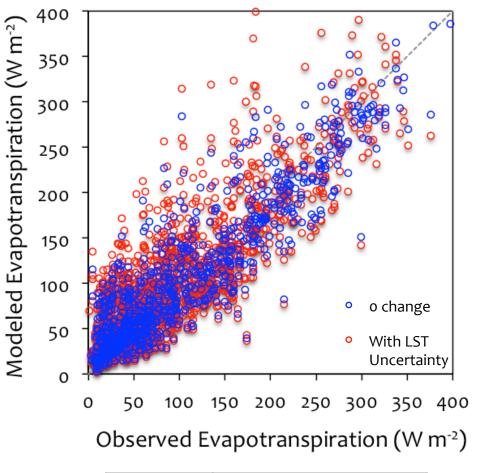
	οΔ	+1°C	±5°C
m			
r ²			
RMSE			







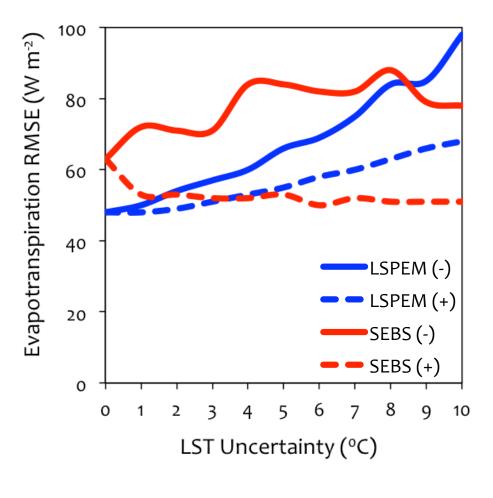
site-level ET uncertainty from LST uncertainty

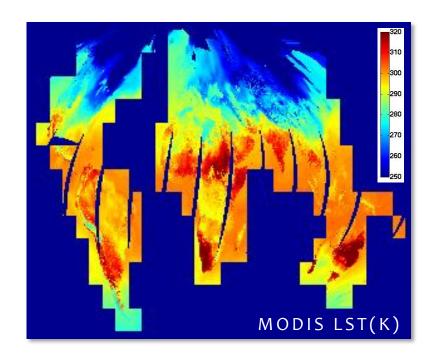


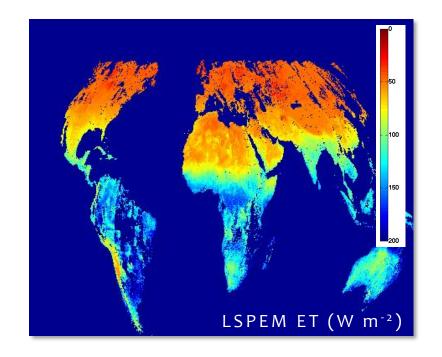
	οΔ	Δ°C
m	0.99	
r ²	0.82	
RMSE	37.7	

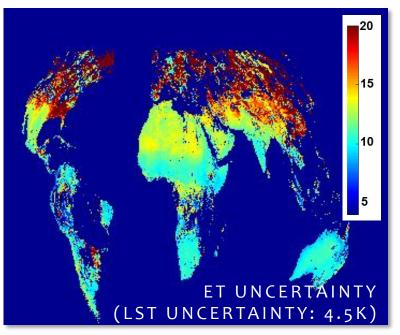


site-level ET uncertainty sensitivity from LST uncertainty









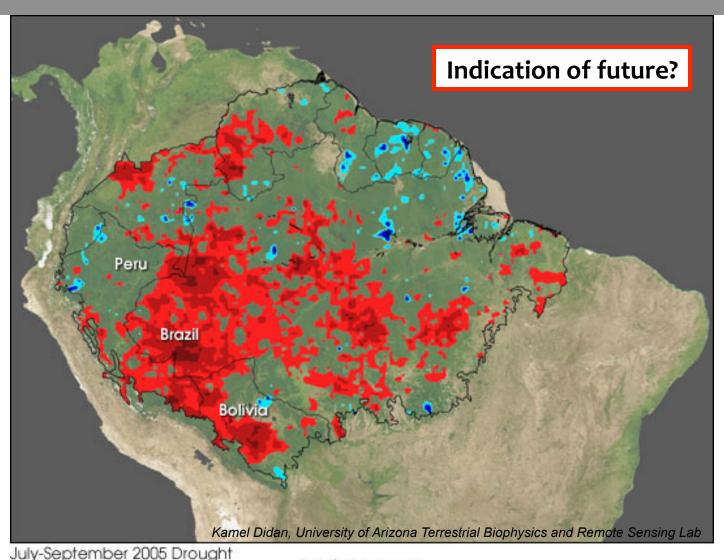
ET UNCERTAINTY

- = abs(ETLSTO-ETLST+)+abs(ETLSTO-ETLST-)
- $= abs(50-51 \text{ W m}^{-2}) + abs(50-58 \text{ W m}^{-2})$
- = 9 W m⁻² (global mean)

ET SENSITIVITY

- = abs(ET^{LST+}-ET^{LST-})/ET^{LSTo}
- $= abs(51-58 \text{ W m}^{-2})/50 \text{ W m}^{-2}$
- = 14% (global mean)

AMAZON DROUGHT 2005

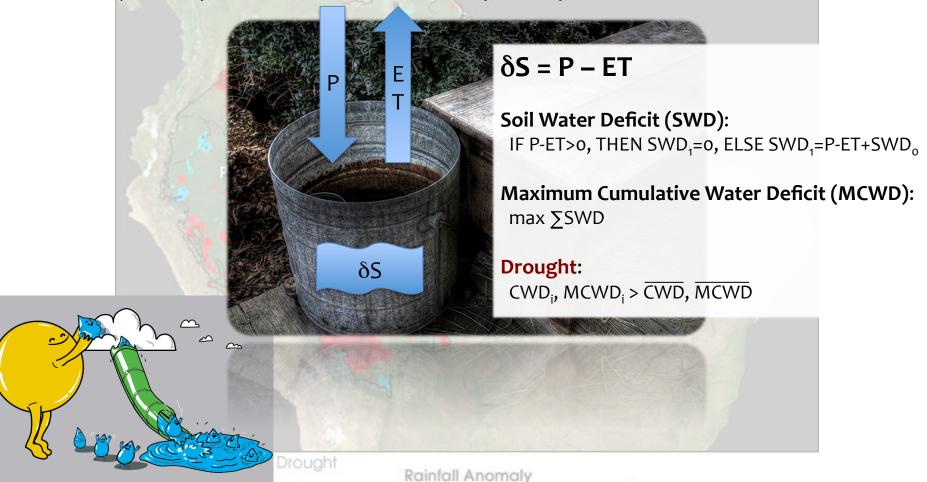


Rainfall Anomaly
below average average above average

DROUGHT?

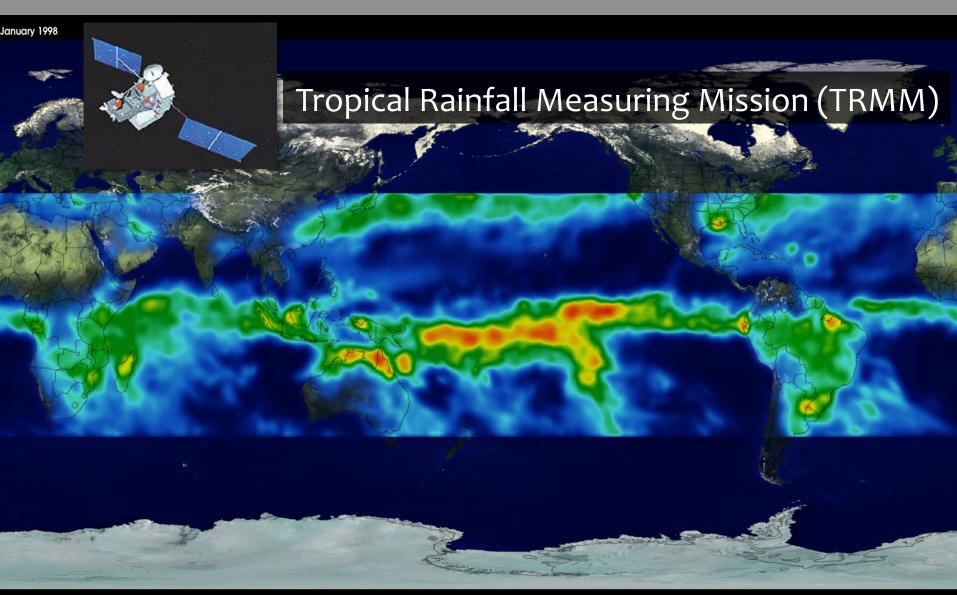
Drought: meteorological (or, climatological, atmospheric), agricultural, hydrologic, socio-economic; exceedance of threshold.

Vegetation drought: physical drying of soil such that the overlying vegetation experiences physiological water stress manifested in a reduction of productivity, loss of leaves/needles, and, ultimately, mortality.



Fisher, J.B., Andreadis, K.M., 2013. Transpiration, physical evaporation and droughts. Encyclopedia of Natural Resources.

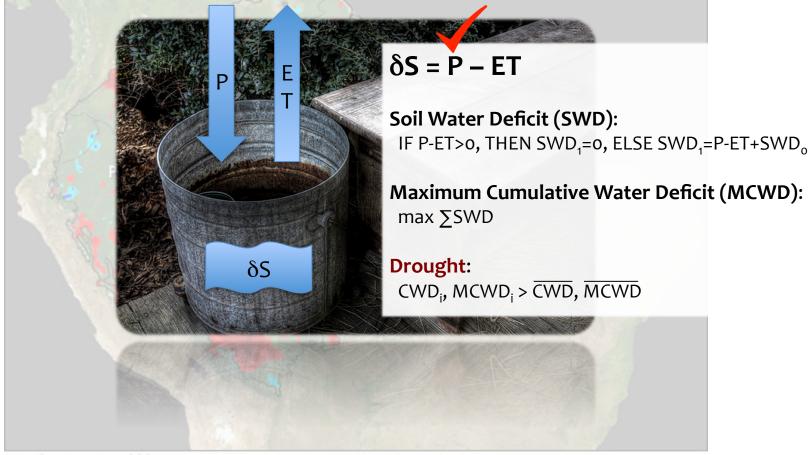
PRECIPITATION



DROUGHT?

Drought: meteorological (or, climatological, atmospheric), agricultural, hydrologic, socio-economic; exceedance of threshold.

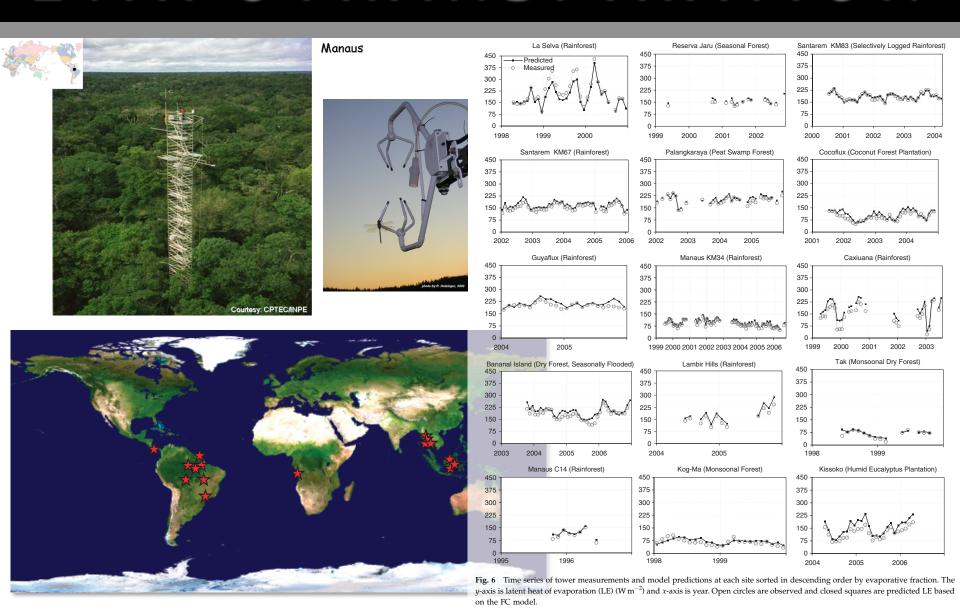
Vegetation drought: physical drying of soil such that the overlying vegetation experiences physiological water stress manifested in a reduction of productivity, loss of leaves/needles, and, ultimately, mortality.



July-September 2005 Drought

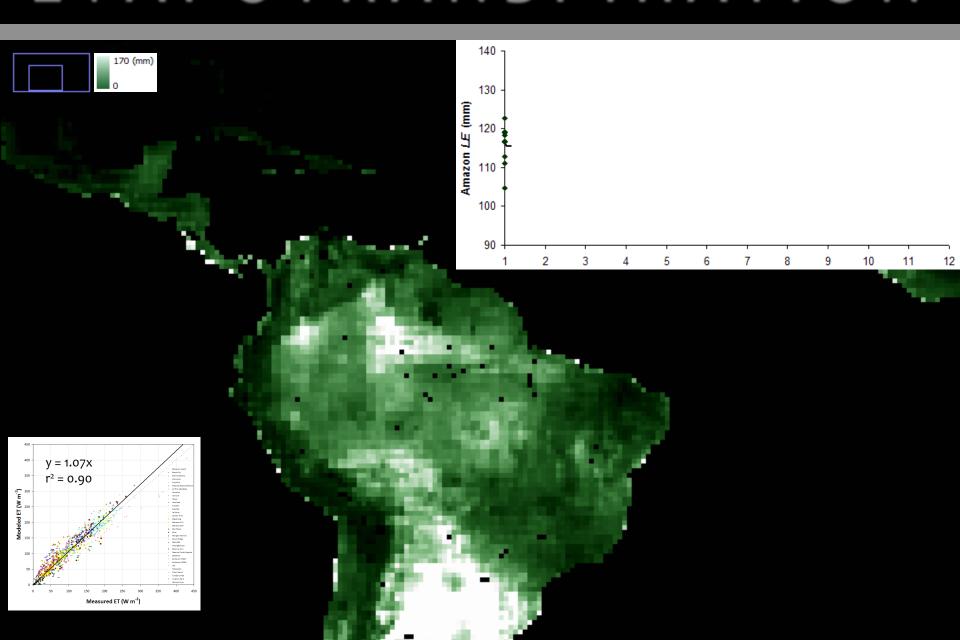
Rainfall Anomaly

EVAPOTRANSPIRATION



Fisher, J.B., et al., 2009. The land-atmosphere water flux in the tropics. Global Change Biology.

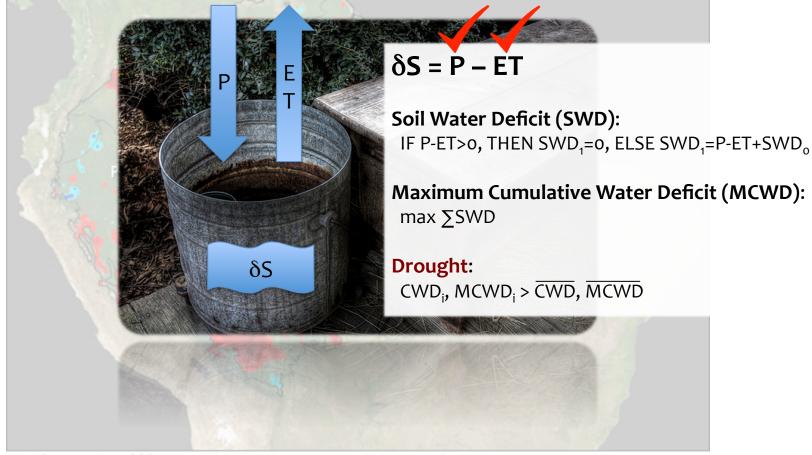
EVAPOTRANSPIRATION



DROUGHT?

Drought: meteorological (or, climatological, atmospheric), agricultural, hydrologic, socio-economic; exceedance of threshold.

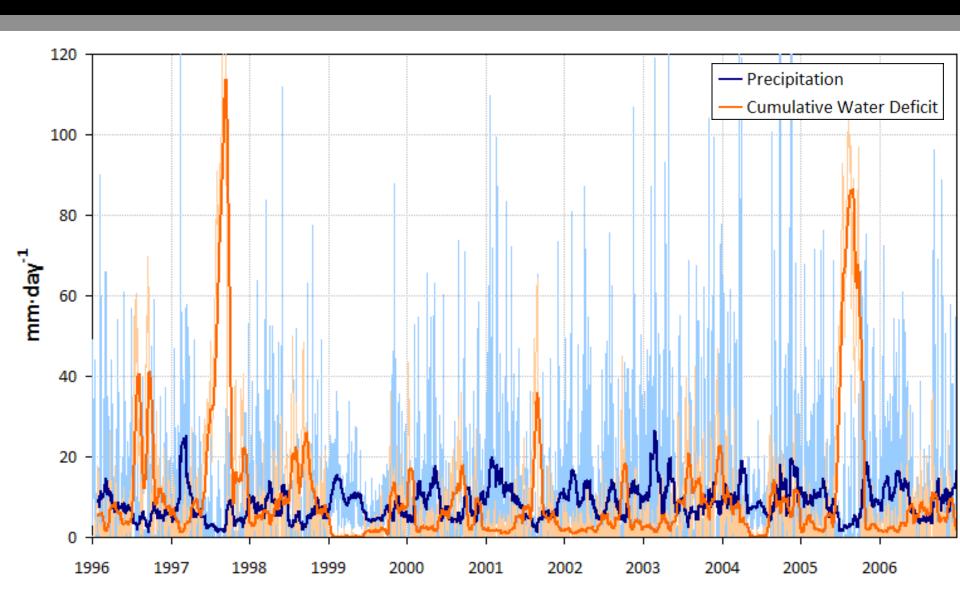
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July-September 2005 Drought

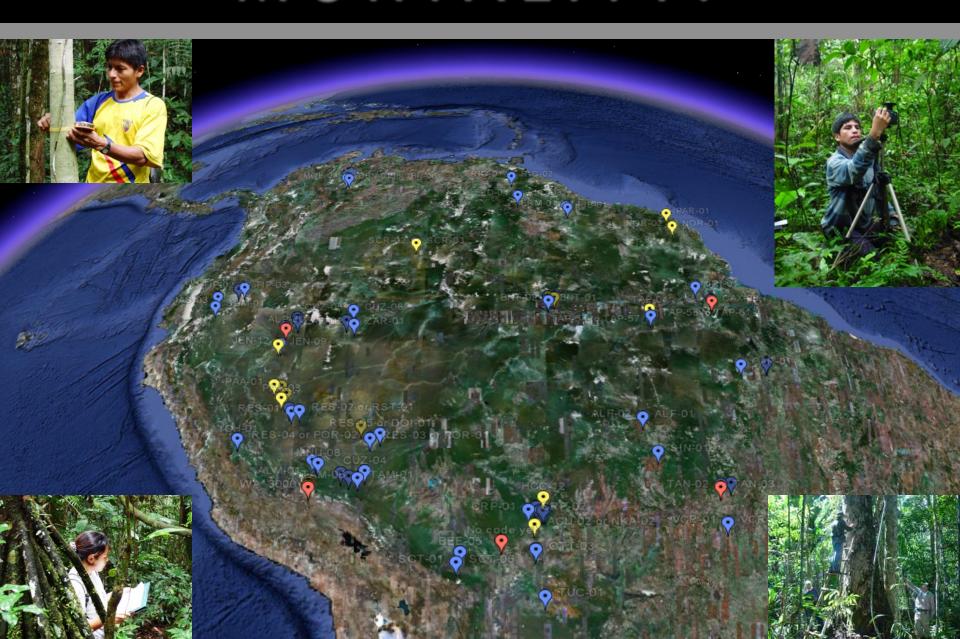
Rainfall Anomaly

DROUGHT?



Phillips, O.L., Aragão, L., Lewis, S.L., Fisher, J.B., et al., 2009. Drought sensitivity of the Amazon rainforest. Science.

MORTALITY?



Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest

Yadvinder Malhi¤1, Luiz E. O. C. Aragãoª, David Galbraithb, Chris Huntingfords, Rosie Fisherd, Przemysław Zelazowskia,

Edited* by Ruth S. DeFries, Columbia University. Drought exerts a strong influence on tropic carbon stocks, and ultimately the flux of carbs Satellite-based studies have suggested that A up during droughts because of increased studies have reported increased tree more droughts. In an effort to reconcile these a findings, we conducted an analysis of climate monte, and improved stability-bayed maxine.

ments, and improved satellite-based meas

thetic activity. Wet-season precipitation and

tosynthetically active radiation (PAR) and air vapor pressure deficit, VPD) increased from proved enhanced vegetation index (EVI) r

2008), we show that gross primary productive declined with VPD and PAW in regions of across a wide range of environments for ea In densely forested areas, no climatic variable

the Basin-wide interannual variability of EVI.

new leaves, even when unaccompanied by LAI, could play an important role in Basin-wi iability. Because EVI variability was greate

PAW, we hypothesize that drought could in nizing leaf flushing via its effects on leaf bu

drought | enhanced vegetation index | moderat

he accumulation of heat-trapping ga

The accumulation of heat-trapping gase may subject large areas of the Amaz tropical forest formations to more frequen

in the coming decades (1). This trend may i

with regional inhibition of rainfall driven

move these tropical forest regions toward

Drier and warmer climate in the region fa

grasses and shrubs over trees in a proces

forest dieback might occur, in part because

regarding the response of forest photosynth Some studies suggest that forest photosyn productivity, GPP) increases during the e-

cause of higher photosynthetically active

16). In contrast, two partial throughfall

conducted in the Amazon region found

ductivity all declined under mild drought

mortality increasing under high cumulative

resulting from limited plant-available water ref. 17). These impacts were observed only af

drought, with the lag probably resulting from

reduced availability of soil water (18).

ecurring fire (8).

It is difficult to assess the drought the

and more frequent sea-surface temperar

spectroradiometer | tropical | carbon cycling

study, we show that monthly EVI was rela area index (LAI) but correlated positively wi measured in the field. These findings sug

School of GeoSciences, University of Edinbu Kingdom; Department of Animal and Plant Centre for Hydro-Meteorological Research, V

Edited by Hans Joachim Schellnhuber, Potsda review June 10, 2008)

We examine the evidence for the po we examine the evidence for the particular of the particular of Amazonian rainforest. We employ uating the rainfall regime of tropical for precipitation-based boundaries for then examine climate simulations by then examine climate simulations by (GCMs) in this context and find that in current rainfall. GCMs also vary greature climate change in Amazonia. current rainfall. GCMs also vary greature climate change in Amazonia. rainfall regimes in the 20th century. dry-season water stress is likely to incre 21st century, but the region tends to priate to seasonal forest than to sava may be resilient to seasonal drought sified water stress caused by higher vulnerable to fires, which are at present Amazonia. The spread of fire ignition deforestation, logging, and fragme points that trigger the transition of fire-dominated, low biomass forests. tation of deforestation and fire may be maintain Amazonian forest resilie 21st-century climate change. Such inte navigate E. Amazonia away from a beyond which extensive rainforest wo

carbon dioxide | drought | fire | tropical

The response of components of the levels of anthropogenic greenhous be continuous and gradual; instead elements" in the system (1). Among the Amazon rainforest, with some possibility of substantial and rapid ' zon forest biome is biologically th hosting ~25% of global biodiversity to the biogeochemical functioning large-scale degradation would leav functioning and diversity of the evidence for such a tipping element climate model projections in the co considering direct human pressures

There is clear and ongoing change of Amazonia, whether through incr dioxide concentrations, associated more direct intervention because ation. Such perturbations are certain timescales. The challenge is to ident

determining the sensitivity-or

¹Ecology and Global (of Leeds, Leeds LS2 9 School of Geography ford OX1 3QY, UK. Pasco, Peru. ⁴Instituto Andre Araujo, 1753 Museu Paraense Em Firme, CEP: 66077-83

International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA. Museo de Historia Natural Noel Kempff Mercado, Casilla 2489, Av. Irala 565, Santa Cruz, Bolivia, 8 Missouri Botanical Garden, Box 299, St. Louis, MO 63166, USA. Programa de Gencias del Agro y del Mar. Herbario Universitario (PORT). Universidad Nacional Experimental de Los Llanos Occidentales Ezeguid Zamora, Mesa de Cavacas, Portuguesa 3350, Venezuela. 10 Nationaal Herbarium Nederland, W.C. van Unnikoebouw. Heidelberglaan 2, 3584 CS Utrecht, Netherlands, 11 Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR EcoFoG, Campus Agronomique, BP 709, 97387 Kourou Cedex, French Guiana. 12 Institut National. de la Recherche Agronomique (INRA), UMR EcoFoG, Campus Agronomique, BP 709, 97387 Kourou Cedex, French Guiana. Instituto de Resouisa Ambiental da Amazônia. Avenida

Nazaré 669, CEP-66035, Belém PA, Brasil. 34Department of

Seasonal and interannual variability of climate and vegetation indices across the Amazon

lew Phytologist (2010) 187: 569-578

Key words: advanced very high resolution

ectroradiometer, phenology, tropical

radiometer, Amazon basin, Brazil, green-up, Landsat, moderate resolution imaging

Research review

Summary

Drought varies spatially

efforts to assess ecologi

offers a range of region

and rainfall, canopy ph

studies of Amazônia w

during drought years;

cantly affected by drou

conditions and increa

controversial areas of

drought and changes in

from field and satellite:

tions and techniques of

observations. We conclu

measurements are crit

responses to drought ar

Drought impacts on the Amazon forest: the remote sensing perspective

Large-scale on-the-ground assessments of the ecological impacts of tropical droughts are com-

pletely lacking, precluding tests of these ideas.

f the Amazon Basin ost intense droughts

providing a unique

aluate the large-scale

est to water deficits.

not by El Niño, as

onia, but by elevated

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Remote sensing detection of droughts in Amazonian forest canopies

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Summary

Author for correspondence iana O. Anderson 'el: +44 1392 848556 mail: liana.and tereived: 30 March 2010 physiological, disturbane

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irought, MODIS (moderate resolution maging spectroradiometer), phenology, tree nortality, tropical forest, vegetation indices.

· Remote sensing

tions such as access have analysed da (MODIS) satellite r drought in Amazon

 We combined v the spatiotemporal relationships betw mortality.

 There were diffe showed no spatial r tinct regions respo increase in the Enha tionship (P < 0.07)difference water (P < 0.09) with tre Previous studies drought was asso changes in the radi

he related to structu

Introduction

stellite-derived information is an attractive tool for vegets ion monitoring at regional and global scales. It provides full coverage of large and remote areas on a regular basis ver extended periods of time. Of the many remote sensing (RS) based techniques available for analysing vegetation dynamics, time-series analysis of vegetation indices (VIs) as become the most common approach for phenology and lrought assessment.

The normalized difference vegetation index (NDVI) was originally generated based on the advanced very high

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nce in net change

Liang Xu,1 Arindam Samanta,1,2 Marcos H. Ramakrishna R. Nemani,5 and Ranga B. My Received 19 January 2011; revised 3 March 2011; accepted

to the 2010 drought

[1] During this decade, the Amazon region has sur severe droughts in the short span of five years -2010. Studies on the 2005 drought present a con sometimes contradictory, picture of how these fo responded to the drought. Now, on the heels of drought, comes an even stronger drought in indicated by record low river levels in the 100 bookkeeping. How has the vegetation in th responded to this record-breaking drought? Here widespread, severe and persistent declines in v greenness, a proxy for photosynthetic carbon fi the Amazon region during the 2010 drought analysis of satellite measurements. The 2010 dr measured by rainfall deficit, affected an area 1 larger than the 2005 drought - nearly 5 millio vegetated area in Amazonia. The decline in g during the 2010 drought spanned an area that times greater (2.4 million km²) and more sever 2005. Notably, 51% of all drought-stricken forest greenness declines in 2010 (1.68 million km2) cor only 14% in 2005 (0.32 million km2). These de 2010 persisted following the end of the dry seaso and return of rainfall to normal levels, unlike Overall, the widespread loss of photosynthetic c Amazonian vegetation due to the 2010 drou represent a significant perturbation to the glob cycle. Citation: Xu, L., A. Samanta, M. H. Costa, S R. R. Nemani, and R. B. Myneni (2011). Widespread greenness of Amazonian vegetation due to the 2010 Geophys. Res. Lett., 38, L07402, doi:10.1029/2011Gl

1. Introduction

[2] There is concern that in a warming climate the moisture stress could result in Amazonian rainfor replaced by savannas [Cox et al., 2004; Salazar et Huntingford et al., 2008; Malhi et al., 2008], in w the large reserves of carbon stored in these fore 100 billion tons [Malhi et al., 2006], could be relea

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Amazon vegetation greenness as measured by satellite sensors over the last decade

P. M. Atkinson, 1 J. Dash, 1 and C. Jeganathan 1

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L07402, doi:10.1029/2011GL046824, 2011

Widespread decline in greenness of Amazonian vegetation due

As drought

increases, live

trees decrease.

Received 3 August 2011; revised 9 September 2011; accepted 12 September 2011; published 12 October 2011.

[1] During the last decade two major drought events, one in biomass carbon storage in the Amazon basin [Lewis et al., 2005 and another in 2010, occurred in the Amazon basin.

Several studies have claimed the ability to detect the effect of climate change. these droughts on Amazon vegetation response, measured through satellite sensor vegetation indices (VIs). Such monitoring capability is important as it potentially links climate changes (increasing frequency and severity of climate changes (increasing frequency and severity of drought), vegetation response as observed through vegetation greenness, and land-atmosphere carbon fluxes which directly feedback into global climate change. However, we show conclusively that it is not possible to detect the response of vegetation to drought from space using VIs. We analysed 11 years of dry season (July-September) Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) and normalised difference vegetation index (NDVI) images. The VI standardised anomaly was analysed alongside the absolute value of EVI and NDVI, and the VI values for drought years were compared with those for nondrought years. Through a series of analyses, the standardised anomalies and VI values for drought years were shown to be of similar magnitude to those for non-drought years. Thus, while Amazon vegetation may respond to drought, this is not detectable through satellite-observed changes in vegetation greenness. A significant long-term decadal decline in VI values is reported, which is independent of the occurrence of drought. This trend may be caused by environmental or noise-related factors which require further investigation. Citation: Atkinson, P. M., J. Dash, and C. Jeganathan (2011), Amazon vegetation greenness as measured by satellite sensors over the last decade, Geophys. Res. Lett., 38, L19105, doi:10.1029/2011GL049118.

1. Introduction

[2] The Amazon region contains around 54% of the world's rainforest and stores more than 100 billion tonnes of carbon [Malhi et al., 2006]. A general increase in temper-ature since the 1970s, and decadal-scale variation in rainfall, have been recorded for the Amazon rainforest [New et al., 2000], while Li et al. [2008] reported a 0.32 per decade decline in the standard precipitation index between 1970 and 1999, suggesting increasingly dry conditions in the Amazon in recent years. Several global circulation models (GCMs) have projected these trends into the future [Marengo, 2005] leading to concerns over the effects of increased frequency and severity of drought on net primary productivity and

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[3] Changes in precipitation amount and duration may affect photosynthetic activity and the functioning and condition of the forest which, in turn, may affect overall carbon fluxes to the atmosphere. In a normal year, the Amazon

rainforest absorbs approximately 1.5 billion tonnes of car-bon from the atmosphere. However, Lewis et al. [2011] predicted, based on a model, a net transfer of 2.2 billion tonnes of carbon to the atmosphere in 2010, a drought year. Thus, the prospect of increasingly dry conditions, and an increasing frequency of drought years, is of great concern as such conditions have the potential to turn the Amazon from a sink of carbon into a source of carbon, greatly affecting rates of global climate change [Lewis et al., 2011].

[4] For an area as vast as the Amazon, satellite remote sensing provides the only possible means of monitoring the impact of droughts on vegetation at the basin scale. Such remote sensing approaches generally rely upon the use of vegetation indices (VIs) to measure vegetation "greenness". The ability to detect from space the effect of drought on vegetation response, in the form of vegetation green potentially of crucial importance in monitoring the effects of

drought on carbon flux in the Amazon.

[5] During the last decade two severe drought events affected the Amazon basin; one in 2005 and the other in 2010. The drought in 2010 was spatially more extensive than that in 2005 and affected more than 3 million km [Lewis et al., 2011]. Saleska et al. [2007] were the first to report a significant increase in vegetation greenness over the Amazon during the 2005 drought using the enhanced vegetation index (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. However, this was later challenged by Samanta et al. [2010] on the basis of poor chairinged by Samanta et al. [2010] on the basis or poor data quality and processing methodology. They suggested greater vegetation browning (or no change) than greening during the 2005 drought. Moreover, Anderson et al. [2010] reported positive EVI anomalies associated with higher tree mortality and questioned Saleska et al.'s [2007] interpreta-tion of the observed changes in VIs. Brando et al. [2010], using climate, satellite and field data found no relation ship between the inter-annual variability in plant available water (PAW) and EVI for densely forested areas in the Amazon, but observed a decline in EVI with decline in PAW for areas with low vegetation cover. Recently, a key paper published in this journal by Xu et al. [2011] suggested, using MODIS VIs, that vegetation browning in 2010 was four times greater than in 2005 affecting more than 50% of the forested area in the Amazon and thus, that the increased browning was a response to the 2010 drought.

Thus, controversy exists in the literature about the effects of

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Precipitation varies spatially and temporally in the Amazor

basin, but long-term station records indicate that annual

rainfall is decreasing by an average 0.32% yr⁻¹ (Li et al.,

2008). Overlain on the long-term trend, there are El Nino-

Southern Oscillation (ENSO) events and other sea surface

temperature anomalies associated with intense drought in

portions of Amazônia (Marengo, 1992; Costa & Foley, 1999; Aragao *et al.*, 2007). Droughts are expected to

crease in frequency, extent and severity with climate

hange (Williams et al., 2007; Malhi et al., 2009), which

will likely have an important impact on biosphere function-

ing and biodiversity (Meir et al., 2008; Loarie et al., 2009).

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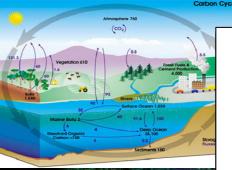
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BRFVIA

The 2010 Amazon Drought

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everal global circulation models (GCMs) anomalies do not necessarily correlate with water project an increase in the frequency and severity of drought events affecting the Amazon region as a consequence of anthropogenic greenhouse gas emissions (1). The proximate cause is twofold, increasing Pacific sea surface temperatures (SSTs), which may intensify El Niño Southern Oscillation events and associated periodic Amazon droughts, and an increase in the frequency of historically rarer droughts associated with high Atlantic SSTs and northwest displacement of the intertropical convergence zone (1, 2). Such droughts may lead to a loss of some Amazon forests, which would accelerate climate change (3). In 2005, a major Atlantic SST-associated drought occurred, identified as a 1-in-100-year event (2). Here, we report on a second drought in 2010, when Atlantic SSTs were again high.

We calculated standardized anomalies from a decade of satellite-derived dry-season rainfall data (Tropical Rainfall Measuring Mission, 0.25° resolution) across 5.3 million km² of Amazonia for 2010 and 2005 (4). We used identical reference periods to allow a strict comparison of both drought events (4). On the basis of this index, the 2010 drought was more spatially extensive than the 2005 drought (rainfall anomalies ≤ -1 SD over 3.0 million km2 and 1.9 million km2 in 2010 and 2005, respectively; Fig. 1 and fig. S1). Because dry-season

stress for forest trees, we also calculated the maximum climatological water deficit (MCWD) for each year as the most negative cumulative value of water input minus estimated forest evapotranspiration (5). This measure of drought intensity correlates with Amazon forest tree mortality (6). In 2010, the difference in MCWD from the decadal mean that significantly increases tree mortality (≤-25 mm) spanned 3.2 million km², compared with 2.5 million km2 in 2005. The 2010 drought had three identifiable epicenters in southwestern Amazonia, north-central Bolivia, and Brazil's Mato Grosso state. In 2005 only a single southwestern Amazonia epicenter was detectable (fig. S1).

The relationship between the change in MCWD and changes in aboveground carbon storage derived from forest inventory plots affected by the 2005 drought (6) provides a first approximation of the biomass carbon impact of the 2010 event. Summing the change in carbon storage predicted by the 2010 MCWD difference across Amazonia gives a total impact of 2.2 Pg C [95% confidence intervals (CI) 1.2 and 3.41, compared with 1.6 Pg C for the 2005 event (CI 0.8, 2.6). These values are relative to the predrought carbon uptake and represent the sum of (1) the temporary cessation of biomass increases over the 2-year drought measurement interval (~0.8 Pg C) and (2) biomass lost

via tree mortality, a committed carbon flux from decomposition over several years (~1.4 Pg C after the 2010 drought). In most years, these forests are a carbon sink; drought reverses this sink.

Considerable uncertainty remains, related to the soil characteristics within the epicenters of the 2010 drought, which could moderate or exacerbate climatic drying, whether a second drought will kill more trees (i.e., those damaged by the initial drought) or fewer (i.e., if most drought-susceptible trees are already dead), and whether drought slows soil respiration (temporarily offsetting the biomass carbon source). New field measurements will be required to refine our initial estimates.

The two recent Amazon droughts demonstrate a mechanism by which remaining intact tropical forests of South America can shift from buffering the increase in atmospheric carbon dioxide to accelerating it. Indeed, two major droughts in a decade may largely offset the net gains of ~0.4 Pg C year in intact Amazon forest aboveground biomass in nondrought years. Thus, repeated droughts may have important decadal-scale impacts on the global carbon cycle.

Droughts co-occur with peaks of fire activity (5). Such interactions among climatic changes, human actions, and forest responses represent potential positive feedbacks that could lead to widespread Amazon forest degradation or loss (7). The significance of these processes will depend on the growth response of tropical trees to increases in atmospheric carbon dioxide concentration, fire management, and deforestation trends (3, 7). Nevertheless, any shift to drier conditions would favor droughtadapted species, and drier forests store less carbon (8). If drought events continue, the era of intact Amazon forests buffering the increase in atmospheric carbon dioxide may have passed.

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- 9. We thank T. Baker and L. Aragão for assistance and the
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Supporting Online Material

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Fig. S1

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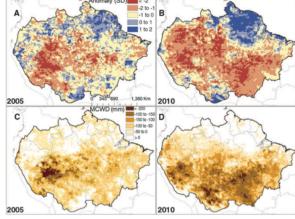


Fig. 1. (A and B) Satellite-derived standardized anomalies for dry-season rainfall for the two most extensive droughts of the 21st century in Amazonia. (C and D) The difference in the 12-month (October to September) MCWD from the decadal mean (excluding 2005 and 2010), a measure of drought intensity that correlates with tree mortality. (A) and (C) show the 2005 drought; (B) and (D) show the 2010 drought.

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