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Trans-Atlantic Connections between North African Dust Flux and Tree Growth in the Florida Keys, United States^①

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Received 26 December 2016; in final form 14 June 2017

ABSTRACT: Atmospheric mineral aerosols include multiple, interrelated processes and feedbacks within the context of land–atmosphere interactions and thus are poorly understood. As the largest dust source in the world, North Africa

^① Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/EI-D-16-0035.s1>.

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DOI: 10.1175/EI-D-16-0035.1

supplies mineral dust aerosols each year to the Caribbean region and southeastern United States that alter cloud processes, ocean productivity, soil development, and the radiation budget. This study uses a suite of Earth Observation and ground-based analyses to reveal a potential novel effect of atmospheric aerosols on *Pinus elliottii* var. *densa* cambial growth during the 2010 CE growing season from the Florida Keys. Over the Florida Keys region, the Earth Observation products captured increased aerosol optical thickness with a clear geographical connection to mineral dust aerosols transported from northern Africa. The MODIS *Terra* and *Aqua* products corroborated increased Ozone Monitoring Instrument (OMI) aerosol optical thickness values. Anomalously high Aerosol Robotic Network aerosol optical depth data corresponding with low Ångström coefficients confirm the presence of transported mineral dust aerosols during the period circa 4–20 July 2010. The fraction of photosynthetically absorbed radiation over the region during July 2010 experienced an anomalous decrease, concurrent with reduced incoming total and direct solar radiation resulting in a reduced growth response in *P. elliottii*. The authors pose one of the primary mechanisms responsible for triggering growth anomalies in *P. elliottii* is the reduction of total photosynthetically active radiation due to a dust-derived increase in aerosol optical depth. As a rare long-lived conifer (300+ years) in a subtropical location, *P. elliottii* could represent a novel proxy with which to reconstruct annual or seasonal mineral dust aerosol fluxes over the Caribbean region.

KEYWORDS: Atmosphere; Tropics; Dust or dust storms

1. Introduction and background

Mineral dust represents a substantial portion of the average global atmospheric loading. The largest current source of mineral dust aerosols to Earth's atmosphere is northern Africa (Ginoux et al. 2012). Dust mobilized from the Sahel and Sahara regions of Africa affects the climate system through radiative forcing (Miller and Tegen 1998; Miller et al. 2004) and through changing cloud characteristics by acting as cloud condensation nuclei (Lohmann and Feichter 2005) and ice nuclei (DeMott et al. 2003; Sassen et al. 2003) in the atmosphere. Mineral dust aerosol is also shown to affect ocean chemistry (Jickells et al. 2005; Mahowald et al. 2005), the biogeochemical processes related to soil development (Muhs et al. 2007), and terrestrial ecosystem function (Swap et al. 1992; Das et al. 2013).

Recent research by Xi and Sokolik (2012) has demonstrated a causal link between mineral dust aerosols impacting vegetation growth by reducing the surface radiative balance and total photosynthetically active radiation (PAR) for C3 plants in an Asian dryland ecosystem. Atmospheric dust deposition can be an important source of new phosphorous (P) inputs into ecosystems and produce increased vegetation growth, particularly for tropical/subtropical forests limited in P (Swap et al. 1992; Chadwick et al. 1999; Okin et al. 2004; Bristow et al. 2010; Yu et al. 2015). Specifically, African mineral dust aerosols were found to account for 25% of total atmospheric P input in forested landscapes of the Yucatan Peninsula during the months of June through August (Das et al. 2013). Forest ecosystems are an extensive part of the biosphere, and as such, understanding how they respond to climate regimes is important. Decadal- to centennial-scale climate normals and extremes of temperature, precipitation, and drought are considered widely as limiting factors on individual tree growth and ecosystem functioning for locations outside of the tropics (Fritts 1976).

Located longitudinally between North Africa and the Yucatan, the southern Florida region is within the region of the easterly trade winds that carry African dust over the Atlantic Ocean to the Caribbean entrained by the Bermuda high. The deposition rate of dust over southern Florida is approximately $9.1 \text{ mg cm}^{-2} \text{ yr}^{-1}$ (Prospero et al. 1987; Landing et al. 1995) with the bulk occurring primarily during the summer months (June–August), albeit with a high variability between years (Prospero 1999). Within the Florida Keys specifically, the Pleistocene-aged soils are derived primarily (60%–80%) from African dust (Muhs et al. 2007), demonstrating a historical transport trajectory to the southern Florida region.

In subtropical/tropical environments, vegetation growth is explained substantially by precipitation, solar radiation, and soil water content, despite significant intra-annual seasonality (Wagner et al. 2014). Seasonal dryness and photoperiodism can induce phenology changes in vegetation growth and flowering (e.g., Borchert and Rivera 2001; Rivera and Borchert 2001; Yeang 2007; Calle et al. 2010). Less understood, however, is the short-term role of atmospheric aerosols within the context of land–atmosphere interactions, which are hypothesized to include multiple, interrelated processes and feedbacks (Carslaw et al. 2010). Short-term changes in cloud cover and atmospheric turbidity both occur with oscillatory weather patterns but also vary over long-term periods forced by both anthropogenic activities (i.e., pollution, black carbon) and natural events (i.e., pollen, volcanic eruptions, mineral dust; Boucher et al. 2013).

Diffuse radiation effects are known to increase photosynthetic rates of canopy trees because indirect radiation has been shown to penetrate the canopy more effectively than direct radiation, affecting vegetation that is normally shaded (Suzaki et al. 2003; Urban et al. 2007; Dengel et al. 2009; Xi and Sokolik 2012; Gu et al. 2002). Yet, the sensitivity of vegetation to indirect sunlight depends on a number of factors, such that ecosystems with lower LAI values (e.g., grassland, woodland) are less sensitive to diffuse radiation compared to a forest with complex vertical structure and dense canopy. Further, a number of other factors related to plant photosynthesis, respiration, and transpiration processes can have varying effects on vegetation response to aerosol-enhanced diffuse radiation (Gu et al. 2003). For instance, lowered leaf/soil temperature from indirect radiation could decrease leaf/soil respiration, whereas a lower vapor pressure deficit would likely increase stomatal conductance (Steiner and Chameides 2005; Yamasoe et al. 2006; Matsui et al. 2008; Wohlfahrt et al. 2008; Xi and Sokolik 2012).

In the Florida Keys, Harley et al. (2011) demonstrated annual growth ring formation in *Pinus elliottii* var. *densa* (hereafter *P. elliottii*), the foundation species and sole canopy tree in endangered pine rockland ecosystems of the United States (Figure S1) but could not find a strong long-term climate signal (i.e., precipitation, temperature) within the annual growth rings of the species. Later, a study by Harley et al. (2012) reported that subannual (monthly) *P. elliottii* cell production during the period March 2010–March 2011 was significantly correlated with solar radiation flux ($r = 0.51$; $\alpha = 0.10$). Of the six total trees included in the study, four were found to form an intra-annual density fluctuation (IADF; commonly known as a false ring), which is an anomalous radial growth characteristic, formed during the sampling period of June–August 2010, concurrent with a period of reduced incoming solar radiation. The IADF noted by the Harley et al. (2012) study was characterized by a decrease in tree growth during the month in July, followed by a

return to normal growth during August, after which tree growth started slowing as normal until the end of the growing season (November–December; Figure S1).

The formation of IADFs and their climatic triggering mechanisms has been studied for various species in temperate latitudes (e.g., [Rigling et al. 2001, 2002](#); [Masiokas and Villalba 2004](#)) and the Mediterranean region (e.g., [Cherubini et al. 2003](#); [Campelo et al. 2007](#); [de Micco and Aronne 2009](#); [Battipaglia et al. 2010](#); [Copenheaver et al. 2010](#); [De Luis et al. 2011](#)). Although the ecophysiological processes responsible for IADF formation can be difficult to ascertain ([De Micco et al. 2012](#)), drought stress is a common mechanism. Drought stress was an unlikely cause for the 2010 IADF in *P. elliottii* as local and regional weather patterns suggest wet conditions during the study period ([Harley et al. 2012](#)). Other than rejecting drought stress as the likely cause for IADF formation, [Harley et al. \(2012\)](#) did not speculate a cause for the formation of the IADF and did not resolve the issue.

In this paper, we reanalyze the monthly *P. elliottii* cell production data presented in [Harley et al. \(2012\)](#) by implementing an explicit strategy to provide evidence for an impact of atmospheric mineral dust aerosols on tree growth in the Florida Keys via reduction in direct solar radiation that exists at both the monthly and annual temporal scale. We suggest that the influence of mineral aerosols transported across the Atlantic Ocean to the Florida Keys region in July of 2010 triggered a decline in tree growth from a reduction in measured direct radiation at the surface. Although the effect of atmospheric turbidity on vegetation response includes multiple and complicated mechanisms, studying the influence of atmospheric conditions, particularly mineral dust aerosols, on intra-annual to annual tree growth might elucidate a deeper understanding of these complex land–atmosphere interactions and potential feedbacks that occur. We present the hypothesis that changes in radiative forcing from an anomalous dust-derived increase in aerosol optical depth (AOD) and subsequent reduced total PAR was the mechanism responsible for triggering the production of the IADF in *P. elliottii* during the peak of the 2010 growing season (July).

2. Materials and methods

We analyzed Earth Observation (EO) products available from NASA, surface meteorological measurements, and modeled irradiance data to reveal a relationship between dust-derived changes in AOD and atmospheric conditions at the surface in southern Florida. Tree growth data used in this study were previously published by [Harley et al. \(2012\)](#) and are described in [section 4](#).

2.1. Earth Observation data

We analyzed a suite of EO products during the 2010 growing season framed within the available historical data from that sensor in an attempt to identify a mechanism behind the proposed interaction between tree growth anomalies (IADFs) and atmospheric conditions. Moderate Resolution Imaging Spectroradiometer (MODIS) on *Terra* (MOD) and *Aqua* (MYD) provides once daily (each) high-resolution AOD and ecosystem properties determined from reflectance

properties (Remer et al. 2005). MODIS level-3, version 6.0, AOD at 550 nm ($1^\circ \times 1^\circ$ resolution) was acquired from NASA's Land Processes Distributed Active Archive Center for the region 23° – 26° N, 85° – 80° W. Although not centered directly on the sample location, this region for the AOD product provided a balance of optimal sample numbers for the areal averaging and minimization of any spectral interference with the Florida mainland. In addition, we used level-4, version 6, 8-day fraction of photosynthetically active radiation (f PAR; MYD/MOD15A2H) that is resolved at a higher resolution of 0.25 km^2 . The f PAR is determined by a combination of the radiation use efficiency concept in conjunction with land surface biome class lookup tables (Myneni et al. 2002). The version 6 f PAR was shown to be considerably better than version 5, with a root-mean-square error of 0.15 for the biome type (Yan et al. 2016b). Further, it should be noted that in addition to the improvements in screening for clouds and improvements in linear interpolation of unresolved pixel retrievals, the algorithms return the maximum f PAR value for the 8-day period attainable when more than one value meets the strict criteria (Running and Zhao 2015; Yan et al. 2016a).

AERONET stations use a sun photometer to measure the extinction properties of the atmosphere from the surface (Holben et al. 1998). A station close to the study site (ca. 180 km east) is located in Key Biscayne, Florida, and has available level-2.0 data (processed for quality control and cloud-free periods) for the AOD product for most of 2010. The extinction Ångström coefficient α is a photometer product generated by measuring the extinction at multiple (440 and 870 nm) wavelengths (Holben et al. 1998). In previous studies, α was shown qualitatively to be inversely proportional to aerosol size (Eck et al. 1999; Kahn et al. 2007). Typically, $\alpha < 0.60$ indicates larger particles when identifying dust sources (Schepanski et al. 2007); however, a more recent study from Ginoux et al. (2012) used values < 0 to provide a more stringent test. For this study, we were interested in the coarse particles associated with mineral dust, but in this case the aerosols have been transported a long distance, resulting in a smaller size than identified at the sources from gravitational settling. Another study in the Caribbean by Jung et al. (2013) found α to reach $\alpha < 0.20$ with a minimum of 0.1 during a dust outbreak. From this reasoning, we have used $\alpha < 0.50$ to identify mineral dust in the study region, with more stringent $\alpha < 0.25$ to identify strong dust outbreaks.

We used the Ozone Monitoring Instrument (OMI) on *Aura* at 500 nm (OMAERUVd level 3) over the trans-Atlantic region (0° – 45° N, 0° – 100° W) to inform the timing of dust activity on a coarse spatial scale of $1^\circ \times 1^\circ$ (Levelt et al. 2006). OMI, along with the previous platforms of *Nimbus-7* and Earth Probe–derived aerosol index (AI), using similar sensors, benefit from having one of the longest temporal record available (albeit discontinuous and with data inconsistencies from 1993 until the launch of OMI) for remotely sensed aerosol data (1978–current) and could be used to suggest a potential effect of African dust on tree growth in the Caribbean region. To also help track specific dust outbreaks across the North Atlantic Ocean, we used the Hybrid Single-Particle Lagrangian Integrated Trajectory 4.5 model (HYSPLIT) from NOAA Air Resources Laboratory (Draxler and Hess 1998) with the Global Data Assimilation System archive to calculate back trajectories over several 10-day periods in 2010 from southern Florida.

2.2. Surface measurements

In addition to the EO products described above, we also analyzed surface meteorological measurements from the southern Florida region. Through the cooperation of the U.S. Fish and Wildlife Service, a local weather station at Big Pine Key [24.70°N, 81.37°W; also site of [Harley et al. \(2011, 2012\)](#) studies] recording hourly solar radiation levels from 2007 to 2014 was used to determine the seasonal variation in total solar radiation (W m^{-2}) at the surface during 2010 from an installed pyranometer (Apogee Instruments, model SP-230).

To complement this site-specific yet relatively short (8 yr) irradiance dataset, irradiance data were sought from surface synoptic observation (SYNOP) stations, but most stations, including all near the Florida Keys, only report the duration of sunshine. A nearby ultraviolet-B (UV-B) monitoring and research program station operated by the U.S. Department of Agriculture in Homestead, Florida, was examined for possible use, but after further analysis it was discovered that errors existed in the PAR pyranometer sensor before it was replaced in 2012 (likely from a lightning strike that went undetected earlier), which is now appropriately flagged on the UV-B website for the time period 2009–11.

The newly validated National Solar Radiation Database (NSRDB) from the National Renewable Energy Laboratory (NREL) has a multisatellite and modeling approach corrected with ground measurements for estimating the surface and clear-sky direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and global horizontal irradiance (GHI; W m^{-2}) at a $4 \text{ km} \times 4 \text{ km}$ and 30-min resolution from 1998 to 2014 ([Sengupta et al. 2015](#)). These three global variables are related through cosine of the angle of incidence of the sun Z , whereby $\text{GHI} = \text{DNI} \cos(Z) + \text{DHI}$. This set of irradiance variables extend ground-based measurements with a combination of a physical model for estimating the global irradiance with cloud and aerosol detecting satellites (e.g., AVHRR Pathfinder Atmospheres–Extended, Geostationary Operational Environmental Satellites) to provide a highly spatially resolved dataset of uncertainties on average less than measurement-based systems ($<5\%$; [Reda 2011](#)). For this study, the majority of the results are based on the $4 \text{ km} \times 4 \text{ km}$ tile centered at 24.69°N, 81.38°W that overlaps with the Big Pine Key weather station (24.70°N, 81.37°W) dataset mentioned above for 2010 (with 2007–14 data utilized for context), while a larger region of data of the Florida Keys is used to look at the spatial homogeneity of the irradiance signal for discriminating local and further field aerosol sources.

3. Results

3.1. Earth Observation data

During any given year, the peak in the annual cycle of dust transported from Africa to the Americas occurs during the month of July (e.g., [Prospero 1999](#)), and this is supported by many satellite platforms (e.g., [Yu et al. 2015](#)) and ground-based measurements (e.g., [Prospero et al. 1987](#)). For the year of inquiry—2010—MODIS AOD over the region displays that the transport of mineral aerosols is anomalously high, specifically during the period 26 June–20 July, as evident in the high AOD

Figure 1. Hovmöller plot over longitudes of 60° to 90°W of daily MODIS *Aqua*-derived AOD at 550 nm for latitudes from 22.5° to 27.5°N. The transportation of the June–July mineral aerosols over the study region is evident in the high AOD values during this time period. Gray values are missing data.

values (>0.4 ; green-blue to blue) during this time period (Figure 1). This Hovmöller plot of AOD values (Figure 1) aids to interpret the frequency of transported aerosols and demonstrates that for 2010 that the time period in July experienced the longest episode of consecutive days when the AOD was anomalously high over the region. Indeed, shorter-lived transported aerosol events are evident from Figure 1 on a 2–3-week interval but at a much smaller magnitude.

The spatial-mean MODIS AOD over a small (23°–26°N, 85°–80°W) area over Big Pine Key further corroborate the increased AOD showing numerous days throughout 2010 where AOD values spike above the annual mean of 0.18 and standard deviation of 0.10 (Figure 2a; black and gray horizontal line, respectively). The AERONET station at Key Biscayne recorded 500-nm AOD values that track with the MODIS AOD from this region (Figure 2a). AERONET AOD values corresponding with high MODIS AOD days were plotted against AERONET-derived α (Figure 2b) to reveal that during the year 2010, the only time period containing high AOD values and α values < 0.25 (associated with large aerosols) was during the period circa 14–20 July. In addition, there are three other days with low values of α ; however, they are in the inferred smaller-mean particle size group between with $0.25 < \alpha < 0.50$. In addition, all other high AOD days correspond with low α values (Figure 2b), except for a value on 5 June 2010 with $\alpha > 1.00$. The 5 June 2010 value is likely a result of the gas and biomass aerosol species that

Figure 2. Particle size of the July 2010 dust event over the Florida Keys region inferred from aerosol optical depth and Ångström coefficient. (a) Mean daily MODIS *Aqua* AOD for the year 2010 (23°–26°N, 85°–80°W; dark gray line) and 10-day running AOD mean that region (black line) plotted with AERONET AOD at 500 nm (blue line) from Key Biscayne, Florida. Horizontal black line and gray line is 2010 mean and one standard deviation of AOD small region, respectively. (b) Relationship between level-2.0 AERONET AOD at 500- and 440–870-nm extinction Ångström coefficient during the year 2010 for day and month data points (black dots) above one standard deviation. Dark gray bar represents high assurance of large particle size associated with dust events and light gray bar represents lesser assurance of dust event-source aerosols.

were transported from an anomalous northerly wind the *Deepwater Horizon* oil spill in the northern Gulf of Mexico (Middlebrook et al. 2012) that started in April 2010.

OMI on *Aura* captured increased AOD over the southern Florida region during the period 13 June–20 July 2010, with a clear connection to North African dust emissions with the HYSPLIT back trajectory model resolving a path (Figure 3) from the AERONET site in Key Biscayne. Specifically, connectivity between the southern Florida region and North Africa dust emissions were discovered from HYSPLIT analysis for dust storm activity commencing on 18 and 26 June and

Figure 3. Aerosol optical depth during the 10-day period (11–20 Jul 2010) over the North Atlantic Ocean. Daily OMI aerosol extinction optical depth at 500 nm (yellow to blue color bar ranging from 0.0 to 1.0) showing an African dust event that influenced the southern Florida region during (a) 17–20 Jun 2010, (b) 24 Jun–6 Jul 2010, and (c) 10–20 Jul 2010. Spatial extent is 0°–45°N, 100°–0°W and OMI spatial resolution is 1° × 1° grid. Overlaid in magenta is the 10-day HYSPLIT back trajectory originating from 500 m at the AERONET site of Key Biscayne annotated with noon of each day (magenta dots) from the last position dated (month, day) of 2010.

arriving in the region on 26 June and 5 July, respectively (Figures 3a,b). Furthermore, a large dust outbreak arrived at the AERONET site on 20 July from a known large source region in the Saharan heat low (Ashpole and Washington 2013) on 10 July (Figure 3c).

The historical 8-day *f*PAR estimated from MODIS (*Terra* and *Aqua* for 2007–14) for the exact study area (0.25 km²) revealed a slightly concave-up parabolic trend over a year with an extreme minimum of *f*PAR in July (Figure 4). The *f*PAR 2010 24-day running mean deviated positively from the historical trend in May to

Figure 4. The *f*PAR over the Florida Keys region. MODIS-derived *f*PAR for the 0.25 km² over the study site grid cell (24.7062°N, 81.3780°W) from (a) *Terra* and (b) *Aqua* platforms. Figures show the long-term mean (gray line) during the total available period 2007–14 (*Terra*) and 2007–14 (*Aqua*) and 24-day running mean for the year 2010 (black line). The shaded gray region represents plus or minus one standard deviation of 8-day mean.

June and negatively in July from MODIS *Terra* (Figure 4a) and exhibited a less pronounced negative anomaly in July from MODIS *Aqua* (Figure 4b), as the historical trend already had a large decrease in *f*PAR in July. The variation in the maximum *f*PAR values over the study region demonstrate a noticeable decrease in July (a 25% reduction) from the historical record, but more importantly the relative increase–decrease–increase pattern compared with the historical trend of *f*PAR over the course of May to September. Smaller fluctuations in the signal of *f*PAR seen in the AOD signal in Figures 1 and 2 are likely due to the longer temporal frequency (24 day) and maximum return value per acquisition period (8 day) from the MODIS product that have been applied in this study to distinguish variations in the 2010 signal relative to the historical signal.

3.2. Surface measurements

The 8-yr (2007–14) trend of incoming solar radiation in the Florida Keys from the climate station at Big Pine Key demonstrates a positive linear pattern of

increased radiation during January–May, a parabola-like pattern during May–August, followed by a negative linear pattern of reduced values during September–December (Figure 5a). Incoming solar radiation during 2010 (Figure 5a; thick black line) follows the historical trend up until the end of May, including the substantial reduction and subsequent recovery to levels as in the historical trend. However, at the beginning of May, the solar radiation for 2010 was elevated above the historical mean until mid-June when the measured solar radiation dropped quickly back to the historical mean from late July. After which, there is a daily increase in solar radiation starting at the end of July; however, this is not anomalous compared with the 7-yr mean pattern measured at the station.

Solar radiation as modeled by the NRSDB for the location centered at the Big Pine Key ground station for 2010 demonstrates a pattern that has numerous deviations from the clear-sky global radiation (Figure S2) at two different frequencies: first, at relatively shorter periods of time on the order of 2 to 3 days of increasing reductions up to $150\text{--}200\text{ W m}^{-2}$ (50%–60% of clear-sky value) and, second, at longer periods on the order of 5 to 6 days at lower reductions of $50\text{--}150\text{ W m}^{-2}$ (15%–60% of clear-sky value). The shorter period and larger magnitude reductions appear to occur quite frequently with several in a month, with a slight reduction of frequency in the latter portion of the year. In contrast, the longer period of moderate reduction in the global radiation appears to only occur twice in the year: once at the beginning of the year in February for a period of circa 20 days and another starting the beginning of July for circa 20 days as well. In both of the above cases, there are some variations in the reduction of irradiance, but with the period in July, there is almost a continual reduction of $50\text{--}60\text{ W m}^{-2}$ ($\sim 20\%$ of clear-sky value) compared to the clear-sky value.

We also analyzed the change in irradiance at the surface relative to the total range of years at this one location for the daily mean direct and diffuse portions in Figures 5b and 5c. In the case of the historical DNI at the surface (Figure 5b), there is a pronounced increase in the daily mean value that peaks at 300 W m^{-2} at the beginning of April, followed by a gradual decrease to circa 200 W m^{-2} that it reaches near the end of June, a value around which values fluctuate for the remainder of the year. On top of this historical pattern, there is a series of substantial differences for 2010, which include three marked periods with values below the mean DNI and one period of values substantially higher than the mean DNI (that occurs directly after the last period of decreased values). The first two periods of decreased values have minimum values in mid-April and mid-May that had a relative decrease of 150 W m^{-2} ($\sim 50\%$ of historical value), where in both cases the periods before the decrease had values similar to the historical mean. The third period of decreased values occurs after a prolonged period of elevated values ($+100\text{ W m}^{-2}$ or $\sim 40\%$) above the mean, resulting in a quick first positive and then negative change of 160 W m^{-2} from 310 W m^{-2} in 10 days, starting in mid-May and end of June, respectively. The period of below-average values at circa 50 W m^{-2} lasts until mid-July before gradually returning to the longer-term mean values, a 110 W m^{-2} increase over 10 days. In contrast, the DHI component displays (Figure 5c) an almost opposite trend for the main, anomalous increases and decreases described above for DNI in 2010 and a much gradually increasing and then decreasing trend that peaks at the end of June. However, in the case of the DHI component, the values only obtain a mean maximum of 125 W m^{-2} , compared

Figure 5. Measured solar radiation and cellular *P. elliotii* growth on Big Pine Key, Florida, and modeled clear-sky direct and global horizontal irradiance. (a) Incoming solar radiation measured from a U.S. Fish and Wildlife Service weather station on Big Pine Key (24.70°N, 81.37°W) during the period 2007–14 displayed as the long-term mean (dark gray line) and plus or minus one standard deviation (shaded gray) and mean during the year 2010 (black line). Inset display is a transverse section of *P. elliotii* on Big Pine Key showing cell production during the 2010 growing season (14 Mar–15 Dec 2010) with defined regions of earlywood (EW) and latewood (LW) cells and the IADF that occurred between July and August 2010 (adapted from Harley et al. (2012)). Tree growth is from bottom left to right in the image

with the DNI that has a mean maximum value of 350 W m^{-2} , and therefore the changes in irradiance for the diffuse fraction are only up to $\pm 50 \text{ W m}^{-2}$.

In a larger spatial context, this same dataset has been plotted as the historical (2007–14) anomalous mean of the GHI for the months associated with both the growing period and high dust activity for the year 2010 as a map over the Florida Keys area (Figure S3). These maps demonstrate that 1) the change in GHI at the surface is almost homogenous for the entire region mapped within each period and 2) that marked values at, above, and then below the 8-yr record average occur for the months of May, June, and July, respectively. These results further emphasize the anomalous record of the change in radiation at the surface for the total radiation as initially discovered at the Big Pine Key station by [Harley et al. \(2012\)](#). In addition, we found negative correlations between MODIS-derived *Terra* AOD and NRSDB GHI ($r = -0.49$, $p = 0.09$) and DNI ($r = -0.51$, $p = 0.07$) over the study area during the year 2010.

4. Tree growth in the Florida Keys

In addition to the surface meteorological measurements and EO products, we include data from a previously published source. Cellular tree growth data (cambial activity) were obtained for six *P. elliotii* trees growing in the Florida Keys during the period March 2010–March 2011. These tree growth data are in the form of monthly cambial growth production and are described in detailed by [Harley et al. \(2012\)](#). These data provide a short-term perspective of *P. elliotii* radial growth on a subannual time scale.

The analysis of subannual punch core data from six trees revealed that during the 2010 growing season, cambial reactivation and dormancy occurred in February and November, respectively ([Harley et al. 2012](#)). Not only did the IADF that formed in four of the six trees occur during July 2010, but that month is characterized by a marked reduction in cell production in all but one tree as well as total solar radiation ([Figure 5a](#)) and DNI ([Figure 5b](#)) based on the monthly sampling times indicated from [Harley et al. \(2012\)](#). Correlation analysis demonstrated a significant positive relationship between the sampled interval tree cell production anomaly and MODIS-derived *f*PAR anomaly in five of the six trees ($r = 0.39$ – 0.65 , $p = 0.09$ – 0.008 ; [Table 1](#)). In all but one tree, the correlations between cell growth and *f*PAR were significantly positive over the collection period in 2010 ($n = 10$). Therefore, the temporal pattern in *f*PAR derived from MODIS explains over 80% of the cell growth from the trees sampled and of those at least 48% of the variation.

←
with dashed lines showing temporal correspondence between the monthly cellular growth data collected by [Harley et al. \(2012\)](#) and solar radiation flux; scale bar is $100 \mu\text{m}$. National Solar Radiation Database modeled mean surface and clear-sky (b) DNI and (c) DHI (W m^{-2}) at a $4 \text{ km} \times 4 \text{ km}$ and 30-min resolution during the period 1998–2014. Results are based on the $4 \text{ km} \times 4 \text{ km}$ tile centered at 24.69°N , 81.38°W that overlaps with the Big Pine Key weather station.

Table 1. Influence of *f*PAR and cloud cover on *P. elliotii* cellular growth. Pearson product correlation coefficients between monthly cell production in *P. elliotii* and MODIS Aqua-derived *f*PAR (MYD15A2) and mean cloud cover fraction (MOD08_D3_6) calculated as the 2010 anomaly from the 2007–14 mean values for the same dates as the punch core intervals presented in Figure 5.

Product	Statistic	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6
<i>f</i> PAR	<i>r</i>	0.52	0.54	0.39	0.65	−0.48	0.14
	<i>p</i> value	0.03	0.02	0.09	0.008	0.04	0.32
Cloud cover	<i>r</i>	−0.25	−0.30	−0.25	−0.16	0.02	−0.19
	<i>p</i> value	0.41	0.32	0.41	0.59	0.94	0.54

5. Discussion

We used a variety of EO products and surface meteorological measurements to track African dust during 2010. Analysis of a suite of satellite-retrieved and ground-based measured data demonstrate that mineral aerosols originating from Saharan dust source regions were transported over the Florida Keys region like in most years during the summer months, but in particular for 2010, these aerosols were anomalously concentrated in only several weeks in July. When compared to the historical trends, the evidence of below-average AODs in the months before and after is also anomalous. The correlating reduction in July and increase before and after July of radiation reaching the surface from both ground measurements made at Big Pine Key, Florida, and modeled NRSDB DNI likely demonstrates the role that these aerosols played in altering the energy budget at the surface. This change in available surface energy can be tracked to a marked decrease in *f*PAR, as estimated from MODIS over the identical time period in 2010. This decrease in *f*PAR concurrent with a period of anomalous radial growth measured in *P. elliotii* on Big Pine Key, first reported by [Harley et al. \(2012\)](#), supports the hypothesis that mineral dust transported from Africa to the southern Florida region reduced the amount of surface PAR resulting in a physiological response from *P. elliotii* trees. The intense but short duration mineral dust aerosol events in July that resulted in reduced total surface solar radiation and *f*PAR specifically triggered the production of latewood tracheid cells (small cell lumen, thick cell walls) during the middle of the growing season. After the mineral dust advected past the region or was deposited, and irradiance levels increased, trees responded positively with increased radial growth in the form of earlywood-like tracheid (larger cell lumen) production before the cessation of the vascular cambium at the end of the growing season.

The increased growth in *P. elliotii* following the mineral dust events during the month of August 2010 could have been a result of a physiological response to increased PAR and direct solar radiation. Collecting the requisite primary growth physiological data (i.e., stomatal conductance, photosynthetic rate) would provide a better understanding of this response, which is a goal of future research. The increased August growth following the dust events could have also been a combined effect of increased PAR with direct inputs of phosphorous (P) derived from dust deposited on the ground surface and incorporated into the ecosystem. We did not collect dust deposition data on Big Pine Key during the study period, which precludes a more in-depth analysis of the potential for the second possible explanation (i.e., direct inputs of P) as the cause of the increased *P. elliotii* growth.

during August 2010. However, the sources and influence of atmospherically deposited P are not widely known, particularly on such short time scales. Previous studies have demonstrated linkages between atmospherically deposited mineral dust and biogeochemical cycling in terrestrial (Swap et al. 1992; Das et al. 2013) and aquatic (Zamora et al. 2013) environments, but these studies highlight that soil P turnover rates and dynamics are influenced by atmospheric mineral dust at longer time scales, from 500 to 2000 years in the Amazon (Swap et al. 1992) to million-year time scales in Hawaii (Chadwick et al. 1999). In a Jamaican montane forest, Tanner et al. (1990) added P fertilizer to plots once a year from 1983 to 1986. Mean foliar P and trunk diameter showed increased concentrations and diameter, respectively, in the P fertilizer plots compared to controls, but only after 2 years of treatment. Thus, we suggest that the response time of a potential P input from such a deposition event would likely be longer than the 1–2 weeks recorded.

Clouds present one of the most difficult uncertainties against which to control regarding their influence on atmospheric dust (Boucher et al. 2013). The absolute effect of clouds on *P. elliottii* growth is unknown and outside of the realm of our study design. Yet, the insignificant correlations between tree growth and cloud cover are supported physiologically. Correlation analysis between MODIS mean cloud cover fraction (MYD08_D3_6 for the same region as the MODIS AOD products used) and *P. elliottii* growth over the study area revealed no significant correlations (Table 1). Annual growth rings in trees are formed because the vascular cambium in the tree stem stops growing for a period of time due to a limiting factor in the environment, which is usually fluctuations in temperature, precipitation, drought, or photoperiod (e.g., Fritts 1976; Speer 2010). Additionally, no evidence exists that reports clouds as a limiting factor of annual radial tree growth (e.g., Fritts 1976). Logically, if cloud cover posed a mechanism for triggering the formation of IADFs in tree growth, then *P. elliottii* would not form annual growth rings in the Florida Keys, as shown by Harley et al. (2011, 2012, 2013), due to the high frequency of summer season convection-generated cloudiness.

The geography of the Florida Keys makes the area vulnerable to tropical storms and cyclones that form in the North Atlantic Ocean basin, which represent another potential event-based atmospheric phenomenon that could be responsible for growth anomalies in *P. elliottii*. During the year 2010, possible cloud-producing storms that could block PAR were as follows: 1) on 30 June 2010, Tropical Storm Alex was a rare June storm that passed 200 km from the Big Pine Key study site; 2) on 23 July 2010, Tropical Storm Bonnie made landfall, tracking 140 km from Big Pine Key as a minimal tropical storm; and 3) on 10 August 2010 (Knapp and Kruk 2010) Tropical Depression Five formed off the southwestern coast of Florida, beyond 200 km from the study site. The only storm of these three that could have partially contributed to the IADF formation would be Tropical Storm Alex (passing during the sampling period as the IADF) and reducing surface PAR from anomalously high cloud cover. However, none of the data analyzed suggests that a reduction in PAR or increase in AOD occurred around that period. In addition, it is more likely that Tropical Storm Alex, Tropical Storm Bonnie, and Tropical Depression Five resulted in the enhanced wet deposition in the region, clearing the atmosphere of any aerosols (mineral or otherwise), and leading to a positive growth response in *P. elliottii*.

We posit that the findings from Miller et al. (2004) that radiative forcing was the major mechanism responsible for triggering the production of the IADF in *P. elliottii*

during the peak of the 2010 growing season reducing total PAR due to a dust-derived increase in AOD. Further, with the removal of the mineral dust from the atmosphere from a combination of advection and wet deposition soon after resulted in the subsequent positive response in *P. elliottii* to increases in total PAR. The reduction in plant photosynthetic rate and primary production due to aerosol-caused reduction in PAR is well documented (Chameides et al. 1999; Bergin et al. 2001). Yet, studies demonstrate the “diffuse radiation fertilization” effect, whereby gross photosynthetic rate increases in response to reduction in PAR (e.g., Niyogi et al. 2004; Dengel et al. 2009). Niyogi et al. (2004) tested the hypothesis that atmospheric aerosols influence the regional carbon cycle across three terrestrial habitats: grassland, forest, and cropland. They found that CO₂ sink increased with aerosol loading for forest and cropland but decreased for grasslands. They hypothesized the difference to be canopy architecture found across different forest types. In the case of Dengel et al. (2009), aerosols enhance the diffuse PAR, promoting higher photosynthetic rates among the light-limited shaded leaves in a forest canopy. Further, because the positive affect of diffuse radiation fertilization on vegetation growth is due to more scattered sunlight reaching shaded leaves, the influence of the effect depends on the LAI of an ecosystem. Thus, ecosystems with lower LAI values (i.e., thinner/more sparse forests) are less sensitive to the effect of dust-enhanced diffuse radiation (Wohlfahrt et al. 2008; Mu et al. 2010; Xi and Sokolik 2012).

In the Florida Keys, *P. elliottii* is the sole canopy tree species within the pine rocklands, and the habitat is composed of open, woodland-like vegetation density. The pine rockland landscape is characterized by the sparse dispersal of only *P. elliottii* with large areas of exposed limestone bedrock rather than continuous soil cover, exposed at the surface and a discontinuous canopy of simple vertical structure (Figure S1; Snyder et al. 1990; Sah et al. 2006; Harley et al. 2013). Typical basal area in most eastern deciduous forest sites ranges 20–40 m² ha⁻¹ (e.g., Oliver and Larson 1990; Keddy 1994), whereas pine rockland sites in the Florida Keys range 6–8 m² ha⁻¹ (Harley et al. 2013). Thus, rockland environments typically have a low LAI. Therefore, diffuse PAR is less likely to have affected the total photosynthetic rate in *P. elliottii* because of the open-canopy conditions in pine rockland ecosystems.

Given that atmospheric aerosols can either have a positive or negative effect on terrestrial vegetation, higher aerosol loading can result in lower solar energy reaching the surface through the light-scattering effect, whereby plant photosynthesis decreases through a reduction in direct PAR (e.g., Cohan et al. 2002; Krakauer and Randerson 2003; Niyogi et al. 2004; Mahowald et al. 2011; Chen and Zhuang 2014). However, forests that have complex vertical structure (e.g., dense forests of eastern North America) can benefit from increased diffuse solar radiation because this energy can be more efficiently absorbed by the plant canopy and used for photosynthesis. In contrast, direct-beam radiation can only be absorbed by the sunlit portion of the canopy, which is each individual tree in pine rockland woodlands because of the sparse structure and minimal understory. Thus, we would not expect trees in the discontinuous canopy areas of pine rocklands to benefit from dust-enhanced diffuse PAR, and this is reflected in the presented observed and modeled radiation and *f*PAR data, respectively. The strong negative relationship between AOD and total GHI and direct DNI on the surface supports the process that higher AOD does decrease (increase) direct (indirect) radiation. In the case of

the pine rockland ecosystem, this reinforces our conclusion that intra-annual growth of *P. elliottii* is likely responding to the decrease in direct radiation. Land–atmosphere interactions are complex and more research—such as direct, site-specific measurements of direct/indirect radiation, aerosol loading, CO₂ flux, and net ecosystem exchange—is needed to more appropriately disentangle the influence of atmospheric aerosols on the ecosystems of southern Florida.

6. Conclusions

The role of aerosols within the context of land–atmosphere interactions is poorly understood. Recently, studies have shown novel connections between atmospheric dust and vegetation dynamics. African dust can have positive effects on plant growth in the Amazon basin, acting as new seasonal inputs of nutrients (e.g., Bristow et al. 2010; Yu et al. 2015). Yet, increased AOD is likely to decrease the amount of direct surface PAR available to plants (e.g., Chameides et al. 1999; Bergin et al. 2001; Urban et al. 2007; Dengel et al. 2009; Mu et al. 2010; Xi and Sokolik 2012). Thus, we posit the mechanism responsible for triggering the 2010 growth anomalies we captured in *P. elliottii* was the reduction of total PAR due to a dust-derived increase in AOD. However, less clear are the mechanisms responsible for the subsequent increase in growth after the dust-derived AOD decreased. The passing of a tropical storm directly after the IADF formation not only could have acted to clear any aerosols in the atmosphere increasing total PAR, but it would have also enhanced nutrient deposition, both of which could have resulted in the positive growth response in *P. elliottii*. Further research should aim to disentangle the complex intra-annual relationship between the potentially radiation-limiting atmospheric dust AOD and fertilizing deposition of dust as a P input.

Future research in the Florida Keys will focus on 1) communicating our results to resource managers tasked with ensuring the persistence of the globally endangered pine rockland community in the Florida Keys and 2) investigating the potential for developing growth anomaly chronologies using *P. elliottii*. As a rare long-lived conifer (300+ years) in a subtropical location (Harley et al. 2015), *P. elliottii* could represent a novel proxy with which to reconstruct annual or seasonal mineral dust aerosol fluxes over the Caribbean region.

Acknowledgments. Analyses and visualizations used in this paper were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC. We thank Kenneth J. Voss for his effort in establishing and maintaining the Key Biscayne AERONET site. The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model used in this publication. We thank three anonymous reviewers for giving their time and energy to offer comments and suggestions that improved earlier drafts of this manuscript. All the authors contributed equally to this work.

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