Temporal Relationships Between African Dust and Chlorophyll-α in the Eastern Caribbean Basin

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Abstract

Seasonal African Dust (AD) transports soluble iron to oligotrophic Caribbean waters, and when bioavailable, it could increase marine primary productivity (PP). Recently, the region has experienced the proliferation of unusually high quantities of Sargassum, an iron-absorbing macroalgae inhabiting the air-sea interface, which possess ecological and economic challenges and whose driving factors are still uncertain. AD events reach Puerto Rico (PR) mostly during boreal summer months. This is also the season when chlorophyll-α (CHL) concentrations are highest, when the algae starts to bloom, and when sediment plumes from the Orinoco River (ORP), also reach nutrient discharge maxima. This study seeks to better understand the temporal relationships between increases in chlorophyll-α (CHL) and the presence of AD events in the region. Aerosol data collected at the Cabezas de San Juan Atmospheric Observatory was used to identify AD events between January 2005 and December 2015. Light scattering coefficients were measured with a integrating Nephelometer, while light absorption coefficients were obtained from either the Particle Soot/Absorption Photometer (PSAP) or the Continuous Light Absorption Photometer (CLAP). Spectral properties suggesting AD events were cross-referenced with surface dust concentration image models and source-attributed air masses corresponding to dusty periods using Hybrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT). For all years with spectral data, modeled monthly wet dust deposition was correlated (R= 0.64) with mean CHL concentrations from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). Daily dust mass column densities from NASA's MERRA-2 model were also correlated (Rˆ2= 0.53) to sea surface iron concentrations from NASA's Ocean Biogeochemical Model. We present the 2010 case study, which coincides with the start of the Sargassum bloom and shows CHL peaks occurring a month before ORPs but during the AD season, suggesting the AD role in enhancing PP. Other possible influencing climatic and oceanographic variables could be associated to these observations. Further efforts include spatially linking the Floating Algae Index in satellite imagery to AD concentrations, to better predict harmful algal blooms and inform management.

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Introduction

- Aeolian dust has been shown to increase phytoplankton concentrations in marine areas characterized by high nutrients, but low chlorophyll concentrations (Jickels et al., 2005).
- However, dust deposition is still one of the sources (alongside coastal upwelling and riverine discharges) thought to determine sea surface nutrient availability in oligotrophic tropical regions (Tagliabue et al., 2017).
- Large amounts of mineral dust travel from the African continent to the Caribbean region.
- African dust events reach Puerto Rico primarily during boreal summer months (Prospero et al., 2013), and transport nitrogen and iron, inducing phosphorous limitations on the sea (Chien et al., 2016).
- African dust has been shown to influence chlorophyll-α concentrations in the tropical north Atlantic ocean (Santos, 2010).
- When bioavailable, nutrients in African dust could help increase marine primary productivity in oligotrophic Caribbean waters.

Research Questions:

- Does African mineral dust enhance primary productivity in the eastern Caribbean basin?
  - ❖ Are African dust events directly correlated to peak chlorophyll concentrations?
  - ❖ If so, do these correlations exhibit a reasonable temporal lag-time to account for deposition and bio assimilation time frames?

Methodology

Sampling Locations:

Figure 1. Cabezas de San Juan Atmospheric Observatory (CSJAO) at the most northeastern tip of Puerto Rico (18º 23' N, 65º 37' W, 60 masl).

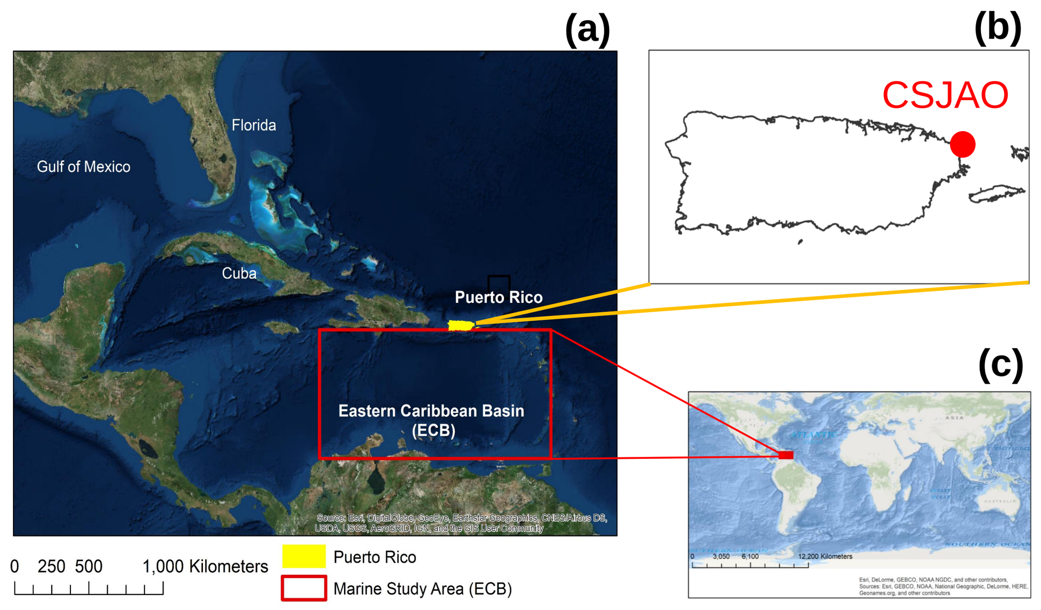


Figure 2. **(a)** Extent of marine study area in the Eastern Caribbean Basin (ECB), as delineated in López et al., 2013 (18°N, 75°W,11°N,61° 116,647 km^2). **(b)** Location of CSJAO sampling site. **(c)** World location.

- Overall study time frame: January 2005 – December 2015

Part 1: Identification of African dust (AD) events over Puerto Rico

Step 1: Characterized possible events according to aerosol optical properties at CSJAO

- Scattering coefficient (σ_s)
  - ❖ TSI Nephelometer Model #3563
- Absorption coefficient (σ_a)
  - ❖ Particle Soot/Absorption Photometer (PSAP)
  - ❖ Continuous Light Absorption Photometer (CLAP)

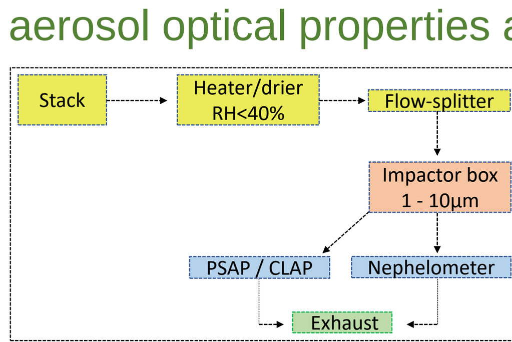


Figure 3. Simplified CSJAO sampling diagram

Step 2: Data processing:

- Averaged to daily values
- Calculated the Scattering Ångström Exponent (SAE), whose values are inversely proportional of particle size

$$SAE = \frac{-\log\left(\frac{\sqrt{\sigma_{s\,700mn}}}{\sqrt{\sigma_{s\,500mn}}}\right)}{\frac{\lambda_{700}}{\lambda_{500}}}$$

Figure 4. SAE equation

Step 3: Confirmed AD events with supporting modeled products:

- NAAPS surface dust forecast (https://www.nrlmry.navy.mil)
- SKIRON dust concentration forecast (http://forecast.uoa.gr/)
- NESDIS daily Aerosol Optical Depth (AOT) (https://www.nesdis.noaa.gov/content/imagery)
- Ten-day air mass back trajectories using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model for three elevations (500m,1500m,3000m) starting 12:00 UTZ (https://ready.arl.noaa.gov)

Part 2: Identification of peak Chlorophyll-α (CHL-α) concentrations, plus relationships to AD and nutrient availability using modelled and remotely sensed products

- Dataset acquisition: (http://giovanni.gsfc.nasa.gov/giovanni/)
- ❖ Instrument: NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite
- ❖ NASA's Models: Ocean Biogeological Model (OBM) and Modern-Era Retrospective analysis for Research and Applications (MERRA-2)
- ❖ Primary productivity proxies: diatom, coccolithophore, cyanobacteria, total CHL and CHL-α concentrations
- ❖ Dust variables: wet and dry deposition, surface mass concentration, dust column mass density
- ❖ Sea surface nutrient concentrations: nitrate and iron

2010 Case Study Results

Dust Events suggested by Aerosol Optical Data:

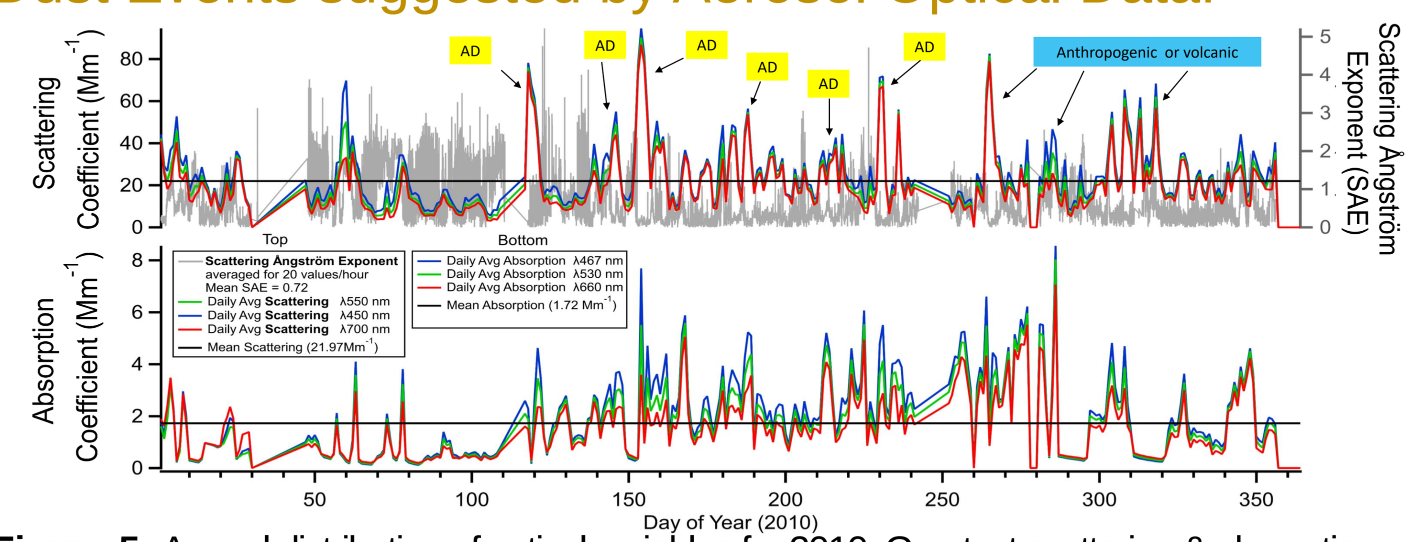


Figure 5. Annual distribution of optical variables for 2010. Greatest scattering & absorption, plus minimum SAE values are indicative of mineral dust influence (Rivera et al., 2017).

(a)

Event #	Start Date	End Date	Maximum Scattering (Mm^{-1}) σ_s	Maximum Absorption (Mm^{-1}) σ_a	Minimum (SAE)
1	Jan-3rd	Jan- 8th	46.148	3.174	0.2877
2	April 28th	May 2nd	46.148	3.174	0.0019
3	May 17th	May 26th	76.050	3.455	0.0126
4	June 2nd	June 5th	49.168	3.714	0.0103
5	June 7th	June 11th	90.216	5.511	0.0125
6	June 15th	June 17th	44.091	4.411	0.0066
7	June 28th	June 30th	34.607	5.588	0.0238
8	July 5th	July 8th	45.938	3.522	0.0150
9	July 29th	Aug 6th	54.870	4.375	0.0137
10	Aug 17th	Aug 25th	39.566	4.744	0.0087
11	Sep 18th	Sep 24th	69.595	4.131	0.0003
12	Sep 30th	Oct 3rd	81.699	3.808	0.0029
13	Oct 31st	Nov 1st	41.706	5.971	0.0078

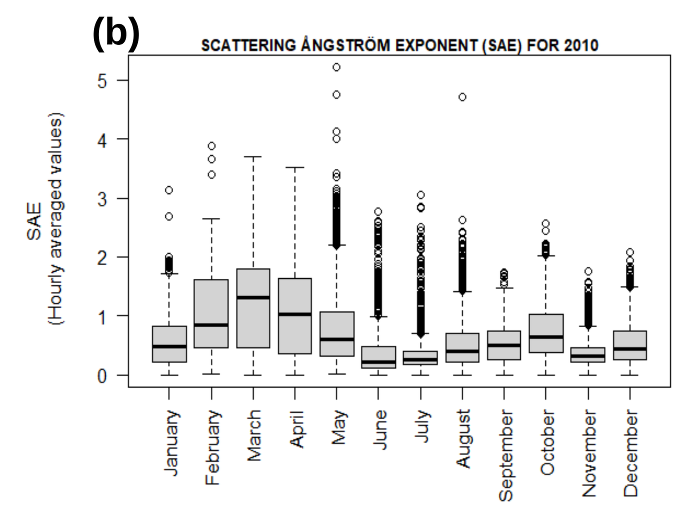


Figure 6. **(a)** Possible African dust events in 2010. Dates were selected for exhibiting the following criteria: 1 standard deviation (SD) above average σ_s, 1 SD above average σ_a and 1 SD below average SAE. Red rows indicate events in which significant AD influence was posteriorly confirmed. **(b)** Distribution of monthly SAE values across 2010.

Confirmation of Air Masses:

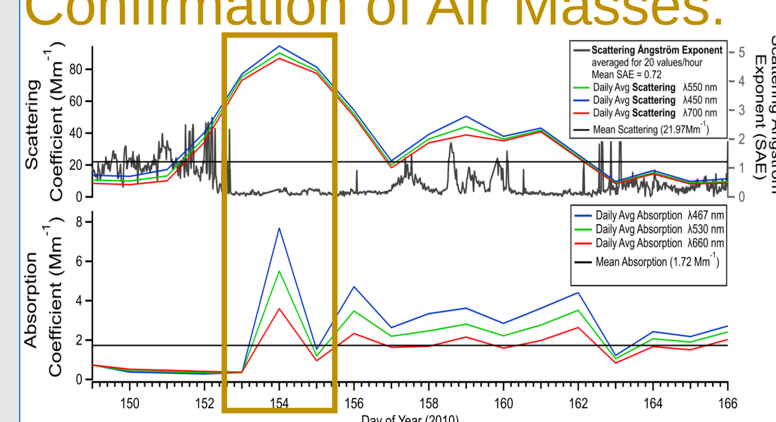
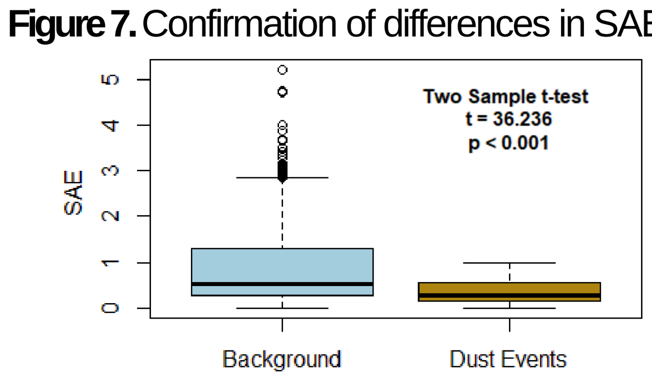


Figure 8. Example of aerosol optical properties indicating dust event #4 from June 2nd - 5th.

Figure 7. Confirmation of differences in SAE



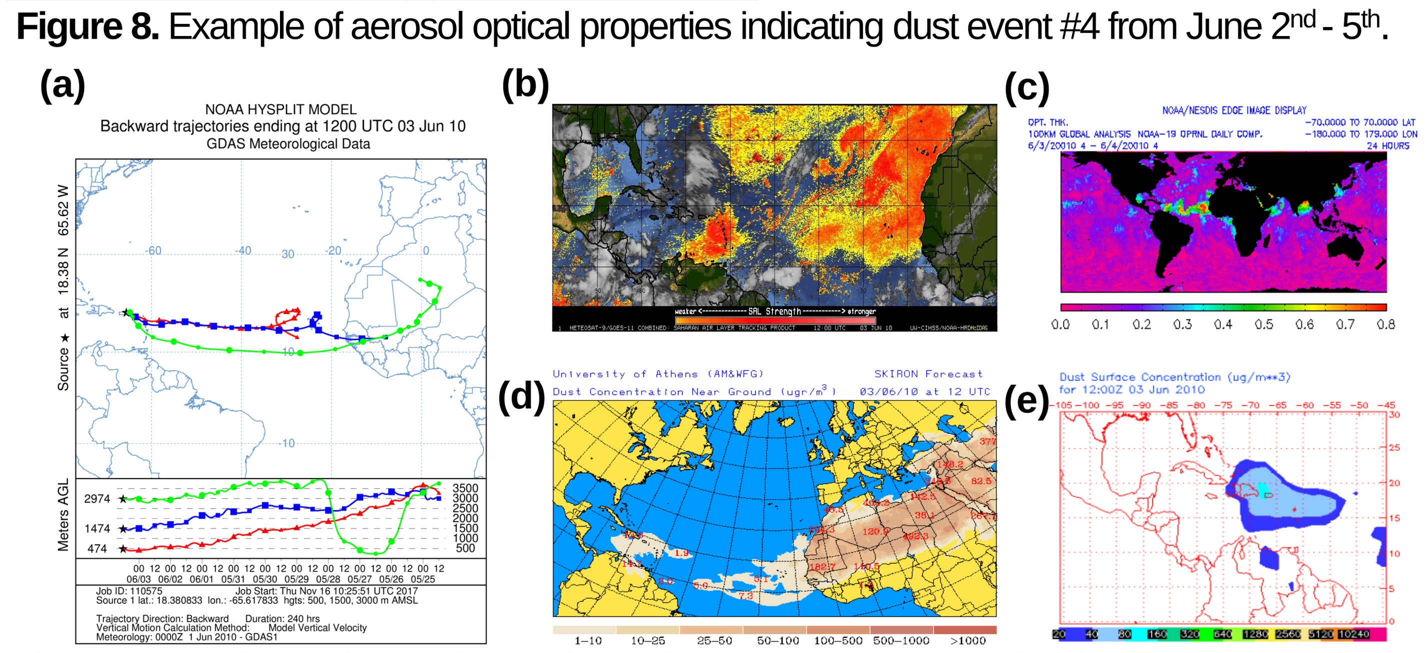


Figure 9. Products of modeling tools confirming the presence of African dust over the ECB during Event #4 of 2010. **(a)** Ten-day HYSPLIT back trajectories starting June 3rd, 12:00 UTZ, showing the air mass sourced to Saharan Africa. **(b)** Saharan Air Layer forecast illustrating a dry air mass over the ECB. **(c)** Aerosol Optical Depth imagery displaying an African dust plume crossing the Atlantic Ocean. **(d)** SKIRON forecast predicting the presence of AD. **(e)** NAAPS surface forecast also indicating dust over the study area.

Links between primary productivity proxies and dust events:

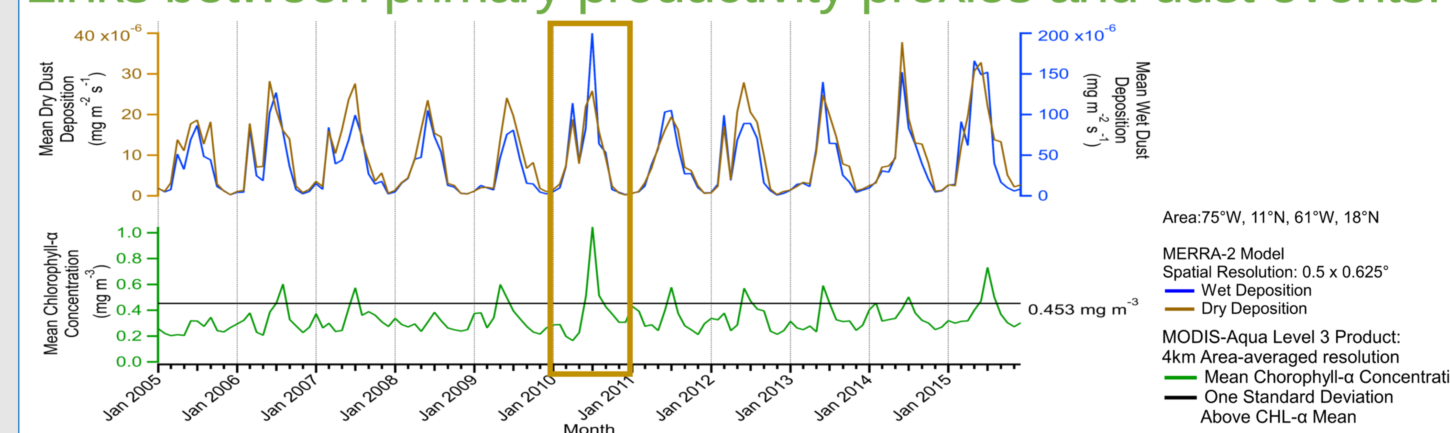


Figure 10. Monthly averages from 2005-2015 of modeled dust deposition and remotely sensed CHL-α. All three variables exhibit summer maxima. This is especially notable for CHL-α during 2010, where June-August surpasses one standard deviation above the decadal average (0.34 $mg\,m^{-3}$). Overall, wet deposition in this model contributes ~400% more dust than dry deposition.

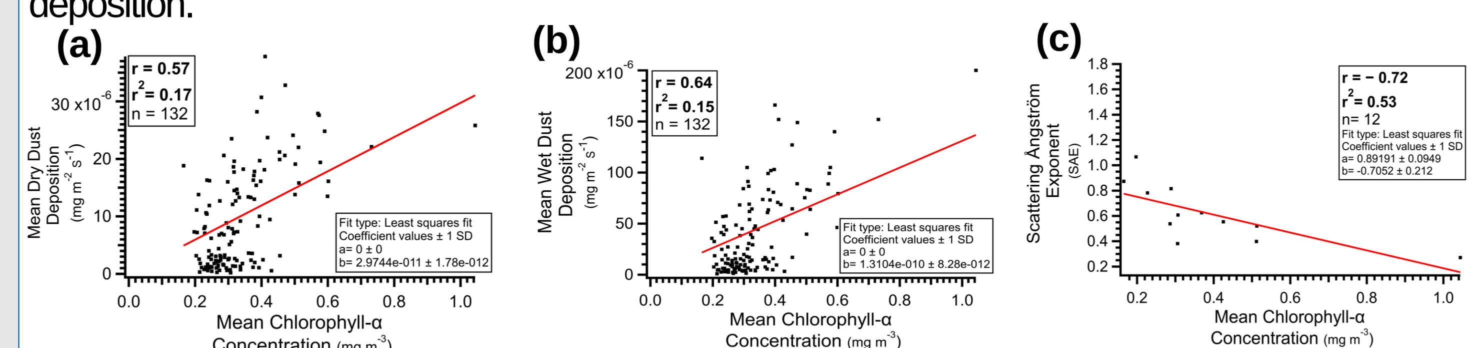


Figure 11. Scatter plots exhibiting coefficients of correlation (r) and of determination (r^2), using monthly averaged values. **(a)** A weak, positive relationship between dry deposition and CHL-α from 2005-2015. **(b)** A slightly stronger positive relationship between wet deposition and CHL-α **(c)** An inversely proportional relationship between SAE and CHL-α only using 2010 values, suggesting the influence of dust over the ECB.

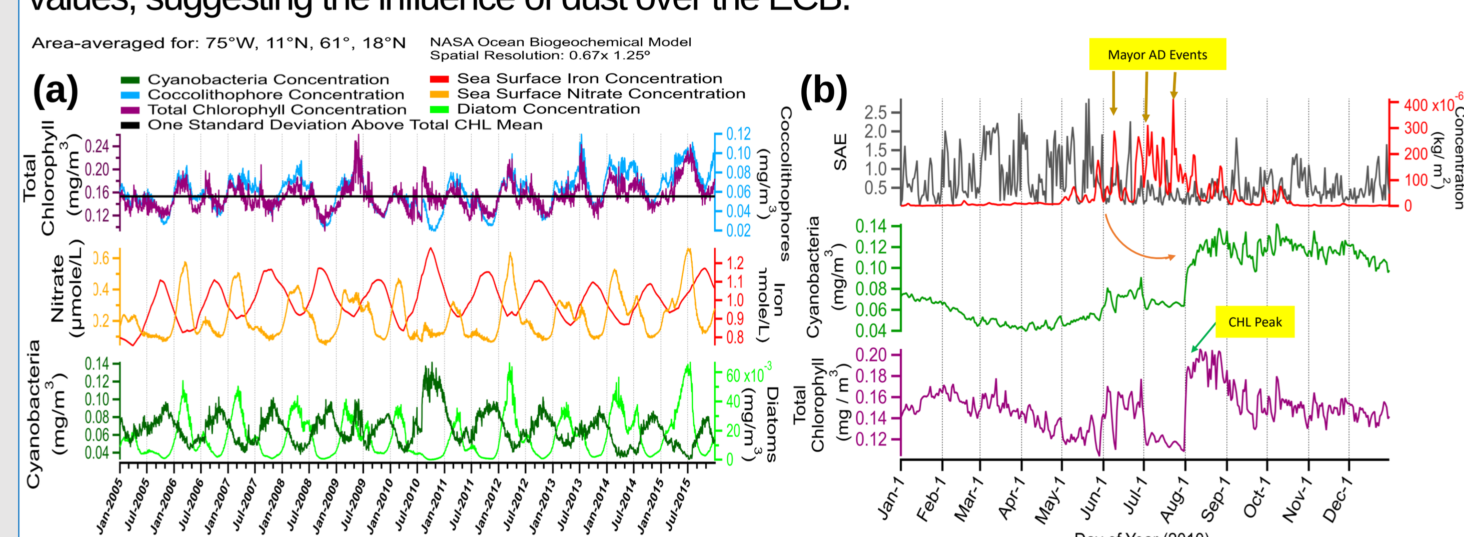


Figure 12. **(a)** Modeled daily-averaged proxies for marine primary productivity and sea surface nutrient concentrations from 2005-2015. These show direct correlations between CHL and coccolithophores (r= 0.83), plus CHL and diatoms (r=0.68). Coccolithophores and diatoms peak when sea surface nitrate concentrations are also maximum (r= 0.73 & r= 0.96 respectively), but coincide when sea surface iron concentrations are minimum (r= -0.45 & r= -0.55). **(b)** A 1 to 2 month temporal lag-time between mayor dust events and peak total CHL, plus cyanobacteria values for 2010.

Influence of the Orinoco River Plume:

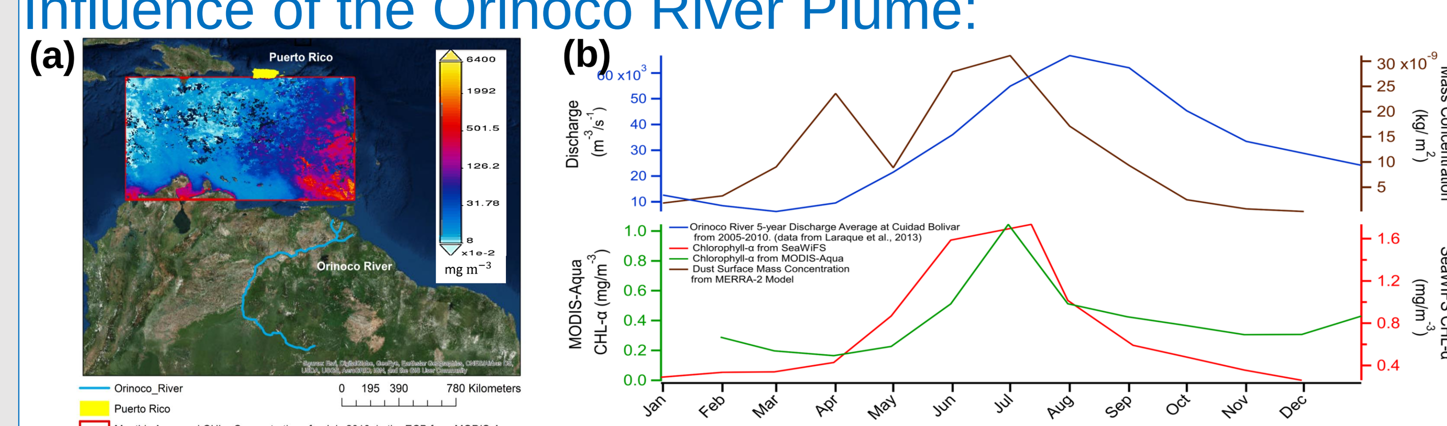


Figure 13. **(a)** Sediment plumes from the Orinoco River are known to influence the ECB's marine production (López et al., 2013), as depicted here with CHL- α concentrations.
(b) However, this simplified schematic shows how CHL- α peaks for 2010 occur 1 month before mean peak river discharges. Also peak CHL- α coincides with the African dust season.

Conclusions

- Periods influenced by African dust were succesfully characterized 77% of all possible dates, using values of scattering and absorption coefficents, plus the Scattering Ångström Exponent.
- Moderate correlations between dust deposition and chlorophyll-α (CHL-α) were obtained, confirming the seasonal coincidence. Further analysis shows that high magnitude three African dust periods were followed by increases in CHL-α concentrations after 1.0-1.5 months, suggesting a link between mineral dust particles and primary productivity. This temporal lag-time is similar to previous observations in the Tropical North Atlantic and ECB (Santos, 2010).
- This study coincided with the unprecedented bloom of *Sargassum spp.* in the Caribbean región. This macro-algae lives in the air-sea interfase and has caused harmful algal blooms during summer and fall seasons of 2010 and posterior years. However, we have not been able to link African dust events in the ECB to these harmful algal blooms.

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