IS SUMMER AFRICAN DUST ARRIVING EARLIER TO BARBADOS?

The Updated Long-Term In Situ Dust Mass Concentration Time Series from Ragged Point, Barbados, and Miami, Florida

Paquita Zuidema, Claudia Alvarez, Samantha J. Kramer, Lillian Custals, Miguel Izaguirre, Peter Sealy, Joseph M. Prospero, and Edmund Blades

Approximately 45 years of daily surface dust mass concentrations indicate a recent shift to earlier dates for the extremely dusty summer events at Barbados, while summer-mean values have mostly decreased at Miami.

Before the satellite era, it was measurements of surface dust mass concentrations made at Barbados in the mid-1960s that first indicated concretely that large concentrations of North African dust routinely reach the Caribbean basin, a distance of 5,000 km from the dust source (Delany et al. 1967; Prospero 1968). Measurements begun in Miami in 1974 further demonstrated that large quantities of African dust are also transported to the mainland United States (Prospero 1999). Subsequent studies highlight the dust's importance to the Earth's net radiation budgets, both longwave and shortwave (e.g., Mahowald et al. 2006; Kok et al. 2017), and to the biogeochemistry of the Atlantic Ocean (e.g., Zamora et al. 2013). The in situ dust loadings over the Caribbean can reach levels that even affect human health (Prospero et al. 2014). The unique, continuous long-term record of in situ measurements of the dust mass within the atmospheric boundary layer contributes to the interpretation of the satellite records, and in combination the satellite and in situ datasets are important for monitoring atmospheric compositional changes at synoptic to interdecadal time scales. This ultimately improves understanding of current climate and future climate prediction.

The ongoing filter-based measurements continue the legacy of the Atmosphere–Ocean Chemistry Experiment, which studied the large-scale spatial and temporal variability of aerosols through filter-based surface measurements at multiple sites (Arimoto et al. 1995). The two remaining locations with continuing records are uniquely situated. Ragged Point (13°6′N, 59°37′W), a promontory on Barbados's easternmost coast, is exposed to air driven by steady trade winds and is unimpacted by local sources. Barbados is the most easterly of the Caribbean Windward Islands, and during the boreal summer, is at a latitude coinciding with the main African dust outflow. The Miami site, located at the Rosenstiel School of Marine and Atmospheric Science approximately 3 km east of the mainland (25°45′N, 80°15′W), experiences a relatively pristine coastal environment except for the summer months, when the aerosol environment is dominated by the dust of the other continent (Prospero 1999). The Miami measurement location is excellent for sampling the portion of the African dust plume that reaches mainland North America.

The last published review of the Barbados time series is arguably Huneeus et al. (2011), in which monthly mean dust mass measurements from 1989 to 2003 contributed a benchmark dataset to a global model dust intercomparison study. This dataset is available through Aerocom (https://aerocom.met .no/databenchmarks.html), an international science initiative on aerosols and climate that promotes the rigorous comparison of models to observations. The full time series presented here is updated through December 2018 for Miami, and through September 2015 for Barbados along with May–September 2016 and January–March and June–August 2017. A consistent sampling and analysis protocol generates a remarkable multidecadal time record that can be robustly analyzed across its entire time record. From these, as will be shown, an assessment can be made of how intercontinental dust transport to the Western Hemisphere's surface has changed in the past decade.

DATA PROTOCOL. Although the Barbados dust record dates back to 1965, the high-volume filter samplers were not implemented at Barbados until February 1973. Aerosol samples are collected almost daily at Barbados, year-round, at approximately 0600 local time, except for holidays, extreme weather, and equipment failure. At Miami, the same filter sampling approach began in July 1974, and typically occurs daily (weather permitting) from May into September, and approximately twice weekly otherwise. Air is drawn through 20 cm × 25 cm Whatman-41 (W-41) filters,

in Barbados at the top of a 17-m tower on a 30-m bluff and in Miami at the top of a 16-m fold-over tower on the roof of a 12-m-high building next to Biscayne Bay. Pumps provide a flow rate of approximately 1 m^3 min^{-1}, yielding a sampled volume of approximately 1,000 m^3 day^{-1}. The flow rate is monitored via the pressure drop across a calibrated orifice plate. An advantage of the W-41 filters is that they enable high flow rates, permitting a collection efficiency of 95% or better for dust (Kitto and Anderson 1988).

The contribution from local sources is minimized by only sampling when the winds arrive from the open waters to the east, with wind speeds greater than 1 m s^{-1}. At Barbados this sampled sector spans 335°–130° and at Miami the sampled sector lies within 45°–202°. This restriction can reduce the amount of sampling time. Data are only included in the distributed dataset when the sampling time exceeds 10% of the possible available time, or 2.4 h day^{-1}.

The exposed filters from both sites have been processed in Miami. These include filters that are exposed to the ambient air but without an activated pump, known as field blanks. The standard W-41 filters have a very low and relatively constant blank value for a wide range of elements, even compared to specially "acid washed" W-41 filters (Morton et al. 2013). The filters are placed in a muffle furnace for about 14 h (overnight) at 500°C, and the ash residue weight, less filter blank, is assumed to be mineral dust. The blanks yield a standard error in the mineral dust concentration that is essentially constant at ±0.1 μg m^{-3} for concentrations less than 1 μg m^{-3}; at higher dust levels the standard error is about ±10%.

Soluble ions are lost during the heating, and bound water is volatilized, while other components can be broken down, so that the filter ash weight underestimates the true dust concentration. Analysis early in the program established a correction factor of 1.3 for the various losses. This correction factor is supported through a subsequent independent activation analysis, which determined an aluminum concentration of 10.4% from 1,349 dust-laden Barbados filter samples (Arimoto et al. 1995). The average crustal abundance of aluminum in soil is 6%–8% (Taylor and McLennan 1985), and an 8% average aluminum concentration in soil dust, adjusted by a factor of 1.3, is consistent with the measured aluminum-filter ash percentage of 10.4%. Many elements have been found within Barbados dust at ratios close to crustal abundances using the same technique (Trapp et al. 2010).

For this study, the daily mean dust masses reported within the original Excel files (early Lotus files were previously transferred to Excel beginning in 1982) are

concatenated into one file, and their monthly mean values derived. These are compared to previously distributed monthly mean values calculated from a formula embedded within the original Excel files, with the original files and filter sample notes consulted on any differences. The data files distributed with this study only contain the daily mean values when the sampling time exceeded 10% of the total available time. The dust mass concentrations from 31 December are set equal to those from the subsequent day, and those for 29 February, when they occur, are neglected. The timestamp follows the UTC time convention.
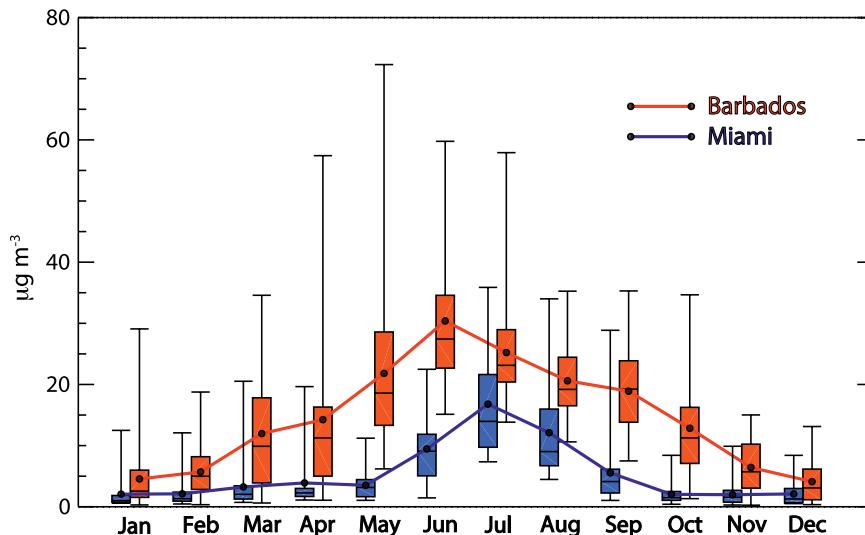

Fig. 1. Annual cycle in the monthly mean dust mass concentrations at Barbados (red; 1973–2017) and Miami (blue; 1974–2018). Box-and-whisker plots indicate the minimum–maximum range and the 25th, median, and 75th quartiles. Mean values are indicated with connected filled circles. Individual months are only included if at least 20 days were sampled. A minimum of 38 months contributed to each monthly mean at Barbados, increasing to 44 for June and July. A minimum of 27 months contributed to each monthly mean at Barbados, increasing to 41–43 during the summer.

ANNUAL CYCLE AND SEASONAL-MEAN ANOMALIES. The updated annual cycle in the monthly mean dust mass concentrations at the two locations indicates mean June–August values for Miami that are slightly higher than those reported for 1989–96 in Prospero (1999), especially in August: 9.4, 16.8, and 12.1 μg m^{-3} versus 8.4, 16.3, and 9.8 μg m^{-3} (Fig. 1). More dust is present throughout the entire year at Barbados, with a broad May–September maximum that peaks a month earlier than the July maximum in Miami. An interesting difference from the Barbados 2000–10 annual cycle shown in Stevens et al. (2016) is that the maximum individual monthly mean dust mass concentration is shown to occur in May, rather than June.

The Miami June–August dust mass concentration anomalies relative to the 1974–2018 mean of 12.83 ± 0.03 μg m^{-3} indicate a skewed distribution, with a long-term mean exceeding the median (11.63 μg m^{-3}), but with only 15 summer seasons out of 39 exceeding the mean. The elevated dust mass concentrations recorded around the 1984 maximum remain so within this longer time series; the largest daily mean dust mass concentration measured in Miami during the 45-yr time series, of 153 μg m^{-3}, occurred on 19 July 1984.
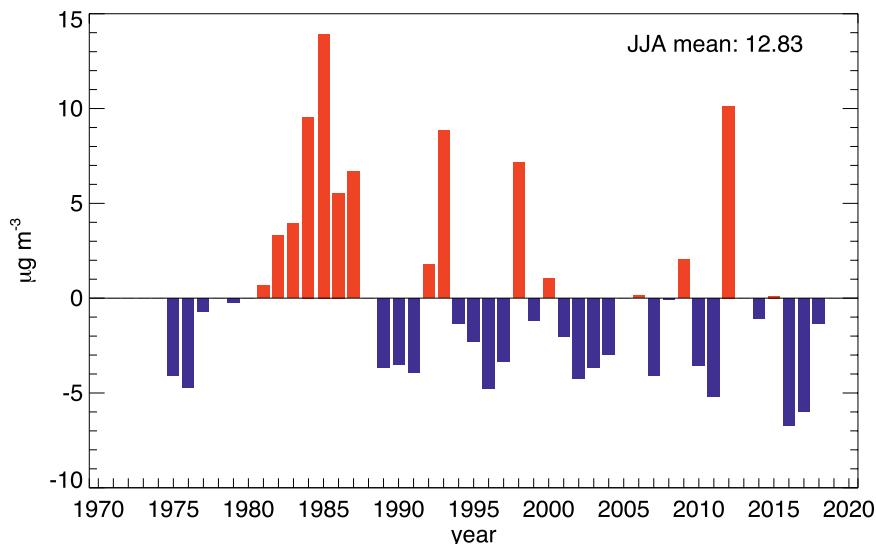

Fig. 2. Summer seasonal-mean anomalies of Miami dust mass concentrations with respect to the 1974–2018 mean June–August value of 12.83 μg m^{-3}. Each year depicted (39 total) is based on three months in which each month includes at least 20 days with data. The last year shown is 2018.

The time series confirms the period analyzed in Prospero (1999) are indeed slightly less dusty than average (Fig. 2). Since 1989, only 6 summer seasons out of the 27 shown indicate clearly-enhanced dust mass concentrations, and a primarily decreasing trend is evident in the summer dust loadings.

The Barbados seasonally resolved time series, shown as seasonal anomalies from their long-term seasonal mean, indicate a mid-1980s maximum centered around the 1985 summer maximum value of 50.2 μg m^{-3} that is mostly coherent across the four seasons (Fig. 3). This remains the clearest signal of interdecadal variability present at both Miami and Barbados and is linked to a period of intense drought in the Sahel by Prospero and Lamb (2003). A decrease is thereafter apparent from 1982 to 2008, also evident across the four seasons. This decrease is consistent with an approximate 10% decrease per decade noted in satellite-derived aerosol optical depths (Ridley et al. 2014). The decrease has been associated with

weakening surface winds over dust source regions (Ridley et al. 2014; Evan et al. 2016) and maps to the tropical arm of a warming sea surface temperature pattern known as the North Atlantic multidecadal oscillation (Yuan et al. 2016).

Notably, however, the decrease in spring–summer Barbados dust mass concentrations does not continue into the present decade, and instead more year-to-year variability is evident. Since 2013, most summers have experienced higher-than-average dust loadings at Barbados, with the 2014 summer dust mass concentrations being the second-highest since 1973 (mean of 44.3 μg m^{-3}). Even more remarkable, the 2015 March–May mean value of 51.2 μg m^{-3} is the maximum within the time series for boreal spring. The dustiest day of boreal spring of 2015 occurred on 21 May 2015 (237 μg m^{-3}), but strong dust events also happened on 24 April and 6 May (all confirmed with satellite imagery), indicating large-scale favorable conditions. This represents a shift in that year's
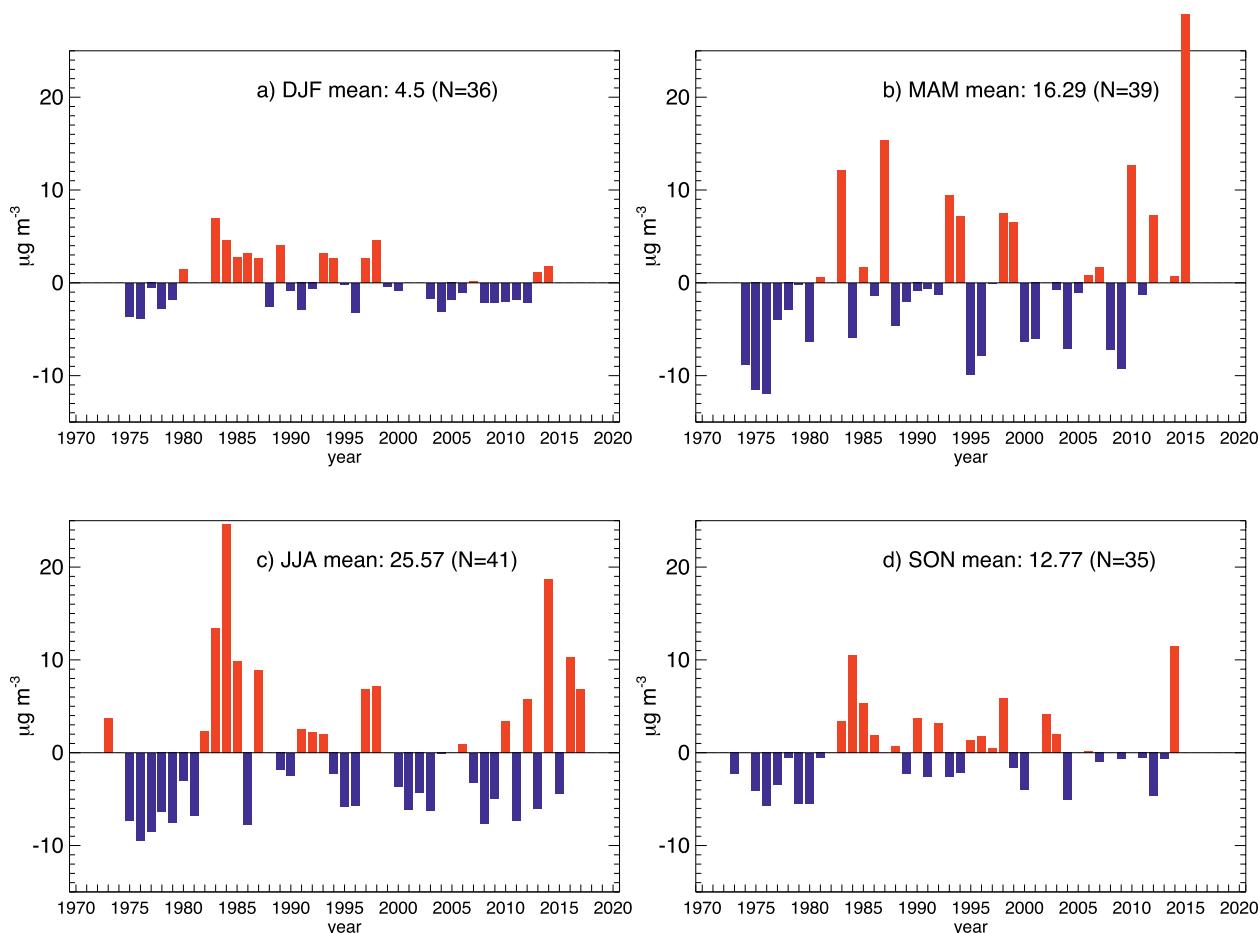
FIG. 3. Seasonal-mean anomalies of Barbados dust mass concentrations with respect to their long-term seasonal mean for (a) December–February through 2014, (b) March–May through 2015, (c) June–August through 2017, and (d) September–November through 2014. Each year's seasonal average is based on all three months including at least 20 days of values. The 2015 March–May anomaly is 35.4 μg m^{-3} (a total of 51.2 μg m^{-3}).

heavy dust events from June to April–May. Intense early summer dust events have occurred previously, for example, the day with the highest dust mass concentration in the entire Barbados time series was measured on 9 April 1994 (272 μg m^{-3}), though pronounced dust events must have been less frequent in April–May than in June over the full 44 years (Fig. 1).

THE FUTURE. A future, deeper study will be needed to correctly attribute the recent changes in the Miami and Barbados dust mass concentrations shown within Figs. 1–3. The rare long-term surface time series of dust data open up other research opportunities as well. Examples include isotopic analysis that allow for the geochemical fingerprinting of dust emission sources (Pourmand et al. 2014). Soluble ions, extracted from the filters, can provide indications of the mixing of anthropogenic pollution with the African dust (e.g., Savoie et al. 1989) that is also useful for understanding cloud-dust interactions after long-range transport. The time series provide context for shorter-term process studies (e.g., Weinzierl et al. 2017) that also integrate data from the University of Miami Barbados Atmospheric Chemistry Observatory (BACO) and the Barbados Cloud Observatory (BCO; Stevens et al. 2016). At Miami, South Florida's Cloud-Aerosol-Rain-Observatory (CAROb; carob.rsmas.miami.edu) also hosts a depolarization micropulse lidar (Delgadillo et al. 2018), allowing characterization of the dust vertical structure over the U.S. mainland. Both sites participate in the Aerosol Robotic Network, so that accurate measurements of the accompanying aerosol optical depth are available.

Global aerosol models currently rely on the assimilation of aerosol optical depth to produce 10–20-day aerosol forecasts (e.g., Randles et al. 2017). In situ dust datasets can usefully aid the further development of global aerosol models through, for example, relating the underlying dust size parameterizations to size-resolved dust measurements, and lidar can assess the model dust vertical structure (e.g., Benedetti et al. 2018). The validation of the modeled dust masses within the atmospheric boundary layer will remain useful, as the entrainment of free-tropospheric dust into the boundary layer is challenging to model and will remain difficult to assess with space-based lidar remote sensing, for which the presence of sea salt within a moist environment may obscure detection of boundary layer dust.

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