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The Discovery of African Dust Transport to the Western Hemisphere and the Saharan Air Layer

A History

Joseph M. Prospero, Anthony C. Delany,
Audrey C. Delany, and Toby N. Carlson

ABSTRACT: There is great interest in wind-borne mineral dust because of the role that dust plays in climate by modulating solar radiation and cloud properties. Today, much research focuses on North Africa because it is Earth's largest and most persistently active dust source. Moreover, this region is expected to be greatly impacted by climate change, which would affect dust emission rates. Interest in dust was stimulated over 50 years ago when it was discovered that African dust was frequently transported across the Atlantic in great quantities. Here we report on the initial discovery of African dust in the Caribbean Basin. We show that there were three independent "first" discoveries of African dust in the 1950s through the 1960s. In each case, the discoverers were not seeking dust but, rather, they had other research objectives. The meteorological context of African dust transport was first elucidated in 1969 with the characterization of the Saharan air layer (SAL) and its role in effecting the efficient transport of African dust over great distances to the Western Hemisphere. The link between dust transport and African climate was established in the 1970s and 1980s when dust transport to the Caribbean increased greatly following the onset of severe drought in the Sahel. Here we chronicle these events and show how they contributed to our current state of knowledge.

KEYWORDS: Atmosphere; Climate records; Climate variability; Interdecadal variability; Dust or dust storms; Aerosols/particulates

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Corresponding author: Joseph M. Prospero, jprospero@miami.edu
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AFFILIATIONS: Joseph M. Prospero—Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida; **Anthony C. Delany and Audrey C. Delany**—Eldorado Springs, Colorado; **Carlson**—The Pennsylvania State University, University Park, Pennsylvania

The effects of dust on climate are broadly similar to those of other types of aerosol in that dust can directly modulate climate by scattering and absorbing solar and terrestrial radiation. Moreover, dust plays a role in climate indirectly, by modifying cloud properties which subsequently can impact both radiation and the hydrological cycle (Ghan et al. 2012). However, dust differs from other aerosols because dust emissions are themselves linked to climate. Changes in climate, especially winds and precipitation, could change the location of sources and affect emission rates in ways that are highly nonlinear (Albani and Mahowald 2019; Hooper and Marx 2018; Okin et al. 2006). In turn, this newly-produced dust can itself modulate climate and lead to complex feedback processes (Shao et al. 2011). Furthermore, mineral dust contains elements such as iron (Fe) and phosphorous (P), which serve as essential nutrients in marine and terrestrial ecosystems. Thus, mineral dust deposited to the ocean can affect primary productivity which, in turn, can affect the atmosphere–ocean carbon cycle and, ultimately, climate (Jickells and Moore 2015; Ravi et al. 2011).

For these reasons, there is an intense focus on arid regions because they are the major sources of mineral dust and they are most sensitive to changes in climate (Evan et al. 2016; Prospero et al. 2002) and also to land use (Ginoux et al. 2012; Webb and Pierre 2018). North Africa is of particular interest because the largest and most persistently-active dust sources are located there. Models estimate that these account for 36%–79% of global emissions (Huneeus et al. 2011; Kok et al. 2021; Wu et al. 2020). This large uncertainty is attributable, in part, to our lack of understanding of dust source processes and to processes occurring during subsequent transport.

The interest in African dust has a long history. In 1833, Darwin, while in the Cape Verde Islands on the *Beagle*, experienced an intense dust storm (Darwin 1846). He reported on his extensive measurements and closed with this prescient comment: "Finally, I may remark that the circumstance of such quantities of dust being periodically blown, year after year, over so immense an area in the Atlantic Ocean, is interesting, as showing by how apparently inefficient a cause a widely expanded deposit may be in the process of formation."

It was not until the mid-twentieth century that Darwin's dust was "discovered" in the western Atlantic and Caribbean. Now, over 50 years later, it is important to chronicle the events linked to this discovery, many aspects of which are not fully known to the recent generations of the atmospheric research community. Here we show that there were three independent "first" discoveries of African dust in the Caribbean. None of these researchers was aware of the work of the others. Furthermore, none of these programs was funded for research on mineral dust. All discoveries involved an element of serendipity.

In discussing this early work, we provide a contextual background to the work. With that purpose in mind, we do not provide an extensive review of the literature, which is now voluminous. We refer the reader to the many excellent reviews (e.g., Knippertz and Stuut 2014; Ravi et al. 2011; Shao et al. 2011). Throughout this paper, we cite selected literature that provides a historical perspective to the research discussed herein. These generally focus on literature that relates most closely to the studies on Barbados and in the Caribbean Basin (Fig. 1).

The first fully documented discovery: D. W. Parkin, A. C. Delany, and A. C. Delany

In 1967 two companion papers were published that conclusively demonstrated that large quantities of African dust were routinely being transported across the Atlantic to the Caribbean (Delany et al. 1967; Parkin et al. 1967). These were the result of a field campaign on Barbados

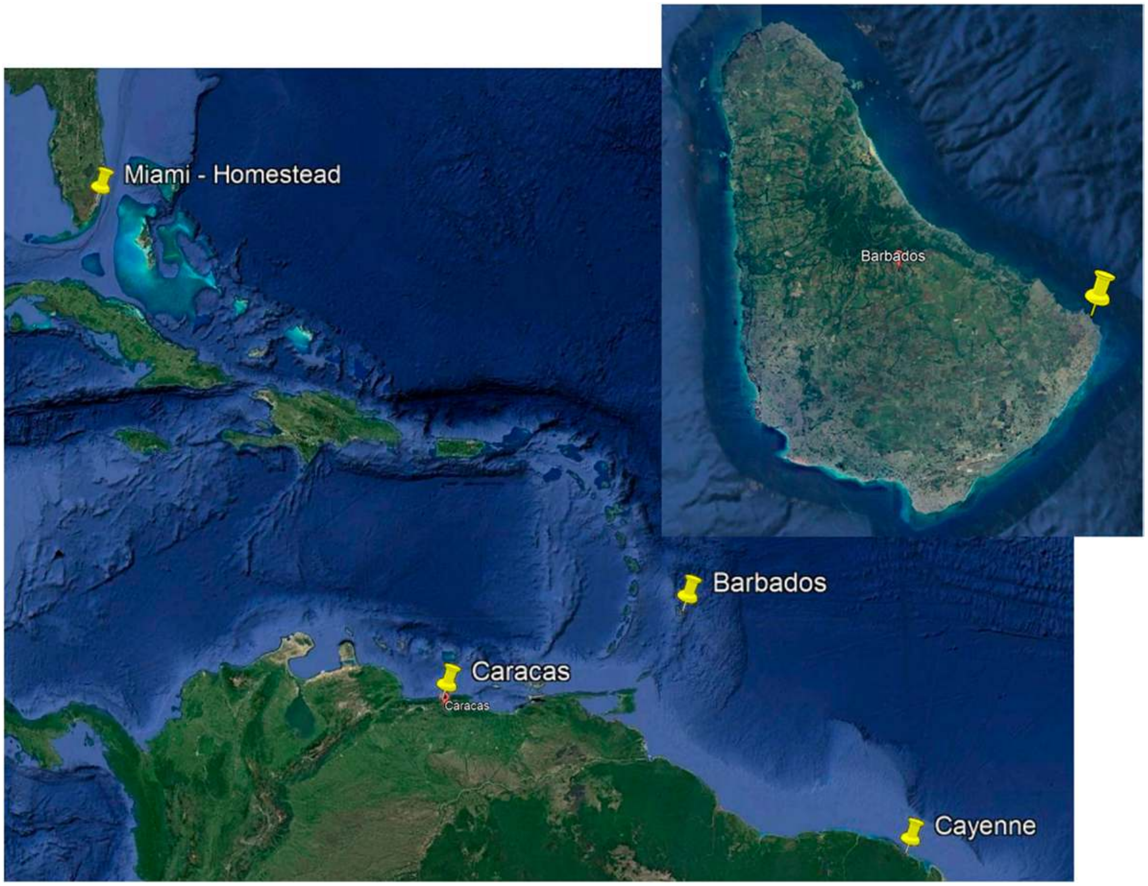

Fig. 1. Locations in the Caribbean and western Atlantic that have played a role in the early history of dust research in the region. Inset: The location of the sampling sites on Barbados. See also Fig. ES1. (Source: Google Earth Pro.)

carried out over 1965–66. The lead scientist of the group was David Parkin, a physicist at the College of Technology, Liverpool. He was assisted by Tony Delany, a graduate student in chemistry at Manchester University, and the latter's wife, Claire Delany, who participated in the research.

In search of cosmic dust. Parkin's program was not designed to measure terrestrial dust but rather to assess the influx rate of cosmic dust. In the 1950s, studies of ocean sediments and ice cores from Greenland found significant concentrations of ferromagnetic particles in the size range of micrometers to a few millimeters in diameter. These were attributed to "cosmic" dust produced by the melting of incoming interplanetary dust and the ablation of large extraterrestrial objects during atmospheric entry (Taylor and Brownlee 1991). Interest in cosmic dust increased greatly in the early 1960s with the launch of space probes that carried rudimentary micrometeorite detectors, in some satellites, simply microphones that monitored the sound of particle impacts. These reported sporadic periods when impact rates were high, which suggested the presence of great dust concentrations. These estimates were later shown to be erroneous because of instrumental errors and the improper interpretation of data (Bandermann and Singer 1969).

Barbados and the discovery of African dust. Parkin had begun his research on cosmic dust in the late 1950s (Parkin and Hunter 1959). In 1965, he initiated studies in the trade winds on Barbados (Fig. 1) which he believed would be minimally impacted by upwind landmasses, the closest being the coast of Africa 4,500 km to the East. Parkin planned to measure the daily concentrations of magnetic particles that might suggest an extraterrestrial origin and then to link the temporal variability to specific cosmological cycles and events.

Work began in March 1965. To minimize the impact of local dust sources, a sampling site was selected on the easternmost point of the island, at Cole's Pasture, Saint Philip (13.154710°N, 59.421748°W); see Fig. 1 and Fig. ES1 in the online supplemental material (https://doi.org/10.1175/BAMS-D-19-0309.2). There they erected a 14-m wooden tower (Fig. 2, also Fig. ES2) on a site within a few meters of the edge of a 14-m coral bluff that rose sheer out of the sea.

Samples were collected using 1-m-square, 0.5-mm diameter, nylon monofilament mesh panels that were hung in the wind (Fig. ES3). Particles are collected by impaction on the filament, which is sticky in the salty, humid environment. Pumps and filters could not be used because there was no electrical power in the area. Under typical trade wind conditions, about one million cubic meters of air pass through the three square meters of mesh that were mounted every day. Later studies involving concurrent measurements with pumped aerosol filter samples would show that the meshes had a particle mass collection efficiency of about 30% for African dust (Prospero and Nees 1977, 1986).

At the end of the day, the meshes were rinsed on the tower, and rinse suspensions were taken to a clean room constructed in a local residence for further processing. Ferromagnetic particles were extracted with a magnet and examined under a microscope.

Sampling started in late July 1965. After a few hours of sampling, the group was surprised to see that the meshes had developed a deep reddish-beige coloration (Fig. ES3). It was quickly determined that the color was due to mineral dust. On dusty days, the bottom of the rinse container would be covered with a substantial layer of fine mud which yielded grams of dry dust. Figure 3 shows the large amount of dust that can be collected during dusty conditions.

Initially, there were concerns that this dust might be derived from local sources. However, it was soon found that the composition of the dust samples was quite different from that of Barbados soils (Delany et al. 1967). Also, the dominance of fine particles, (i.e., under about 20-μm diameter), and the relative scarcity of large particles argued against local dust sources. The profusion of fine particles stands out in Fig. 4, a scanning electron microscope (SEM) image of dust on a filter collected later in the program (Barkley et al. 2021). Furthermore, measurements of particle size showed that the magnetic particle size distribution was identical

Fig. 2. African dust sampling tower, on the coast at Cole's Pasture, Saint Philip, Barbados (13.1547109°N, 59.421748°W). Parkin et al. named the facility "Öpik Tower" to honor Ernst Öpik, the Estonian astronomer and astrophysicist who had done much research on meteors, most notably on the entry of high-speed bodies into the atmosphere and their consequent ablation. Dust is collected on nylon mesh screens that were suspended from the crossbars at the front of the tower, which faces to the east, into the trade winds. See Figs. ES2 and ES3 for other images related to tower activities.

to that of nonmagnetic particles (Fig. 5). This suggested that both particle types were derived from the same source material and that it was not cosmic. If a cosmic source were to contribute significantly to the magnetic particle fraction, the relative slopes of the two components would be more variable.

Fig. 3. African dust sample. The sample was collected with 3 m^2 of mesh samplers over two days, 27–29 May 1967. The weight of the sample is 15.2 g. A dime is shown for scale.

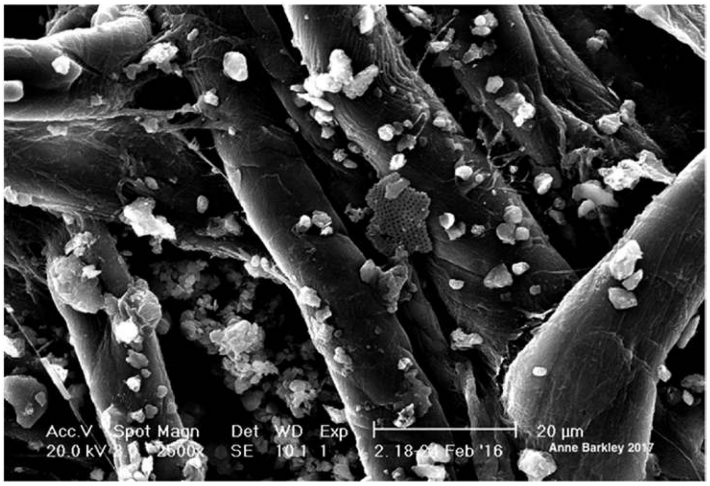

Fig. 4. SEM image of African dust collected on a Whatman-41 filter. Note the predominance of particles several micrometers in diameter and the absence of large particles. Many particles have a platey character and some are agglomerates. The volume median diameter of the dust is about 2–3 μm. Note that the finer particles will tend to be captured deeper in the filter matrix. At the center of the image is a fragment of a freshwater diatom. The large fibers in the image are the filter matrix. [Image: A. Barkley, U. Miami. See also Barkley et al. (2021).]

Dust and Atlantic sediments. The mineral and biological components in the dust particles were similar to those of the detrital particles found in tropical Atlantic deep-sea sediments (Delany et al. 1967). This suggested that the dust came from Africa. Especially persuasive was the presence of fragments of freshwater diatoms including species found in lakes in mountainous regions in Africa and in sediments off the southwest coast of North Africa (Romero et al. 1999). Later studies would show that immense quantities of freshwater diatoms are carried to the Atlantic, possibly from the Bodélé Depression in northern Chad (Ben-Ami et al. 2010). During the Holocene, the Bodélé was flooded to create Lake Mega-Chad, where huge deposits of diatoms are found today (Armitage et al. 2015). Satellite images often show white diatom-laden dust plumes, hundreds of kilometers in length, emerging from the Bodélé and streaming to the west (Ben-Ami et al. 2010; Prospero et al. 2002).

Dust seasonal variability. Delany et al. (1967) commented on the great day-to-day variations in concentration observed throughout their study. But they could not definitively comment on the seasonal variability of transport because, at the time the paper was written, they had only acquired data over the period August 1965–April 1966 (see their Table 1), thereby missing the summer maximum transport period that peaks in June and July. The strong seasonality was first reported by Prospero (1968), who took over operations at the Barbados site in August 1966 (see the section “Miami takes over Barbados operations”). Prospero (1968) combined the data in Delany et al. (1967) with data that they subsequently acquired through September 1966 (when they ceased operations) and the data obtained by the Miami group through August 1967. These data yielded two complete seasonal cycles as seen in Fig. 6, redrawn from the original in Prospero (1968), shown in Fig. ES4.

This figure conclusively established for the first time the strong seasonally-modulated character of African dust transport, a feature that has persisted over the entire record to the present day (Prospero and Lamb 2003; Prospero and Mayol-Bracero 2013; Zuidema et al. 2019). Figure 6 also suggests that there could be considerable interannual variability, a feature that would later be seen throughout the 50-yr record, presenting further evidence of the modulating effects of climate (see the section "Dust transport and African climate: African studies").

Although Parkin et al. did observe an array of large particles, they eventually concluded that these were mostly due to contamination. In the end, they could not arrive at a definitive estimate of the influx rate of the cosmic component of particles in their collections. They could only provide a range of estimates. It is important to note that even today, using advanced instrumental techniques, the range of estimates remains very large (Plane 2012).

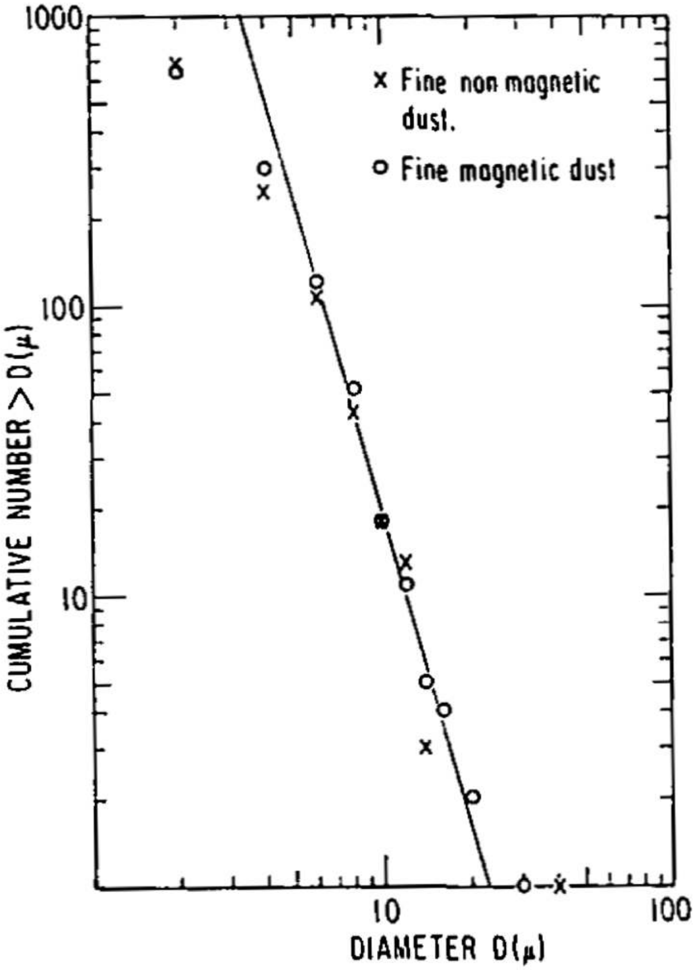

Fig. 5. Dust particle size distribution of magnetic and nonmagnetic dust particle fractions collected at Barbados (Fig. 4; Delany et al. 1967). The fact that the size distributions are identical for both particle types suggests that they are derived from the same noncosmic source.

Other species in dust. Although the Parkin group was primarily interested in mineral species, they observed a large variety of nonmineral species including fungus hyphae, waxy lumps, and "cokey balls," which they attributed to ship emissions although today we would include biomass burning in Africa as a source (Barkley et al. 2019; Zamora et al. 2013). Later work on Barbados would show that increased concentrations of cultivable bacteria and fungi were associated with the advection of African dust (Prospero et al. 2005). Perhaps the most remarkable example of biological transport occurred in mid-October 1988 when swarms of African desert locusts (*Schistocerca gregaria*) crossed the Atlantic and landed on islands of the eastern Caribbean including Barbados (Rosenberg and Burt 1999). Richardson and Nemeth (1991) suggest that the locusts were able to travel this great distance because they were assisted by the winds of Tropical Cyclone Joan, which passed through the southern Caribbean at this time.

Tracing dust to Africa: First use of satellites to identify dust sources. Barbados dust was definitively attributed to a specific African source region using satellite images. On 11–12 June 1967, an intense dust event yielded an unusually large concentration of particles above 20-μm diameter (Prospero et al. 1970). Using an *Environmental Science and Services Administration 5* (*ESSA-5*) satellite image, the sample was linked to a dust storm that crossed the coast of West Africa over Mauritania and Senegal on 7 June (Fig. ES5a). A crude wind-vector-based back-trajectory, calculated from Barbados for the date 12 June, intersected with the position of the image plume on 7 June along the coast of Senegal and Mauritania. Here we recalculated the trajectory using NOAA HYSPLIT (Stein et al. 2015) for that same day (Fig. ES5) and obtained the same result. The transit time of about five days would prove to be typical for such events.

Kahn (2015), in a review of the use of satellites in aerosol remote sensing, cites Prospero et al. (1970) as the first to use a satellite to link samples collected at a specific receptor site to a source located on another continent. Later, Carlson and Prospero (1972, henceforth C&P72) presented many case studies where dust outbreaks could be tracked across the entire Atlantic in *ESSA-5* satellite images.

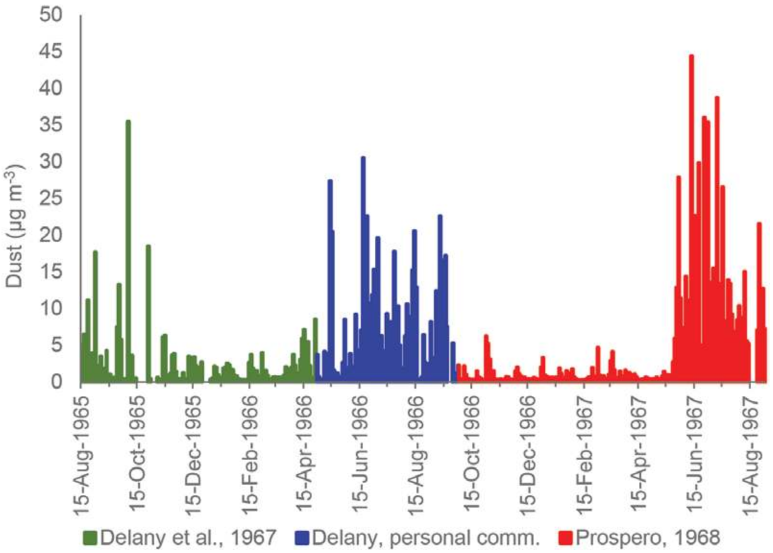

Fig. 6. The interannual variability of African dust transport by trade winds on Barbados as reflected in the bidaily average concentrations: August 1965–August 1967. Replotted from Prospero (1968). The original figure is shown in Fig. ES4 where the data are presented as monthly means. The concentrations from August 1965 to April 1966 (green) are calculated from data presented in Delany et al. (1966). Concentrations from May to August 1966 (blue) are calculated from data received directly from the Delanys at the completion of their operations in September 1966. Concentrations after September 1966 (red) were based on measurements made by the University of Miami group after taking over the program on Barbados. Note that the concentrations shown here differ from those in Prospero (1968), because they were recalculated according to the collector calibration presented in Prospero and Nees (1977, 1986).

The actual, but incidental, first discovery: C. Junge

Although the Parkin group was the first to fully identify and conclusively document the transport of African dust to the western Atlantic, they were not the first to identify the presence of this dust in the Western Hemisphere and to attribute the dust to African sources. This was accomplished by Christian Junge in south Florida in 1954 (Junge 1956). In the years following World War II, Junge played a pioneering role in atmospheric chemistry. His status was firmly established with the publication of his book, *Air Chemistry and Radioactivity* (Junge 1963). Although other books had dealt with various aspects of atmospheric chemistry at that time, Junge's book was unique in the breadth of its scope, its emphasis on aerosols, and its global integrative approach. Junge's book served as the basic reference work for a generation of young atmospheric scientists (Duce 1997; Jaenicke 2012).

Junge links meteorology with atmospheric chemistry. Junge was one of the first to consistently apply a global methodology to atmospheric chemistry and to interpret his results, and those of others, in the context of large-scale atmospheric processes. [For an extensive discussion of Junge's history and his impact on atmospheric chemistry, see Duce (1997) and Jaenicke (2012).] It should be noted that Junge was not a chemist. He was trained as a meteorologist in Hamburg and Frankfurt in the early 1930s (Jaenicke 2012). In 1952, he took a position at the U.S. Air Force Cambridge Research Center, Boston, Massachusetts, where he was primarily concerned with characterizing the atmospheric distribution of radioactive debris produced in nuclear weapon tests—hence, the presence of "radioactivity" in the title of his book. However, his research extended far beyond that specific role. It was in the course of his radioactivity program that he discovered the stratospheric sulfate aerosol layer (the "Junge layer"), which he showed to be comprised largely of sulfuric acid droplets produced by the photochemical reactions of sulfur-containing gases (e.g., carbonyl sulfide) transported from the troposphere and by the sporadic injection of SO_2 from volcanic eruptions. Because of his many contributions across a wide spectrum of disciplines in the field, he was widely regarded as the "father" of modern atmospheric chemistry (Duce 1997; Jaenicke 2012).

Finding African dust in Florida. Junge had also begun studies of the chemistry of sulfur and nitrogen species in the troposphere. By 1954, he had completed a series of investigations in the Boston area, which was heavily impacted by pollution sources. Wishing to make measurements in unpolluted air, in July and August 1954 he traveled to a coastal site near Homestead, Florida (25.5°N, 80.5°W), at that time, a small agricultural town 40 km south of Miami. There he could make measurements in the steady onshore trade wind flow of air unimpacted by local emissions. The results of this study were reported in Junge (1956).

Junge's paper focuses almost entirely on nitrogen and sulfur species except for one paragraph, buried deep in the paper, where he mentions dust:

> It might be mentioned here as a matter of curiosity that during the last three days, beginning with 31 July, the aerosol samples of both sizes ["fine" and "coarse" size classes] contained considerable, though decreasing [over the following days] amounts of reddish-yellow dust. Investigation of the weather maps ruled out the American continent as the source of this dust. Very steady easterly (trade) winds prevailed at all levels above the Atlantic Ocean during this period. It is very probable that this dust was carried across the Atlantic from West Africa, where several dust storms had occurred during the first half of July. It is a well-known fact that dust from the Sahara Desert, carried aloft by strong winds, can be transported to places such as Central Europe, the Azores, and the Cape Verde Islands. In this case, however, it must be assumed that the dust was carried all the way across the Atlantic Ocean below the inversion layer. It is surprising that it was not washed out by the trade-wind showers.

Junge does not present any measurements of dust properties. He does show the dust event graphically in his Fig. 1, shown here, in part, in Fig. 7. To our knowledge, this was the first statement in the scientific literature that identifies dust in marine aerosol samples collected in the Western Hemisphere and that credibly speculates on the possibility of transport from Africa. Out of curiosity, we ran NOAA HYSPLIT back-trajectories (Stein et al. 2015) for the entire period of Junge's field program, 19 July–3 August. Only on one day, 31 July, the day Junge observed the highest dust concentrations, did trajectories unambiguously trace back to North Africa (Fig. ES6). The trajectories had crossed the coast of Mauritania a week earlier and tracked inland across northern Mali and into southern Algeria. This region would later be shown to be a major source of dust outbreaks in the summer months (Bozlaker et al. 2018; Formenti et al. 2011; Yu et al. 2020).

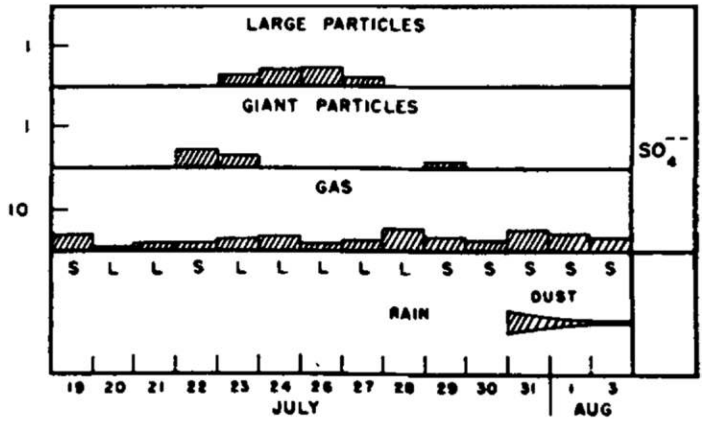

Fig. 7. The first identification of African dust in the Western Hemisphere (Junge 1956). This figure is a copy of a portion of Fig. 1 from Junge (1956), which symbolically identifies a dust event on 31 Jul 1954. The letters "S" and "L" indicate whether the sample was collected under sea-breeze or land-breeze conditions. Junge used an impactor to collect two size classes: 0.08–0.8 and 0.8–8 μm. Although here he shows the different fractions for sulfate and other species, he does not provide such data for dust. The dust plot scale has no units.

The problem of long-range dust transport. In the last line of the Junge quotation, he remarks with surprise that dust could survive the transit of the Atlantic, typically a journey of about 7 to 10 days from the coast of Africa to south Florida, without being washed out in rain. His stated assumption is that the dust is carried below the trade wind inversion, an inference that we now know to be incorrect. The fact that such large amounts of dust survive this journey is attributable in part to the role of the Saharan air layer (SAL) as discussed in the section "The definitive discovery of the Saharan air layer and its role in dust transport: J. M. Prospero and T. N. Carlson."

It should be noted that Junge was well primed for his identification of the dust source. During World War II, he was a meteorologist with the Luftwaffe (Jaenicke 2012). At one point, he was stationed in Libya where he would have become familiar with dust storms and the distinct reddish-beige appearance of African dust.

Junge's dust discovery, overlooked. Except for that one paragraph, the word "dust" does not appear elsewhere in the paper. Given the slow and inefficient process of indexing literature at midcentury, this paper was largely overlooked by those few scientists who had an interest in dust. This was especially true for many young scientists who migrated to the Earth sciences from other fields, a category that includes the authors of this paper, none of whom had seen the paper or were aware of Junge's book.

In his paper, Junge presents no information about the dust collected in Florida other than its color. Later work (Prospero 1999; Prospero et al. 2001) would definitively show that African dust impacts south Florida every year in a seasonal cycle like that characterized at Barbados (e.g., Prospero and Lamb 2003; Prospero and Mayol-Bracero 2013; Zuidema et al. 2019). Later, African dust would be measured in substantial quantities in the southern states (Bozlaker et al. 2013, 2019; Hand et al. 2016) and throughout the eastern United States as far north as New England (Aldhaif et al. 2020; Hand et al. 2016).

Notably, Junge made no effort to claim "discovery." In his book, there is only one sentence relating to the dust event described in Junge (1956). It simply states (with no citation): "The author collected Sahara dust in Florida, which was apparently transported in the steady trade winds during summer." Also, in later dust-related publications, he does not cite his discovery, not even in a paper (Junge 1972), that reviews the literature on the properties of aerosols, including dust, in the undisturbed marine environment. Even today, despite the huge number of publications on African dust, his pioneering paper has only been cited 109 times. Even so, most of these refer to the nitrogen and sulfur chemistry results; only six refer to dust (Web of Science).

The unrecognized discovery of dust and the Saharan air layer: G. Zuloaga

Given the great interest and intense research focused on African dust over the western Atlantic and Caribbean for the past 50 years, it is surprising that dust advection events have not received more attention from observers on the northern coast of South America, which we now know to be impacted at levels comparable to those on Barbados. This omission is perhaps due to the masking of dust effects by the "calina," a dense haze that is often observed during boreal winter and spring along the Caribbean coast. The calina (in some literarture, "calima") has generally been attributed to sea salt particles, smoke from biomass burning, and pollution. However, it seems that nobody had examined the properties of calina aerosols until the late 1950s with the research by Guillermo Zuloaga, a petroleum geologist in Venezuela (Geological Society of America 1994).

Working on his own initiative in Caracas, Zuloaga (1966) made an extensive series of simple experiments in which he collected particles impacted on balsam-coated microscope slides extended from a car window as he drove over mountain roads along the coast. Although his primary interest was the sea-salt droplets and crystals, he commented that through the microscope he frequently saw abundant quantities of fine mineral particles, only a few micrometers in diameter, along with sea-salt deposits. Zuloaga also made studies aboard a small aircraft on flights over the Caribbean, using slides exposed out of a window. He noted that under typical trade wind conditions, the calina extended at least to 100 km north of the coast and, thus, he concluded that the haze and the mineral particles could not be attributed to Venezuelan sources.

Zuloaga's "discovery" of the SAL. In his flights, Zuloaga described the properties of what we know today to be the SAL: dense haze, high temperature, very low relative humidity, and the presence of mineral dust. He noted the great depth of the layer with a top at 2,700–3,000 m, and that the top was extremely flat, a feature that we now know to be due to a sharp inversion at the top of the SAL. In his paper, he shows a photo (Zuloaga 1966, his Fig. 1) of the haze top, taken from a Cessna-type rented aircraft. He also observed that the haze had a brown tinge, an appearance, he noted, that one would not expect of sea salt haze. His accurate description of the SAL was made a decade before the work of C&P72 and Prospero and Carlson (1972, henceforth, P&C72) who first documented the SAL as discussed in the section "The definitive discovery of the Saharan air layer and its role in dust transport: J. M. Prospero and T. N. Carlson".

Zuloaga comments on the seasonality of the calina and the associated dust, noting that it occurs most commonly in winter and spring. This seasonal cycle differs from that observed at Barbados where the maximum occurs in summer. Dust transport out of Africa undergoes a seasonal cycle that shifts latitudinally with the seasonal changes in the large-scale circulation over the Atlantic, a shift that is manifested most visibly with the seasonal migration of the intertropical convergence zone (ITCZ) as documented in various satellite products (e.g., Adams et al. 2012; Chin et al. 2014; Yu et al. 2019).

Quantifying dust transport to South America. Dust transport to South America was first quantitatively characterized by measurements made in the trade winds at Cayenne, French Guiana, in 1978–79 (Prospero et al. 1981). These yielded concentrations comparable to those in Barbados in summer. These results led to considerable speculation about the role of African dust as a source of nutrients, especially phosphorus, and its role as "fertilizer" for the Amazon basin (e.g., Ben Ami et al. 2010; Bristow et al. 2010; Swap et al. 1992; Yu et al. 2015b). This transport was later characterized more definitively in studies in Cayenne (Barkley et al. 2019; Prospero et al. 2014, 2020) where the 15-yr air quality aerosol record clearly documents the strong seasonal variability and the important role of African dust transport to South America. It is notable that Zuloaga (1966), based on the composition of dissolved species in rain, also speculated that the rain during the calina season could serve to fertilize the soils although he apparently did not recognize that the nutrient species were associated with dust.

Recognition for Zuloaga's work. Unfortunately, Zuloaga's work has gone unrecognized because it was not published in a readily available English language scientific journal. Its only English appearance was in the "Amateur Scientist" column of Scientific American (Stong 1961). Even today, searches in literature databases (e.g., Scopus, Google Scholar, Web of Science) yield no citations to his work. The citation presented here (Zuloaga 1966) was obtained from Zuloaga's obituary (Geological Society of America 1994). Although he did not characterize his dust to any extent nor identify the dust as African, it is appropriate to credit Zuloaga for the systematic pursuit of his studies and for being the first to recognize and describe the anomalous meteorological conditions, which puzzled him greatly, and to tenuously associate these conditions with dust. In effect, Zuloaga was the first to describe the SAL.

The definitive discovery of the Saharan air layer and its role in dust transport: J. M. Prospero and T. N. Carlson

Early history. As was the case of the previously discussed early dust researchers, Prospero and Carlson entered the field inadvertently. Prospero's involvement began in the mid-1960s when there was a growing interest in marine aerosols. Early work on aerosols collected in nominally "remote" regions, usually in the North Atlantic, had shown that the composition of these marine aerosols could differ greatly from that which one might expect of material derived predominantly from the ocean. There was much interest in the role of bubble rupture at the sea surface that might produce a fractionation of seawater components (Duce and Hoffman 1976; Quinn et al. 2015). Early bubbling studies often yielded interesting results which, in retrospect, were largely due to poor techniques in laboratory-based studies (Salter et al. 2016). However, the bubble studies could not explain the highly anomalous compositions that were often observed and which we now know are often linked to the long-range transport of natural and anthropogenic materials from the continents, the importance of which was not recognized in the 1960s.

African dust and Atlantic Ocean sediments. In the mid-1960s, Prospero was engaged in bubble fractionation studies at the University of Miami Marine Laboratory (now the Rosenstiel School of Marine and Atmospheric Sciences). Using a floating, in situ, bubble apparatus in the Gulf Stream, he could not produce any substantial enrichments. Coincidentally, in discussions with colleagues studying Atlantic pelagic sediments, he learned of two recent publications that provided the first substantial support for the idea that there was a significant transport of African dust to the Atlantic. One, previously mentioned (Goldberg and Griffin 1964), focused on the properties of sediments deposited on the Mid-Atlantic Ridge. Although they made no aerosol measurements, they specifically identified the importance of wind transport—"a major fraction of these nonbiogenic phases appeared to arrive at the deposit site from the continents via wind-transport at the mid-latitudes."

In the second paper, Biscaye (1965) carried out X-ray diffraction analyses of 500 deep-sea sediment core-top samples, collected mostly in the Atlantic. Based on the spatial distribution of the mineral concentrations, Biscaye concluded that the bulk of recent Atlantic Ocean deep-sea clay is comprised of detritus from the continents and that these materials are delivered by South American rivers and "by rivers and wind from Africa." However, there are no major rivers on the west coast of Africa and, consequently, transport by wind would likely dominate. Using the sediment clay mineral accumulation rates cited in these two papers, a simple calculation suggested that the atmospheric concentration of African dust should be readily measurable over the tropical Atlantic.

These two papers appeared at about the same time. Indeed, Biscaye's dissertation, which served as the basis of Biscaye (1965), is cited in a footnote in Goldberg and Griffin. Thus, both papers should be credited with being the first to highlight the role of wind-borne African dust as a major source of sedimentary material in the tropical mid-Atlantic as contrasted to the coastal areas of West Africa where the impact of African source was well documented as described in Darwin (1846) among others. These two papers validated Darwin's speculation that dust could be playing a large role in supplying material to ocean sediments.

On the basis of these papers, Prospero and Enrico Bonatti, a colleague at Miami and a marine sedimentologist, were motivated to look further into the long-range transport of dust to the oceans (e.g., Prospero and Bonatti 1969).

Miami takes over Barbados operations. In the summer of 1966, the Parkin group was ending their study on Barbados. On his return trip to England from Barbados, Parkin had a plane change in Miami during which time he made an impromptu visit to Bonatti's laboratory at the university. After a brief discussion about our mutual interest in African dust, Parkin generously offered to transfer the Barbados tower to the Miami group who took over operations in the fall of 1966 (Prospero 1968). This site remains active to this day as discussed in the section "Beyond discovery: The evolution of atmospheric aerosol studies on Barbados." But for Parkin's fortuitous stopover at Miami, Prospero would not have learned of the availability of the tower until much later when it would have been difficult to resuscitate the facility and resume sampling.

Linking African dust and easterly waves. The day-to-day and seasonal variability of dust concentrations measured by Delany et al. (1967) and Prospero (1968) suggested that dust transport was closely linked to meteorological processes and that, consequently, dust studies should incorporate a strong meteorological component. These issues were eventually addressed in a series of studies by Carlson and Prospero.

In 1968, Carlson, with a recent Ph.D. in meteorology from Imperial College, London, took a position with NOAA's National Hurricane Research Laboratory in Miami. He focused on the study of waves because of the role that they might play in the development of tropical cyclones and hurricanes (Carlson 1969), a topic of continuing interest (Dunion and Velden 2004; Grogan and Thorncroft 2019; Xian et al. 2020; Zipser et al. 2009).

Following a chance social encounter in early 1968, Prospero and Carlson began to discuss the possible relationship between the pulsing character of African dust events observed at Barbados and the passage of easterly waves. This led to their ad hoc involvement with a NOAA DC-6 transatlantic research flight in October 1968 on a mission to investigate waves (Prospero and Carlson 1970, henceforth P&C70). Neither Prospero nor Carlson participated in the flight and they had no role in the planning.

Fortuitously, the DC-6 had previously been used in NOAA programs to monitor airborne radioactive weapons-test debris and, to that end, it had been outfitted with an aerosol sampling system. The flight was specifically instrumented to measure Rn-222 as part of a NOAA program to use radon as a tracer of atmospheric transport and mixing (Machta and Lucas 1962). Atmospheric Rn-222 (half-life, 3.82 days) is a radioactive decay product of uranium-238 naturally present in soils; radon diffuses to the atmosphere and can be used as a tracer of air that has recently been in convective contact with the Earth's surface. Radon decays to a series of products including radioactive lead-214 (half-life, 26.4 min) and bismuth-214 (half-life, 19.9 min). In the atmosphere, these species rapidly attach to aerosols that are readily captured on filters and measured; the decay data can then used to calculate the air concentration of Rn-222.

Radon concentrations varied greatly as the aircraft penetrated through the waves. Figure 8 (Fig. 2 in P&C70) shows the sketch made by the flight meteorologist of his observations during the flight along with the radon concentrations. Dense haze was encountered at various times during the flights (Fig. 8). The highest concentrations of radon and dust haze were found in the regions to the east of the wavefront, a relationship that was consistent with the pulse-like concentrations of dust that were typically observed on Barbados. The lowest concentrations of radon and dust haze were measured immediately to the west of the leading edge of the wave where northeasterly winds carried marine dust-free air from the midlatitude North Atlantic, "aged" air in which radon concentrations would be expected to be low because of decay.

It was during this flight that the unique meteorological characteristics of dust outbreaks were first noted, primarily on the basis of sonde profiles (e.g., Fig. 1 in P&C70) with features that we now associate with the SAL: hot, dry, and dusty. On the NOAA flight, it was established for the first time that there were strong inversions at the base and top of the SAL and that these inversions served to strongly suppress convection, a relationship that stands out clearly in the flight meteorologist's sketches during the flight (Fig. 8). Between these inversions, there was a homogeneous (isentropic) layer wherein the densest haze was observed.

An example of a present-day dust event at Barbados. Although we have no photos from the NOAA flight, in Fig. ES7, we show a photo taken on a commercial airline flight out of Barbados on 26 June 2007, a day when dust concentrations at Ragged Point were high, 46 μg m^{-3} and aerosol optical depths in the region were in the range of 0.5–0.7. In Fig. ES7, we also show a rawinsonde profile taken that day at the airport. This sonde shows all the features of a classic SAL profile including a sharp inversion at the base at about 2 km and a second at the top at 4.2 km. Between the two inversions, there is a deep isentropic layer with

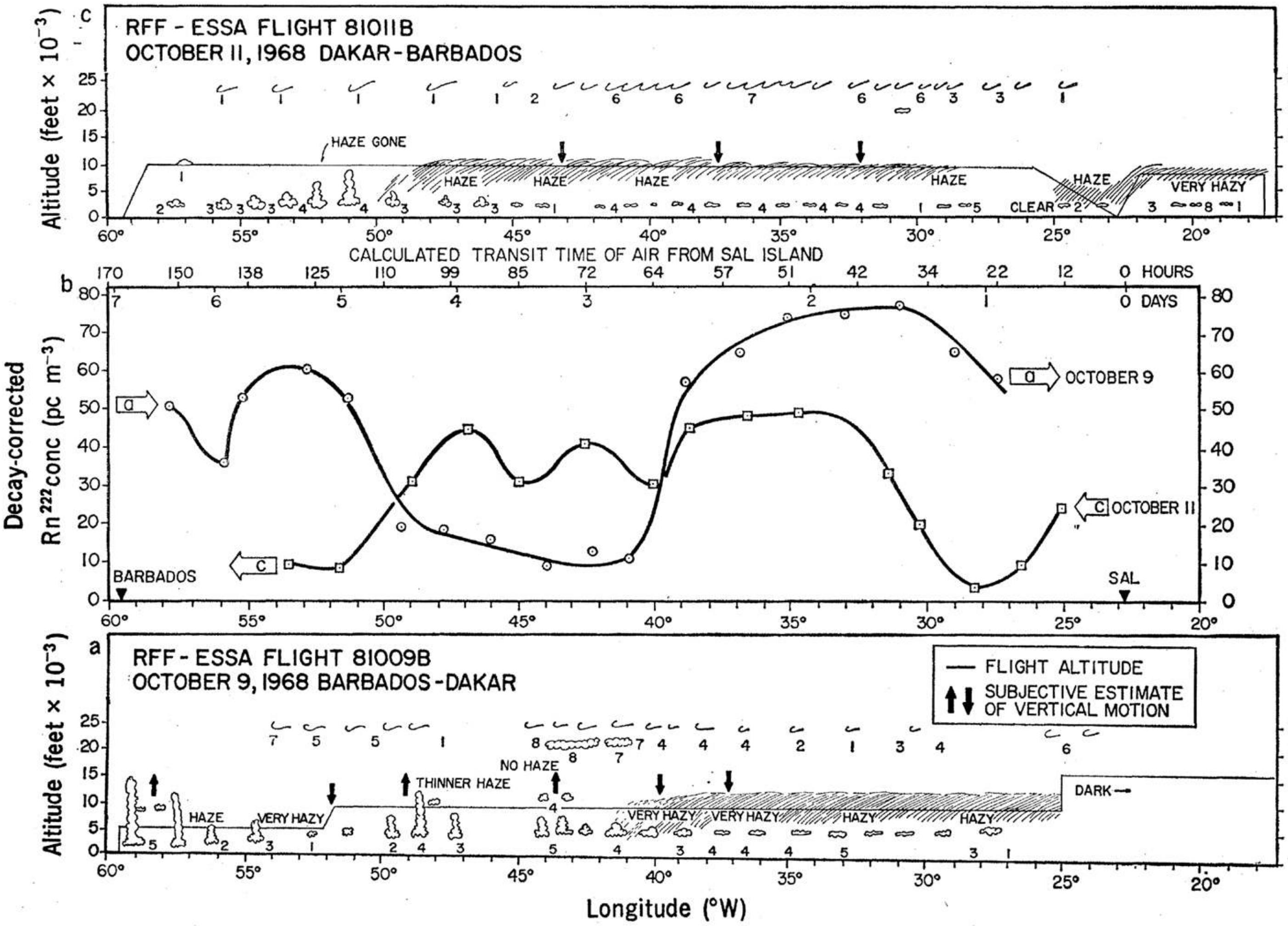

Fig. 8. Dust and African easterly waves. Meteorological conditions along the Barbados–Dakar aircraft transects, 9–11 October 1968 (Fig. 2 in P&C70). Flight meteorologist's sketches: (top) westbound and (bottom) eastbound. Numerals indicate cloud cover in tenths. The altitude of the haze top is based on visual estimates. (middle) Radon-222 concentrations corrected for decay in transit from the African coast; calculated transit times are shown at the top of the figure. In the flight sketches, the width of the haze hatching is not intended to be representative of the thickness of the haze layer, which was difficult to estimate under flight conditions. The flight meteorologist was Neil Frank, at that time a recent hire at NOAA. Frank would go on to become the director of the National Hurricane Center in 1974.

a potential temperature of about 40°C. Also, the layer is extremely dry with a mixing ratio of 2–7 g kg^{-1}. MODIS (Fig. ES7) shows that the region extending from Puerto Rico to South America was covered by a dense dust cloud. On this day, the spaceborne lidar Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*) passed 1° east of Barbados (Fig. ES8). It shows a dense dust layer with a top at 4–5 km, altitudes consistent with the Barbados sonde temperature and moisture profile. Dust extends to about 22°N along the track and, to the South (not shown), reaching the ITCZ at the equator, spanning a total of 20° of latitude. The dust observed on this day was part of a major dust event that had moved into the area late on 25 June. MODIS on 26 June shows heavy dust extending from the coast of Africa, across the entire Atlantic, and into the Caribbean (https://worldview.earthdata.nasa.gov/).

To our knowledge, P&C70 was the first paper to identify the meteorological signature of African dust outbreaks and its relationship to the tropical meteorological environment and, furthermore, to suggest a link between easterly waves and African dust transport. Unfortunately, no measurements of mineral dust were carried out on this flight.

Characterizing the SAL: BOMEX. Although the P&C70 paper provided some initial insights on the SAL, the definitive publications appeared in 1972: C&P72 and P&C72. These presented the results of measurements made in the Barbados Oceanographic and Meteorological Experiment (BOMEX), which was held in a region of the Atlantic immediately east of Barbados in the summer of 1969. BOMEX was one of the first "big science" ocean–atmosphere experiments (Kuettner and Holland 1969). The core objective of BOMEX was to compare vertical fluxes measured on a synoptic-scale over the tropical ocean east of Barbados using budget methods (Fleagle 1972) wherein radiation measurements would normally be a major activity (Kuettner and Holland 1969). Yet at that time in atmospheric climate science, aerosols were of minor interest. Consequently, BOMEX did not include specific plans to incorporate focused aerosol measurements in the design of the program although sporadic measurements were made in other contexts (see the section "Aerosol studies in BOMEX" in the supplement).

Prospero and Carlson's participation in BOMEX was entirely on an ad hoc basis since neither was funded to study dust aerosols. Arrangements were made with NOAA for Prospero to sample aerosols aboard the NOAA DC-6 using the same sampling system that had been used in the transatlantic flight in October 1968. Sampling was carried out from May through July; 1,300 filter samples were taken during 300 h of flight time at altitudes ranging from the surface to 3 km. The results of this study (P&C72) showed that dust concentrations were greatest in the SAL, on average about 3 times greater than in the marine boundary layer below the inversion at the SAL base. The strong layering of African dust has been extensively documented in recent years in aircraft research programs (e.g., Reid et al. 2003; Weinzierl et al. 2017) and in lidar studies performed at ground sites (Groß et al. 2015, 2016), aboard ships transiting the Atlantic (Bohlmann et al. 2018; Gasteiger et al. 2017) and also with the CALIOP lidar aboard the *CALIPSO* satellite (Adams et al. 2012; Yu et al. 2015a) and as shown in Fig. ES8

Linking the SAL to meteorological process in Africa. A companion paper, C&P72 shows that the SAL properties could be traced to processes taking place over West Africa a week earlier. Over the Sahara, the intense heating produces a deep isentropic mixing layer that has a potential temperature of about 45°C. Convection carries dust to altitudes as high as 6–7 km (Knippertz and Todd 2012). As this hot, dry, dust-laden Saharan air mass reaches the west coast of Africa, it is lifted above the cooler trade winds, forming the elevated layer that we now refer to as the SAL. Also, an anticyclonic flow develops behind the easterly wave. These processes are broadly sketched in Fig. 9 (C&P72) and, in three dimensions, in Fig. ES9 (Karyampudi et al. 1999).

As the dust moves across the Atlantic, the top and base of the SAL decrease in altitude as depicted schematically in Fig. ES10 (Weinzierl et al. 2017). During transit, dust is transferred from the SAL to the underlying boundary layer, primarily by convective erosion, as depicted in Fig. ES10. Some dust might also be injected directly into the boundary layer along the coast of Africa (Reid et al. 2003). The complexity of these processes presents a challenge to our understanding of the life cycle of dust emissions and transport from Africa (Knippertz and Todd 2012) and the relationship to easterly waves (Grogan and Thorncroft 2019; Nathan et al. 2019).

Impact of dust on radiative properties of the atmosphere. The large concentrations of dust in the SAL have a significant impact on the radiative properties of the SAL and the marine boundary layer as first described by Carlson and Caverly (1977) and Carlson and Benjamin (1980). The strong dust-related heating in the SAL acts to partially offset the radiative cooling of the layer and, thereby, to preserve the inversion (Tao et al. 2018). This serves to extend the lifetime of the SAL and explains, to a degree, how African dust could be carried such great distance. This addresses, in part, Junge's surprise that dust could be so efficiently carried such a great distance over the Atlantic.

African dust and meteorological processes over the tropical Atlantic. The elucidation of the properties of the SAL and the link to meteorological processes over the Sahara played an important role in the development of dust transport models and this has led to the development of major field campaigns in North Africa (e.g., Knippertz and Todd 2012). Indeed, the ability of models to replicate the SAL structure serves as a test of their performance. This is important in assessing the impact on tropical cyclones since the injection of the hot dry SAL air into tropical cyclones is believed to play an important role in the weakening of tropical cyclones (e.g., Braun et al. 2012; Dunion and Velden 2004; Dunion 2011; Reed et al. 2019; Xian et al. 2020). Indeed, the generation of many dust storms in West Africa is closely linked to the genesis of easterly waves in that region (Bercos-Hickey et al. 2020; Nathan et al. 2019). There are efforts underway to assess these impacts in a systematic way through models (e.g., Strong et al. 2018).

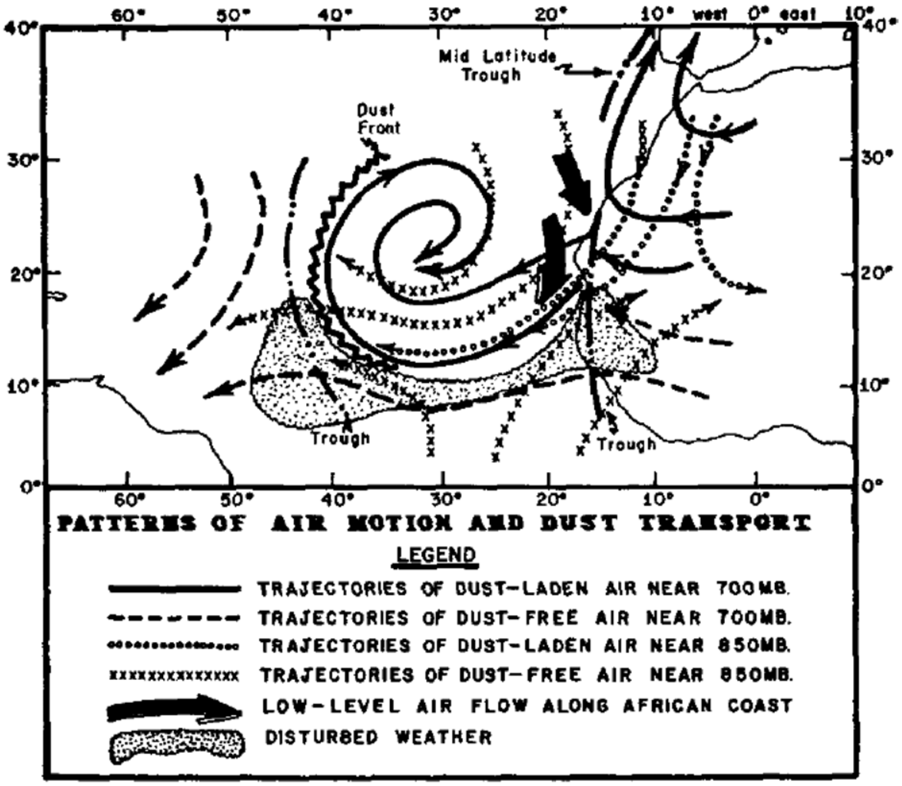

Fig. 9. Processes involving the formation of the SAL along the coast of North Africa during a Saharan dust outbreak. The schematic shows that as the hot, dry, dust-laden air mass emerges from the coast, it is undercut by the low-level trade winds. This leads to the formation of the elevated SAL. The figure shows that the emerging air mass undergoes an anticyclonic circulation behind the trough of the easterly wave (C&P72).

Because of the important role of Saharan air outbreaks in weather, during the hurricane season weather forecasts often focus on the SAL (Kuciauskas et al. 2018). Many real-time modeling products are available on the web (e.g., NASA: https://fluid.nccs.nasa.gov/wxmaps/chem2d/; Naval Research Laboratory: www.nrlmry.navy.mil/aerosol/icap.1135.php; University of Wisconsin: http://tropic.ssec.wisc.edu/real-time/sal/.)

In 2007, because of concerns about the health impacts of soil dust (see the section “The impact of African aerosol transport on air quality” in the supplement), the WMO established the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) to improve capabilities for more reliable sand and dust storm forecasts (https://sds-was.aemet.es/forecast-products/dust-forecasts/ensemble-forecast).

Beyond discovery: The evolution of atmospheric aerosol studies on Barbados

In 1971, the Miami group obtained funding from NSF and sampling was moved to Ragged Point (Fig. 1, Fig. ES1), (13.16504°, −59.43207°), a promontory where electrical power was available. From that time forward, all sampling was done with vacuum pumps and filters (Prospero and Nees 1977). Initially, the facility at Ragged Point consisted of a small wooden shack located on a 30-m sloping bluff at the eastern end of the promontory (Figs. 10, Fig. ES1). Samples were collected with filters mounted at the top of fold-over masts. In 1989 with support from NSF, the facility was upgraded with the installation of a 17-m walk-up aluminum scaffold tower (Fig. 11, Fig. ES11). A converted 6-m cargo container located at the base of the tower served as a laboratory. A second cargo-container chemistry laboratory was installed in 2008.

Dust transport and African climate: African studies. A wide range of studies has been carried out at Ragged Point over the past 50 years. An important aspect was that they show how dust transport across this huge region is linked to the climate in North Africa. Figure 12 shows the record of annual mean dust concentrations at Barbados from 1965 to 2011 along with Sahel precipitation anomalies, which serve as a proxy for large-scale meteorological changes over North Africa. The dust data in the figure are coded according to the publication in which the data first appeared. This relationship to rainfall was first discerned in the early 1970s when concentrations increased sharply, coincident with the onset of prolonged drought in West Africa (Prospero and Nees 1977). The greatest concentrations over the entire record occurred in the mid-1980s when drought was most severe (Prospero and Lamb 2003; Prospero and Mayol-Bracero 2013), the worst in the twentieth century (Mbourou et al. 1997; Nicholson 2013). The long-term variability of dust concentrations at Barbados parallels that of dust storm activity across North Africa (Mbourou et al. 1997). It is also notable that throughout the record some of the largest peaks occur in years that are associated with exceptionally strong ENSO events: 1972/73, 1982/83, 1987, 1992, 1997/98 (Prospero and Nees 1986; Prospero and Lamb 2003). There are many aspects of the link between climate and African dust generation and transport that are not fully understood and that remain a subject of debate (e.g., Evan et al. 2016; Ginoux et al. 2012; Ridley et al. 2014; Jury and Jiménez 2021). The difficulties that models have in producing consistent results are one consequence of these uncertainties. It is especially challenging to understand the factors that drive unusually large dust outbreaks such as the historically intense “Godzilla” event that occurred in June 2020. This outbreak impacted an immense area of the Tropical Atlantic, Caribbean Basin, and the Southern United States for over two weeks (Pu and Jin 2021) as discussed in the supplement and shown in Fig. ES12.

Fig. 10. The first University of Miami research facility located on the easternmost end of Ragged Point, 1971 (13.165040°N, 59.432070°W). The filter heads were located at the top of the fold-over masts. Several years later, the masts in the photo were replaced by a 10-m fold-over tower that was used until 1989.

Fig. 11. The University of Miami Barbados Atmospheric Chemistry Observatory, Ragged Point, from 1989 to present. The aluminum walk-up scaffold tower is 17 m tall; the elevation of Ragged Point is 30 m. The structure at center and the one on the right are the University of Miami laboratories, converted 6-m ship containers. The building on the left is the laboratory of the Advanced Global Atmospheric Gases Experiment (AGAGE) program (Archibald et al. 2015; see the section “The impact of African aerosol transport on air quality” in the supplement). The view in the photo is to the northeast. See Fig. ES11 for other images related to site facilities.

Today, the site at Ragged Point is an official facility of the University of Miami: the Barbados Atmospheric Chemistry Observatory (BACO; https://baco.rsmas.miami.edu/history/index.html).

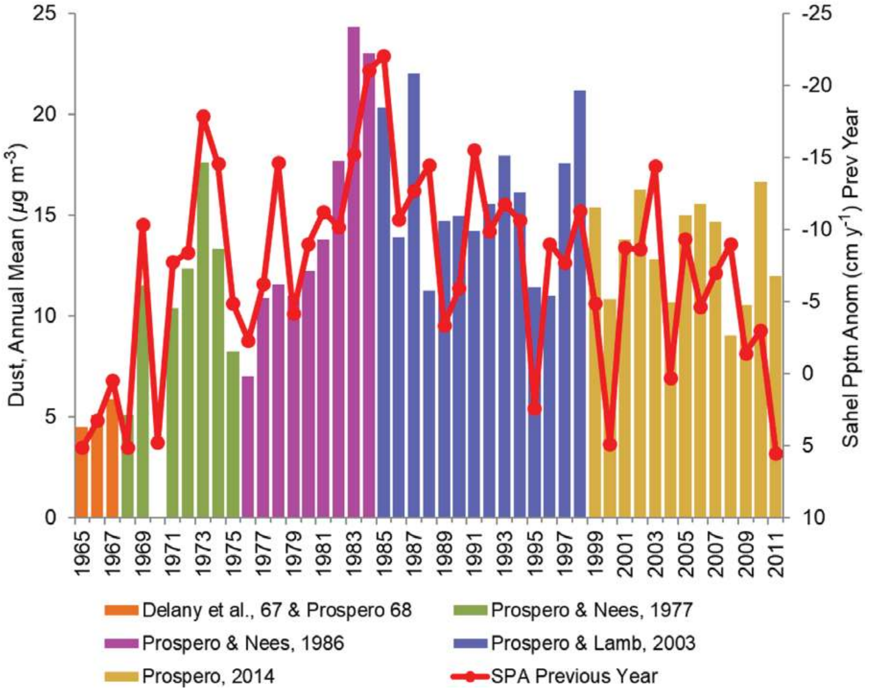

Fig. 12. Barbados annual mean dust concentrations and June–October Sahel precipitation anomalies (SPA), 1965–2011. The dust data are color coded to identify the publications where the data were first presented. Note that the right axis scale is inverted. SPA data are taken from www.jisao.washington.edu/data_sets/sahel/. Anomalies were calculated from means over the period 1950–2011. [Figure from Prospero et al. (2014), replotted.]

BACO is directed by C. Gaston at the Rosenstiel School. The program focuses on aerosol chemistry and particle properties. African dust remains a major theme along with research that seeks to relate dust transport and properties to sources and processes in North Africa, especially climate. Also, of interest is the role of aerosol "aging" during transport. Activities at BACO are coordinated with M. Pöhlker at Max Planck Institute for Atmospheric Chemistry (MPI; Mainz). MPI carries out an extensive program that focuses primarily on aerosol physical properties (e.g., Kandler et al. 2018). The BACO site is also widely used by investigators from other institutions under arrangements with the University of Miami (UM) and coordinated with MPI. MPI Hamburg operates the Barbados Cloud Observatory (BCO) on Deebles Point, a promontory about 0.5 km southeast of BACO (see Fig. ES1). At BCO they carry out an extensive program that focuses on radiation and cloud processes (Stevens et al. 2016).

Over the years, the aerosol chemistry research on Barbados attracted the attention of a broad group of the atmospheric community and many programs were initiated on the island. A summary of these activities is presented in the section "Ancillary programs on Barbados deriving from University of Miami research at Ragged Point" in the supplement.

Barbados research has been complemented by long-term aerosol studies initiated over the past 20 years at sites in the eastern Caribbean. The University of Puerto Rico, under the direction of Olga Bracero-Mayol, operates an atmospheric research facility at a coastal site on Cape San Juan (18.3814°, −65.6182°) on the easternmost end of the island (Denjean et al. 2016). These studies are coupled with aerosol, cloud, and precipitation research (Valle-Díaz et al. 2016) at a mountain site on top of El Yunque (18.3106°, −65.7927°, elevation 1,080 m). Air quality monitoring is carried out on Martinique (14.70°, −61.02°), Guadeloupe (16.26°, −61.55°), and French Guiana (4.94894°, −52.30969°), all departments of France. These programs have produced a valuable continuous aerosol ($PM_{2.5}$ and PM_{10}) time series that begins in the early 2000s (see Prospero et al. 2014, 2020). It is expected that more air quality sites will be activated in the region as governments continue to address issues of aerosols and public health. These measurements, made at a time resolution of one hour, have greatly enhanced our understanding of African dust transport to the region by presenting a detailed synoptic picture of dust clouds as they move through the region.

Conclusions

The purpose of this paper was to document the discovery of African dust transport to the western Atlantic. We have shown that there were multiple "discoveries" and that in each case the discoverers were not seeking dust. Serendipity has played a major role in these discoveries. However, following the pioneering studies by Parkin and Delany group in 1965–66, developments moved rapidly. By the end of BOMEX in 1969, the studies of Carlson and Prospero had firmly established all the basic elements of African dust phenomenon. This was accomplished without any specific funding for dust studies.

Today, given the clearly visible impact of African dust incursions in the region, we wonder why nobody was motivated to examine these events more closely. Even after the nature of these dust events was characterized in the late 1960s, the meteorological community was slow to consider their possible impact. For example, during BOMEX in 1969, Prospero discussed his ongoing measurements with one of the leaders of the program. His response was to caution Prospero that Africa was "five synoptic situations away" and that the dust events were unlikely to have much meteorological significance. A week later, Prospero briefly returned to Miami to make a presentation to a review panel from the Office of Naval Research which was funding his bubble fractionation research. When he discussed his dust studies in BOMEX, the panel advised him that they did not see dust as having much relevance to ocean studies; they suggested that the meteorological community might be interested.

The disinterest in dust at that time reflected a general lack of appreciation of the importance of long-range transport and the role of aerosols in climate. It was not until the 1980s that the importance of aerosols began to be recognized, especially the significance of mineral dust aerosols, the production of which, as noted, was affected by climate change and which can itself modulate climate. It was not until the third IPCC report (IPCC 2001) that aerosols were given prominent attention. Today, the atmospheric and ocean communities are both heavily engaged in dust research.

Given the broad impact that African dust has had in the western Atlantic, there are concerns about the effects that future climate change might have on dust emissions in Africa. However, models used in the recent IPCC assessments could not agree on projections for precipitation and winds in those regions of Africa that are today known to be the most active dust sources (e.g., Evan et al. 2016). Indeed, dust models have difficulty estimating current emission rates. In a recent comparison of 15 models participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), the global dust emissions in these models vary by a factor of 4–5 (Wu et al. 2020). Much of this uncertainty is due to a piecemeal approach to research in major source regions. Although major programs have focused on specific regions in North Africa (as discussed in Knippertz and Stuut 2014) at different times over the past several decades, there is a need for a more integrated approach.

In this context, it might be helpful to have a history of dust research in North Africa where much early work on dust processes was carried out during a time period that parallels that covered in this present work. Also, in this way, the pioneers in African dust studies receive proper recognition for their research which is often overlooked.

In past decades, dust measurements on Barbados have served as a critical dataset for testing models. It is important to continue aerosol studies at Barbados and sites in the Caribbean Basin so that changes in emissions and transport can be accurately and systematically monitored and characterized, thereby furthering our understanding of the interlinked roles of dust and climate.

Acknowledgments. This work does not include recent data and, thus, no current funding is cited. We do provide a section "Historical acknowledgments" in the supplement.

Data availability statement. The daily mean and monthly mean dust mass concentration values measured at Barbados are available in netCDF format and as Excel files at the University of Miami Data Repository under https://doi.org/10.17604/q3vf-8m31.

References

Adams, A. M., J. M. Prospero, and C. Zhang, 2012: *CALIPSO*-derived three-dimensional structure of aerosol over the Atlantic basin and adjacent continents. *J. Climate*, **25**, 6862–6879, https://doi.org/10.1175/JCLI-D-11-00672.1.

Albani, S., and N. M. Mahowald, 2019: Paleodust insights into dust impacts on climate. *J. Climate*, **32**, 7897–7913, https://doi.org/10.1175/JCLI-D-18-0742.1.

Aldhaif, A. M., D. H. Lopez, H. Dadashazar, and A. Sorooshian, 2020: Sources, frequency, and chemical nature of dust events impacting the United States East Coast. *Atmos. Environ.*, **231**, 117456, https://doi.org/10.1016/j.atmosenv.2020.117456.

Archibald, A., and Coauthors, 2015: Long-term high frequency measurements of ethane, benzene and methyl chloride at Ragged Point, Barbados: Identification of long-range transport events. *Elementa*, **3**, 000068, https://doi.org/10.12952/journal.elementa.000068.

Armitage, S. J., C. S. Bristow, and N. A. Drake, 2015: West African monsoon dynamics inferred from abrupt fluctuations of Lake Mega-Chad. *Proc. Natl. Acad. Sci. USA*, **112**, 8543–8548, https://doi.org/10.1073/pnas.1417655112.

Bandermann, L. W., and S. F. Singer, 1969: Interplanetary dust measurements near the Earth. *Rev. Geophys.*, **7**, 759–797, https://doi.org/10.1029/RG007i004p00759.

Barkley, A. E., and Coauthors, 2019: African biomass burning is a substantial source of phosphorus deposition to the Amazon, tropical Atlantic Ocean, and Southern Ocean. *Proc. Natl. Acad. Sci.*, **116**, 16 216–16 221, https://doi.org/10.1073/pnas.1906091116.

——, and Coauthors, 2021: Atmospheric transport of North African dust-bearing supermicron freshwater diatoms to South America: Implications for iron transport to the equatorial North Atlantic Ocean. *Geophys. Res. Lett.*, **48**, e2020GL090476, https://doi.org/10.1029/2020GL090476.

Ben-Ami, Y., I. Koren, Y. Rudich, P. Artaxo, S. T. Martin, and M. O. Andreae, 2010: Transport of North African dust from the Bodélé depression to the Amazon basin: A case study. *Atmos. Chem. Phys.*, **10**, 7533–7544, https://doi.org/10.5194/acp-10-7533-2010.

Bercos-Hickey, E., T. R. Nathan, and S.-H. Chen, 2020: On the relationship between the African easterly jet, Saharan mineral dust aerosols, and West African precipitation. *J. Climate*, **33**, 3533–3546, https://doi.org/10.1175/JCLI-D-18-0661.1.

Biscaye, P. E., 1965: Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. *Geol. Soc. Amer. Bull.*, **76**, 803–832, https://doi.org/10.1130/0016-7606(1965)76[803:MASORD]2.0.CO;2.

Bohlmann, S., H. Baars, M. Radenz, R. Engelmann, and A. Macke, 2018: Ship-borne aerosol profiling with lidar over the Atlantic Ocean: From pure marine conditions to complex dust–smoke mixtures. *Atmos. Chem. Phys.*, **18**, 9661–9679, https://doi.org/10.5194/acp-18-9661-2018.

Bony, S., and Coauthors, 2017: EUREC^{4}A: A field campaign to elucidate the couplings between clouds, convection and circulation. *Surv. Geophys.*, **38**, 1529–1568, https://doi.org/10.1007/s10712-017-9428-0.

Bozlaker, A., J. M. Prospero, M. P. Fraser, and S. Chellam, 2013: Quantifying the contribution of long-range Saharan dust transport on particulate matter concentrations in Houston, Texas, using detailed elemental analysis. *Environ. Sci. Technol.*, **47**, 10 179–10 187, https://doi.org/10.1021/es4015663.

——, ——, J. Price, and S. Chellam, 2018: Linking Barbados mineral dust aerosols to North African sources using elemental composition and radiogenic Sr, Nd, and Pb isotope signatures. *J. Geophys. Res. Atmos.*, **123**, 1384–1400, https://doi.org/10.1002/2017JD027505.

——, ——, ——, and ——, 2019: Identifying and quantifying the impacts of advected North African dust on the concentration and composition of airborne fine particulate matter in Houston and Galveston, Texas. *J. Geophys. Res. Atmos.*, **124**, 12 282–12 300, https://doi.org/10.1029/2019JD030792.

Braun, S. A., J. A. Sippel, and D. S. Nolan, 2012: The impact of dry midlevel air on hurricane intensity in idealized simulations with no mean flow. *J. Atmos. Sci.*, **69**, 236–257, https://doi.org/10.1175/JAS-D-10-05007.1.

Bristow, C. S., K. A. Hudson-Edwards, and A. Chappell, 2010: Fertilizing the Amazon and equatorial Atlantic with West African dust. *Geophys. Res. Lett.*, **37**, L14807, https://doi.org/10.1029/2010GL043486.

Carlson, T. N., 1969: Synoptic histories of three African disturbances that developed into Atlantic hurricanes. *Mon. Wea. Rev.*, **97**, 256–276, https://doi.org/10.1175/1520-0493(1969)097<0256:SHOTAD>2.3.CO;2.

——, and J. M. Prospero, 1972: The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic. *J. Appl. Meteor.*, **11**, 283–297, https://doi.org/10.1175/1520-0450(1972)011<0283:TLSMOS>2.0.CO;2.

——, and R. S. Caverly, 1977: Radiative characteristics of Saharan dust at solar wavelengths. *J. Geophys. Res.*, **82**, 3141–3152, https://doi.org/10.1029/JC082i021p03141.

——, and S. G. Benjamin, 1980: Radiative heating rates for Saharan dust. *J. Atmos. Sci.*, **37**, 193–213, https://doi.org/10.1175/1520-0469(1980)037<0193:RHRFSD>2.0.CO;2.

Chin, M., and Coauthors, 2014: Multi-decadal aerosol variations from 1980 to 2009: A perspective from observations and a global model. *Atmos. Chem. Phys.*, **14**, 3657–3690, https://doi.org/10.5194/acp-14-3657-2014.

Darwin, C., 1846: An account of the fine dust which often falls on vessels in the Atlantic Ocean. *Quart. J. Geol. Soc.*, **2**, 26–30, https://doi.org/10.1144/GSL.JGS.1846.002.01-02.09.

Davis, P. A., 1971: Applications of an airborne ruby lidar during a BOMEX program of cirrus observations. *J. Appl. Meteor.*, **10**, 1314–1323, https://doi.org/10.1175/1520-0450(1971)010<1314:AOAARL>2.0.CO;2.

Delany, A., A. C. Delany, D. Parkin, J. Griffin, E. Goldberg, and B. Reimann, 1967: Airborne dust collected at Barbados. *Geochim. Cosmochim. Acta*, **31**, 885–909, https://doi.org/10.1016/S0016-7037(67)80037-1.

Denjean, C., and Coauthors, 2016: Size distribution and optical properties of African mineral dust after intercontinental transport. *J. Geophys. Res. Atmos.*, **121**, 7117–7138, https://doi.org/10.1002/2016JD024783.

Drummond, A. J., and G. D. Robinson, 1974: Some measurements of the attenuation of solar radiation during BOMEX. *Appl. Opt.*, **13**, 487–492, https://doi.org/10.1364/AO.13.000487.

Duce, R. A., 1997: Christian Junge (1912–1996). *Eos, Trans. Amer. Geophys. Union*, **78**, 39–40, https://doi.org/10.1029/97EO00026.

——, and E. J. Hoffman, 1976: Chemical fractionation at the air/sea interface. *Annu. Rev. Earth Planet. Sci.*, **4**, 187–228, https://doi.org/10.1146/annurev.ea.04.050176.001155.

Dunion, J. P., 2011: Rewriting the climatology of the tropical North Atlantic and Caribbean sea atmosphere. *J. Climate*, **24**, 893–908, https://doi.org/10.1175/2010JCLI3496.1.

——, and C. S. Velden, 2004: The impact of the Saharan air layer on Atlantic tropical cyclone activity. *Bull. Amer. Meteor. Soc.*, **85**, 353–366, https://doi.org/10.1175/BAMS-85-3-353.

Evan, A. T., C. Flamant, M. Gaetani, and F. Guichard, 2016: The past, present and future of African dust. *Nature*, **531**, 493–495, https://doi.org/10.1038/nature17149.

Fleagle, R. G., 1972: BOMEX: An appraisal of results. *Science*, **176**, 1079–1084, https://doi.org/10.1126/science.176.4039.1079.

Formenti, P., and Coauthors, 2011: Recent progress in understanding physical and chemical properties of mineral dust. *Atmos. Chem. Phys.*, **11**, 8231–8256, https://doi.org/10.5194/acp-11-8231-2011.

Garstang, M., N. LaSeur, K. Warsh, R. Hadlock, and J. Petersen, 1970: Atmospheric-oceanic observations in the tropics: Direct observation of interacting scales of motion in the tropical ocean-atmosphere system provides the basis for viewing the atmosphere as a heat-driven system. *Amer. Sci.*, **58**, 482–495.

Gasteiger, J., S. Groß, D. Sauer, M. Haarig, A. Ansmann, and B. Weinzierl, 2017: Particle settling and vertical mixing in the Saharan air layer as seen from an integrated model, lidar, and in situ perspective. *Atmos. Chem. Phys.*, **17**, 297–311, https://doi.org/10.5194/acp-17-297-2017.

Geological Society of America, 1994: Memorial to Guillermo Zuloaga, 1904-1984. *Geol. Soc. Amer. Meml.*, **25**, 3.

Ghan, S. J., X. Liu, R. C. Easter, R. Zaveri, P. J. Rasch, J.-H. Yoon, and B. Eaton, 2012: Toward a minimal representation of aerosols in climate models: Comparative decomposition of aerosol direct, semidirect, and indirect radiative forcing. *J. Climate*, **25**, 6461–6476, https://doi.org/10.1175/JCLI-D-11-00650.1.

Ginoux, P., J. M. Prospero, T. E. Gill, N. C. Hsu, and M. Zhao, 2012: Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Rev. Geophys.*, **50**, RG3005, https://doi.org/10.1029/2012RG000388.

Goldberg, E. D., and J. J. Griffin, 1964: Sedimentation rates and mineralogy in the South Atlantic. *J. Geophys. Res.*, **69**, 4293–4309, https://doi.org/10.1029/JZ069i020p04293.

Groß, S., V. Freudenthaler, K. Schepanski, C. Toledano, A. Schäfler, A. Ansmann, and B. Weinzierl, 2015: Optical properties of long-range transported Saharan dust over Barbados as measured by dual-wavelength depolarization Raman lidar measurements. *Atmos. Chem. Phys.*, **15**, 11 067–11 080, https://doi.org/10.5194/acp-15-11067-2015.

——, J. Gasteiger, V. Freudenthaler, T. Müller, D. Sauer, C. Toledano, and A. Ansmann, 2016: Saharan dust contribution to the Caribbean summertime boundary layer—A lidar study during SALTRACE. *Atmos. Chem. Phys.*, **16**, 11 535–11 546, https://doi.org/10.5194/acp-16-11535-2016.

Grogan, D. F. P., and C. D. Thorncroft, 2019: The characteristics of African easterly waves coupled to Saharan mineral dust aerosols. *Quart. J. Roy. Meteor. Soc.*, **145**, 1130–1146, https://doi.org/10.1002/qj.3483.

Haarig, M., and Coauthors, 2017: Dry versus wet marine particle optical properties: RH dependence of depolarization ratio, backscatter, and extinction from multiwavelength lidar measurements during SALTRACE. *Atmos. Chem. Phys.*, **17**, 14 199–14 217, https://doi.org/10.5194/acp-17-14199-2017.

Hand, J. L., W. H. White, K. A. Gebhart, N. P. Hyslop, T. E. Gill, and B. A. Schichtel, 2016: Earlier onset of the spring fine dust season in the southwestern United States. *Geophys. Res. Lett.*, **43**, 4001–4009, https://doi.org/10.1002/2016GL068519.

Holland, J. Z., 1972: The BOMEX Sea-Air Interaction program: Background and results to date. NOAA Tech. Memo. ERL BOMAP-9, 34 pp.

Hooper, J., and S. Marx, 2018: A global doubling of dust emissions during the Anthropocene? *Global Planet. Change*, **169**, 70–91, https://doi.org/10.1016/j.gloplacha.2018.07.003.

Huneeus, N., and Coauthors, 2011: Global dust model intercomparison in AeroCom phase 1. *Atmos. Chem. Phys.*, **11**, 7781–7816, https://doi.org/10.5194/acp-11-7781-2011.

IPCC, 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.

Jaenicke, R., 2012: Die Erfindung der Luftchemie—Christian Junge. *100 Jahre Kaiser-Wilhelm-/Max-Planck-Institut für Chemie (Otto-Hahn-Institut)*, H. Kant and C. Reinhardt, Eds., Max Planck Institute, 187–202.

Jickells, T., and C. M. Moore, 2015: The importance of atmospheric deposition for ocean productivity. *Annu. Rev. Ecol. Evol. Syst.*, **46**, 481–501, https://doi.org/10.1146/annurev-ecolsys-112414-054118.

Junge, C. E., 1956: Recent investigations in air chemistry. *Tellus*, **8**, 127–139, https://doi.org/10.3402/tellusa.v8i2.8971.

——, 1963: *Air Chemistry and Radioactivity*. Academic Press, 382 pp.

——, 1972: Our knowledge of the physico-chemistry of aerosols in the undisturbed marine environment. *J. Geophys. Res.*, **77**, 5183–5200, https://doi.org/10.1029/JC077i027p05183.

Jury, M. R., and A. T. N. Jiménez, 2021: Tropical Atlantic dust and the zonal circulation. *Theor. Appl. Climatol.*, **143**, 901–913, https://doi.org/10.1007/s00704-020-03461-4.

Kahn, R. A., 2015: Satellites and satellite remote sensing. *Encyclopedia of Atmospheric Sciences*, 2nd ed. G. R. North, Ed., Elsevier, 51–56.

Kandler, K., K. Schneiders, M. Ebert, M. Hartmann, S. Weinbruch, M. Prass, and C. Pöhlker, 2018: Composition and mixing state of atmospheric aerosols determined by electron microscopy: Method development and application to aged Saharan dust deposition in the Caribbean boundary layer. *Atmos. Chem. Phys.*, **18**, 13 429–13 455, https://doi.org/10.5194/acp-18-13429-2018.

Karyampudi, V. M., and Coauthors, 1999: Validation of the Saharan dust plume conceptual model using lidar, Meteosat, and ECMWF data. *Bull. Amer. Meteor. Soc.*, **80**, 1045–1076, https://doi.org/10.1175/1520-0477(1999)080<1045:VOTSDP>2.0.CO;2.

Knippertz, P., and M. C. Todd, 2012: Mineral dust aerosols over the Sahara: Meteorological controls on emission and transport and implications for modeling. *Rev. Geophys.*, **50**, RG1007, https://doi.org/10.1029/2011RG000362.

——, and J.-B. W. Stuut, 2014: *Mineral Dust: A Key Player in the Earth System*. Springer, 509 pp.

Kok, J. F., and Coauthors, 2021: Contribution of the world's main dust source regions to the global cycle of desert dust. *Atmos. Chem. Phys.*, **21**, 8169–8193, https://doi.org/10.5194/acp-21-8169-2021.

Kuciauskas, A. P., P. Xian, E. J. Hyer, M. I. Oyola, and J. R. Campbell, 2018: Supporting weather forecasters in predicting and monitoring Saharan air layer dust events as they impact the greater Caribbean. *Bull. Amer. Meteor. Soc.*, **99**, 259–268, https://doi.org/10.1175/BAMS-D-16-0212.1.

Kuettner, J. P., and J. Holland, 1969: The BOMEX project. *Bull. Amer. Meteor. Soc.*, **50**, 394–403, https://doi.org/10.1175/1520-0477-50.6.394.

Machta, L., and H. F. Lucas, 1962: Radon in the upper atmosphere. *Science*, **135**, 296–299, https://doi.org/10.1126/science.135.3500.296.

Mbourou, G. N. T., J. J. Bertrand, and S. E. Nicholson, 1997: The diurnal and seasonal cycles of wind-borne dust over Africa north of the equator. *J. Appl. Meteor.*, **36**, 868–882, https://doi.org/10.1175/1520-0450(1997)036<0868:TDASCO>2.0.CO;2.

Nathan, T. R., D. F. P. Grogan, and S.-H. Chen, 2019: Saharan dust transport during the incipient growth phase of African easterly waves. *Geosciences*, **9**, 388, https://doi.org/10.3390/geosciences9090388.

Nicholson, S. E., 2013: The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteor.*, **2013**, 453521, https://doi.org/10.1155/2013/453521.

Okin, G., D. Gillette, and J. Herrick, 2006: Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. *J. Arid Environ.*, **65**, 253–275, https://doi.org/10.1016/j.jaridenv.2005.06.029.

Parkin, D., and W. Hunter, 1959: Cosmic dust in the atmosphere. *Nature*, **183**, 732–734, https://doi.org/10.1038/183732a0.

——, A. Delany, and A. C. Delany, 1967: A search for airborne cosmic dust on Barbados. *Geochim. Cosmochim. Acta*, **31**, 1311–1320, https://doi.org/10.1016/S0016-7037(67)80017-6.

Plane, J. M., 2012: Cosmic dust in the Earth's atmosphere. *Chem. Soc. Rev.*, **41**, 6507–6518, https://doi.org/10.1039/c2cs35132c.

Prospero, J. M., 1968: Atmospheric dust studies on Barbados. *Bull. Amer. Meteor. Soc.*, **49**, 645–652, https://doi.org/10.1175/1520-0477-49.6.645.

——, 1999: Long-term measurements of the transport of African mineral dust to the southeastern United States: Implications for regional air quality. *J. Geophys. Res.*, **104**, 15 917–15 927, https://doi.org/10.1029/1999JD900072.

——, and E. Bonatti, 1969: Continental dust in atmosphere of the eastern equatorial Pacific. *J. Geophys. Res.*, **74**, 3362–3371, https://doi.org/10.1029/JC074i013p03362.

——, and T. N. Carlson, 1970: Radon-222 in the North Atlantic trade winds: Its relationship to dust transport from Africa. *Science*, **167**, 974–977, https://doi.org/10.1126/science.167.3920.974.

——, and ——, 1972: Vertical and areal distribution of Saharan dust over the western equatorial North Atlantic Ocean. *J. Geophys. Res.*, **77**, 5255–5265, https://doi.org/10.1029/JC077i027p05255.

——, and R. T. Nees, 1977: Dust concentration in the atmosphere of the equatorial North Atlantic: Possible relationship to the Sahelian drought. *Science*, **196**, 1196–1198, https://doi.org/10.1126/science.196.4295.1196.

——, and ——, 1986: Impact of the North African drought and El Niño on mineral dust in the Barbados trade winds. *Nature*, **320**, 735–738, https://doi.org/10.1038/320735a0.

——, and P. J. Lamb, 2003: African droughts and dust transport to the Caribbean: Climate change implications. *Science*, **302**, 1024–1027, https://doi.org/10.1126/science.1089915.

——, and O. L. Mayol-Bracero, 2013: Understanding the transport and impact of African dust on the Caribbean Basin. *Bull. Amer. Meteor. Soc.*, **94**, 1329–1337, https://doi.org/10.1175/BAMS-D-12-00142.1.

——, E. Bonatti, C. Schubert, and T. N. Carlson, 1970: Dust in the Caribbean atmosphere traced to an African dust storm. *Earth Planet. Sci. Lett.*, **9**, 287–293, https://doi.org/10.1016/0012-821X(70)90039-7.

——, R. A. Glaccum, and R. T. Nees, 1981: Atmospheric transport of soil dust from Africa to South America. *Nature*, **289**, 570–572, https://doi.org/10.1038/289570a0.

——, I. Olmez, and M. Ames, 2001: Al and Fe in PM 2.5 and PM 10 suspended particles in south-central Florida: The impact of the long range transport of African mineral dust. *Water Air Soil Pollut.*, **125**, 291–317, https://doi.org/10.1023/A:1005277214288.

——, P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill, 2002: Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Rev. Geophys.*, **40**, 1002, https://doi.org/10.1029/2000RG000095.

——, E. Blades, G. Mathison, and R. Naidu, 2005: Interhemispheric transport of viable fungi and bacteria from Africa to the Caribbean with soil dust. *Aerobiologia*, **21**, 1–19, https://doi.org/10.1007/s10453-004-5872-7.

——, ——, R. Naidu, G. Mathison, H. Thani, and M. C. Lavoie, 2008: Relationship between African dust carried in the Atlantic trade winds and surges in pediatric asthma attendances in the Caribbean. *Int. J. Biometeor.*, **52**, 823–832, https://doi.org/10.1007/s00484-008-0176-1.

——, F.-X. Collard, J. Molinié, and A. Jeannot, 2014: Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. *Global Biogeochem. Cycles*, **28**, 757–773, https://doi.org/10.1002/2013GB004802.

——, A. E. Barkley, C. J. Gaston, A. Gatineau, A. Campos y Sansano, and K. Panechou, 2020: Characterizing and quantifying African dust transport and deposition to South America: Implications for the phosphorus budget in the Amazon basin. *Global Biogeochem. Cycles*, **34**, e2020GB006536, https://doi.org/10.1029/2020GB006536.

Pu, B., and Q. Jin, 2021: A record-breaking trans-Atlantic African dust plume associated with atmospheric circulation extremes in June 2020. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-21-0014.1, in press.

Querol, X., and Coauthors, 2019: Monitoring the impact of desert dust outbreaks for air quality for health studies. *Environ. Int.*, **130**, 104867, https://doi.org/10.1016/j.envint.2019.05.061.

Quinn, P. K., D. B. Collins, V. H. Grassian, K. A. Prather, and T. S. Bates, 2015: Chemistry and related properties of freshly emitted sea spray aerosol. *Chem. Rev.*, **115**, 4383–4399, https://doi.org/10.1021/cr500713g.

Ravi, S., and Coauthors, 2011: Aeolian processes and the biosphere. *Rev. Geophys.*, **49**, RG3001, https://doi.org/10.1029/2010RG000328.

Reed, K. A., J. T. Bacmeister, J. J. A. Huff, X. Wu, S. C. Bates, and N. A. Rosenbloom, 2019: Exploring the impact of dust on North Atlantic hurricanes in a high-resolution climate model. *Geophys. Res. Lett.*, **46**, 1105–1112, https://doi.org/10.1029/2018GL080642.

Reid, J. S., and Coauthors, 2003: Analysis of measurements of Saharan dust by airborne and ground-based remote sensing methods during the Puerto Rico Dust Experiment (PRIDE). *J. Geophys. Res.*, **108**, 8586, https://doi.org/10.1029/2002JD002493.

Richardson, C. H., and D. J. Nemeth, 1991: Hurricane-borne African locusts (*Schistocerca gregaria*) on the Windward Islands. *GeoJournal*, **23**, 349–357, https://doi.org/10.1007/BF00193608.

Ridley, D. A., C. L. Heald, and J. M. Prospero, 2014: What controls the recent changes in African mineral dust aerosol across the Atlantic? *Atmos. Chem. Phys.*, **14**, 5735–5747, https://doi.org/10.5194/acp-14-5735-2014.

Romero, O. E., C. B. Lange, R. Swap, and G. Wefer, 1999: Eolian-transported freshwater diatoms and phytoliths across the equatorial Atlantic record: Temporal changes in Saharan dust transport patterns. *J. Geophys. Res.*, **104**, 3211–3222, https://doi.org/10.1029/1998JC900070.

Rosenberg, J., and P. J. Burt, 1999: Windborne displacements of desert locusts from Africa to the Caribbean and South America. *Aerobiologia*, **15**, 167–175, https://doi.org/10.1023/A:1007529617032.

Salter, M. E., and Coauthors, 2016: Calcium enrichment in sea spray aerosol particles. *Geophys. Res. Lett.*, **43**, 8277–8285, https://doi.org/10.1002/2016GL070275.

Shao, Y., and Coauthors, 2011: Dust cycle: An emerging core theme in Earth system science. *Aeolian Res.*, **2**, 181–204, https://doi.org/10.1016/j.aeolia.2011.02.001.

Stein, A. F., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, and F. Ngan, 2015: NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bull. Amer. Meteor. Soc.*, **96**, 2059–2077, https://doi.org/10.1175/BAMS-D-14-00110.1.

Stevens, B., and Coauthors, 2016: The Barbados Cloud Observatory: Anchoring investigations of clouds and circulation on the edge of the ITCZ. *Bull. Amer. Meteor. Soc.*, **97**, 787–801, https://doi.org/10.1175/BAMS-D-14-00247.1.

Stong, C. L., 1961: An amateur investigates the origin of Venezuela's peculiar fog: The calina. *Sci. Amer.*, **205**, 172–183, https://doi.org/10.1038/scientificamerican1061-172.

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2018: The climatological effect of Saharan dust on global tropical cyclones in a fully coupled GCM. *J. Geophys. Res. Atmos.*, **123**, 5538–5559, https://doi.org/10.1029/2017JD027808.

Swap, R., M. Garstang, S. Greco, R. Talbot, and P. Kållberg, 1992: Saharan dust in the Amazon basin. *Tellus*, **44B**, 133–149, https://doi.org/10.3402/tellusb.v44i2.15434.

Tao, Z., S. A. Braun, J. J. Shi, M. Chin, D. Kim, T. Matsui, and C. D. Peters-Lidard, 2018: Microphysics and radiation effect of dust on Saharan air layer: An HS3 case study. *Mon. Wea. Rev.*, **146**, 1813–1835, https://doi.org/10.1175/MWR-D-17-0279.1.

Taylor, S., and D. E. Brownlee, 1991: Cosmic spherules in the geologic record. *Meteoritics*, **26**, 203–211, https://doi.org/10.1111/j.1945-5100.1991.tb01040.x.

Uthe, E. E., and W. B. Johnson, 1971: Lidar observations of the lower tropospheric aerosol structure during BOMEX. SRI Project Final Rep. 7929, 128 pp.

Valle-Díaz, C. J., and Coauthors, 2016: Impact of long-range transported African dust on cloud water chemistry at a tropical montane cloud forest in northeastern Puerto Rico. *Aerosol Air Qual. Res.*, **16**, 653–664, https://doi.org/10.4209/aaqr.2015.05.0320.

Webb, N. P., and C. Pierre, 2018: Quantifying anthropogenic dust emissions. *Earth's Future*, **6**, 286–295, https://doi.org/10.1002/2017EF000766.

Weinzierl, B., and Coauthors, 2017: The Saharan Aerosol Long-Range Transport and Aerosol–Cloud-Interaction Experiment: Overview and selected highlights. *Bull. Amer. Meteor. Soc.*, **98**, 1427–1451, https://doi.org/10.1175/BAMS-D-15-00142.1.

Wu, C., Z. Lin, and X. Liu, 2020: The global dust cycle and uncertainty in CMIP5 (Coupled Model Intercomparison Project phase 5) models. *Atmos. Chem. Phys.*, **20**, 10 401–10 425, https://doi.org/10.5194/acp-20-10401-2020.

Xian, P., P. J. Klotzbach, J. P. Dunion, M. A. Janiga, J. S. Reid, P. R. Colarco, and Z. Kipling, 2020: Revisiting the relationship between Atlantic dust and tropical cyclone activity using aerosol optical depth reanalyses: 2003–2018. *Atmos. Chem. Phys.*, **20**, 15 357–15 378, https://doi.org/10.5194/acp-20-15357-2020.

Yu, H., and Coauthors, 2015a: Quantification of trans-Atlantic dust transport from seven-year (2007–2013) record of CALIPSO lidar measurements. *Remote Sens. Environ.*, **159**, 232–249, https://doi.org/10.1016/j.rse.2014.12.010.

——, and Coauthors, 2015b: The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. *Geophys. Res. Lett.*, **42**, 1984–1991, https://doi.org/10.1002/2015GL063040.

——, and Coauthors, 2019: Estimates of African dust deposition along the trans-Atlantic transit using the decadelong record of aerosol measurements from CALIOP, MODIS, MISR, and IASI. *J. Geophys. Res. Atmos.*, **124**, 7975–7996, https://doi.org/10.1029/2019JD030574.

Yu, Y., and Coauthors, 2020: Disproving the Bodélé depression as the primary source of dust fertilizing the Amazon rainforest. *Geophys. Res. Lett.*, **47**, e2020GL088020, https://doi.org/10.1029/2020GL088020.

Zamora, L. M., J. M. Prospero, D. A. Hansell, and J. M. Trapp, 2013: Atmospheric P deposition to the subtropical North Atlantic: Sources, properties, and relationship to N deposition. *J. Geophys. Res. Atmos.*, **118**, 1546–1562, https://doi.org/10.1002/jgrd.50187.

Zhang, X., L. Zhao, D. Tong, G. Wu, M. Dan, and B. Teng, 2016: A systematic review of global desert dust and associated human health effects. *Atmosphere*, **7**, 158, https://doi.org/10.3390/atmos7120158.

Zipser, E. J., and Coauthors, 2009: The Saharan air layer and the fate of African easterly waves: NASA's AMMA field study of tropical cyclogenesis. *Bull. Amer. Meteor. Soc.*, **90**, 1137–1156, https://doi.org/10.1175/2009BAMS2728.1.

Zuidema, P., and Coauthors, 2019: 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. *Bull. Amer. Meteor. Soc.*, **100**, 1981–1986, https://doi.org/10.1175/BAMS-D-18-0083.1.

Zuloaga, G., 1966: La calina y el viento salante: *Bol. Acad. Cienc. Fis., Mat. Nat.*, **26**, 101–114.