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Dust vertical distribution in the Caribbean during the Puerto Rico Dust experiment

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[1] As part of Puerto Rico Dust Experiment (PRIDE), a Piper Navajo research aircraft, equipped with particle probes and an airborne Sun photometer, was deployed to Puerto Rico in July 2000. During the study, mid-visible optical depths in Puerto Rico due to dust reached 0.5. In the middle of the summer transport season, the vertical distributions of dust were similar to that commonly assumed in the region with dust concentrated in the Saharan Air Layer (SAL) aloft. However, during the first half of the study period, dust had the highest concentrations in the marine and convective boundary layers, with lower dust concentrations above the trade inversion despite the presence of a strong SAL. Supporting meteorology suggests that the state of the monsoon on the coast of Africa influences the nature of the vertical distribution of dust in the Caribbean. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0330 Atmospheric Composition and Structure: Geochemical cycles; 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry

1. Introduction

[2] Saharan dust transport mechanisms into the tropical Atlantic region have been qualitatively understood since they were first identified in short term meteorological studies [e.g., *Prospero and Carlson*, 1972]. Modeling and LIDAR studies suggest that the predominant mode in summer time involves warm and dry dust-laden air (the Saharan air layer, or SAL) being advected off of the African continent in the easterly trade winds and subsequently sliding over the marine boundary layer [e.g., *Westphal et al.*, 1987; *Karyampudi et al.*, 1999]. Once in the free troposphere the dust is transported across the Atlantic into the Caribbean region. Despite this qualitative understanding, there is little quantitative data on dust during this transport. Questions relating to the vertical distribution and transport mechanisms of dust involve significant areas of research including climate, radiative transfer, cloud microphysics, dust fertilization of the oceans and Amazon basin, and regional air quality.

[3] As part of the Puerto Rico Dust Experiment (PRIDE), the vertical distribution of dust in the Caribbean region was studied for the month of July 2000. In this manuscript we discuss the principal findings from the Piper Navajo research aircraft used in PRIDE as they relate to dust transport and vertical distribution.

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2. Study Design and Methods

[4] PRIDE occurred between June 28 and July 24, 2000, at Naval Station Roosevelt Roads, on the eastern end of the island of Puerto Rico. The principal aircraft used for PRIDE was a twin-engine, 8-seat Piper Navajo owned and operated by Gibbs Flite Center and contracted by SPAWAR Systems Center San Diego (SSC-SD). Included on the Navajo were basic meteorological instrumentation (Rosemount temperature ±0.3 C, EGG dew point ±0.5 C, Vaisala relative humidity ±5%, Vaisala temperature ±0.3 C, and static pressure ±0.2 mb), a 6 channel airborne Sun photometer to measure aerosol optical thickness [*Matsumoto et al.*, 1987], and two optical particle counters (PMS Forward Scattering Spectrometer Probe: FSSP-100 and Passive Cavity Aerosol Spectrometer Probe: PCASP-100X) mounted on the Navajo wingtips. Both the FSSP and PCASP underwent the Droplet Measurement Technologies, Inc. upgrade and nominally measured particles sized in 20 channels from 0.75 to 18 μm and 0.1 to 3 μm in diameter, respectively. In this manuscript we are principally concerned with the coarse mode aerosol concentration as measured by the FSSP. As discussed by *Collins et al.* [2000], and *Reid et al.* [2002] the FSSP-100 is insensitive to particle size in the 1 to ∼10 μm range due to inflection points in the Mie size-scattering cross section curves. Hence, in this manuscript for illustrative purposes, we display the FSSP number concentration in channels 2 through 19 (∼1.5–16 μm). We are confident in these values as the FSSP-100 and a surface based University of Miami APS 3310 (aerodynamic particle sizer) showed excellent agreement during 15 flybys.

[5] During PRIDE, the Navajo flew 21 flights (61 hours of data collection over eighty flight hours) near the islands of Puerto Rico, St. Thomas, and St. Croix. Each flight began with a continuous vertical profile (∼30 m to 5,000 m) over the aerosol/radiation site at Cabras Island (Lat. ∼18.21° N, Long. ∼65.60°W) to characterize the local environment. Once at altitude the Navajo proceeded to cloud-free regions 50–170 km away and performed additional profiles. By the end of PRIDE, the Navajo had performed 55 vertical profiles.

[6] Particle speciation for the Cabras Island site was performed by the University of Miami using ion chromatography and ashing techniques on surface filter samples. In calculations presented in this manuscript it was assumed that the salt-to-dust ratio was constant in altitude in the marine boundary layer, and that no salt was present in the SAL. Salt concentrations in the convective boundary layer were assumed to follow the water vapor mixing ratio (this was a minor correction to the total salt loading, <20%). Because the salt/dust partition was done at the surface, this assumption probably overestimates the amount of salt in the atmosphere.

3. Results

[7] At the surface, winds varied from 5 to 10 m s^{-1} out of the ESE to ENE. Temperature and relative humidity were consistent at 25–28°C and 70–90%, respectively. Vertical soundings were typical of the subtropical marine environment, with a marine boundary layer (MBL) inversion at ∼500 m, and a convective boundary

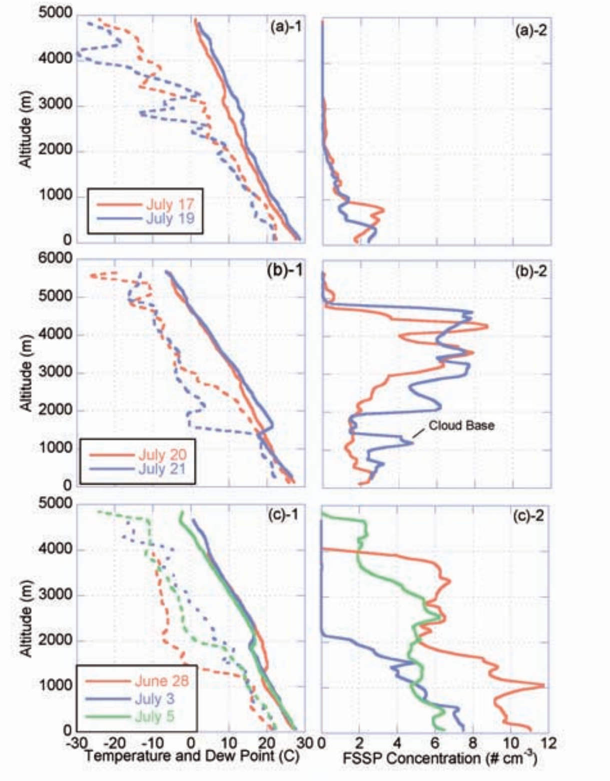

Figure 1. Dust vertical profile and atmospheric soundings for 3 typical dust distribution categories. Total number concentration from the FSSP 100 channel 2–19 (1.5–16 μm) is presented. (a) Clean marine conditions (no dust) (b) Classic SAL profile (c) Dust in both the MBL and SAL.

layer (CBL) up to the trade inversion at 1 to 3 km [*Augstein et al.*, 1974]. In the MBL, the water vapor mixing ratio (w_v) ranged between 15–20 g kg^{-1} and usually monotonically decreased in the CBL. The presence of a SAL with continental origins was clearly indicated by a dry layer immediately above the trade inversion with w_v on the order of 3 to 5 g kg^{-1} and neutral stability. At the top of the SAL was a secondary inversion, above which w_v dropped to <1 g kg^{-1}. On days where the region was under the influence of tropical wave and tropical wave remnants, the atmospheric profile was moister, with very weak inversions and w_v values on the order of 10 g kg^{-1} at altitudes to 4000 m.

[8] Summary information of the atmospheric state during the Navajo flights is presented in Table 1. Aerosol Optical Thickness (AOT) in the mid-visible (525.7 nm) ranged from 0.07 for clean marine background days without any sign of dust, to ~0.55 on the dustiest days. AOTs at the top of the dust layers (>~5 km), varied from 0.01 to 0.03 during non-cirrus contamination periods. Filter samples taken at the surface site by the University of Miami showed the 24 hour sea salt (dry) and dust concentrations varied between ~10–20 μg m^{-3} and 3–70 μg m^{-3}, respectively.

[9] During the PRIDE field campaign, the Navajo sampled 5 significant dust events, arriving at Puerto Rico on June 28, and July 5, 9, 15, and 21, 2000. SeaWiFS (http://seawifs.gsfc.nasa.gov/SEAWIFS.html) and TOMS (http://toms.gsfc.nasa.gov/aerosols/aerosols.html) satellite imagery showed these events leaving the coast of Africa roughly on June 23 and 29, and July 4, 10, and 15, respectively, suggesting a ~5 to 6 day transit time across the subtropical Atlantic Ocean.

[10] The vertical profile of the dust varied considerably during the study. The fraction of total profile AOT in the SAL varied from 5 to 85%. The contribution of accumulation mode particles was minimal in this marine site, typically AOT contributions were <0.05. On average, only 40% of the vertical profile AOT and 50% of the dust mass were attributable to the SAL layer, and almost no correlation existed between the AOT and the SAL AOT fraction (r^2 < 0.25).

[11] Figure 1 depicts thermodynamic and particle soundings for 7 flights. Figure 1a shows typical profiles for two clean marine

Table 1. Summary Vertical Profile Information in the Vicinity of Puerto Rico

Date	Trade Inv.	Dust Max Altitude	Profile AOT	SAL AOT Fraction	SAL Dust Fraction	C_{md} Surface	Ratio Dust/Salt
6/28	1100	4000	0.48	0.61	0.6	(100)	(4–8)
6/30	1600	3790	0.24	0.54	0.6	(30)	(1.5–3)
7/1	2000	2530	0.13	0.16	<0.1	(30)	(1.5–3)
7/3	1800	2280	(0.20)	(0.05)	<0.1	31	1.7
7/4	2000	2360	0.29	0.37	0.4	32	1.4
7/5	1900	4900	0.35	0.44	0.5	40	1.8
7/6	1000	4700	0.25	0.76	0.8	39	2.2
7/8	none	3540	~0.06	none	<0.1	17	1.4
7/10	1600	3500	0.15	0.28	0.4	67	3.2
7/11	2800	2500	0.06	0.06	<0.1	5	0.2
7/12	2100	3235	0.12	0.06	<0.1	5	0.3
7/13	1350	2800	0.17	0.38	0.5	30	1.4
7/15	1150	4500	0.26	0.52	0.8	24	1.4
7/16	1950	4200	0.23	0.42	0.5	56	3.9
7/17	2000	2345	0.07	0.07	<0.1	4	0.2
7/19	2100	2430	0.06	0.01	<0.1	4	0.2
7/20	2300	5230	0.27	0.72	0.8	11	0.8
7/21	1350	5050	0.35	0.87	0.8	31	1.8
7/22	1950	4470	0.11	0.55	0.8	9	0.8
7/23	1650	4260	0.30	0.79	0.9	11	1.1
7/24	2000	3600	0.15	0.53	0.9	29	2.2

Values in parenthesis are approximations based on PMS probe data. Time is ~12:00–14:00 UTC. Date is for the year 2000. Trade Inv. = Trade inversion height (m). Dust Max Alt = Dust maximum altitude (m). Profile AOT is the difference in the total AOT and the AOT at the Dust maximum Altitude at 525.7 nm. At no time was the AOT above the dust maximum altitude greater than 0.03. SAL AOT Fraction = The total fraction of the profile AOT in the SAL. SAL Dust Fraction = The total course mode dust mass fraction in the Saharan air layer calculated with the FSSP-100 and making a correction based on the surface sea salt concentration. C_{md} = dust mass concentration at the surface (μg m^{-3}). Ratio Dust/Salt = 24 hour dry mass ratio of dust and sea-salt at the surface.

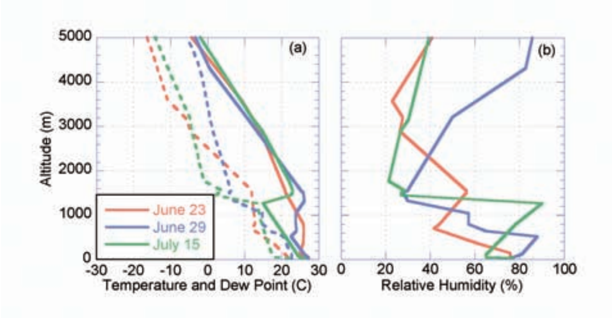

Figure 2. 23 Z Atmospheric soundings of dust events arriving at Dakar for June 23, (red), June 29 (blue) and July 15, 2001 (green). Left plot is temperature and dew point. Right plot is relative humidity. The dust event at Dakar on June 29 was also very similar to the Dakar July 5 sounding.

days with very little dust (<5 μg m^{-3}). In the latter third of the study, dust exhibited what is considered the ''typical'' Saharan Air Layer transport mechanism into the Caribbean region (Figure 1b). A distinct SAL layer, containing >80% of the dust, is visible in the sounding, although at the surface there is still more dust than dry sea salt-Table 1. Under these cases dust reached altitudes in excess of 5 km. Consistent with the SAL transport commonly assumed for the region, we found significant vertical stratification without significant shifts in the water vapor mixing ratio. Occasionally, a slight increase in particle concentrations was observed at the lifting condensation level as sea salt particles grew.

[12] During the first part of the study, vertical distribution of dust was atypical with significant transport occurring outside of the SAL. Figure 1c depicts three separate dust events where dust is actually concentrated below the SAL on July 3, and seems to have maxima both below the SAL and in the SAL on June 28 and July 5. *Prospero and Carlson* [1972] found similar structures where dust was well mixed from the top of the SAL to the surface, although we found dust in much higher concentrations at all levels, rivaling the total dust AOT for the typical SAL conditions. Vertical soundings on these uniform profile days tended to show weaker inversions than during the strongest SAL days, though the strength of the trade inversion was not indicative of dust vertical distribution in general. We also found cases where the highest dust concentrations were below the trade inversion. On the highest AOT day of the study (∼0.5, June 28), dust concentrations aloft were on the order of those on the strongest upper level SAL transport days, but concentrations were also nearly twice as high below the trade inversion, resulting in near surface visibility at Roosevelt Roads dropping below 6 km, and dust falls throughout the region. At others times, such as July 3, the dust was completely confined to the MBL and CBL with very few coarse mode particles found above the trade inversion, and a ratio of dry mass to dry sea salt at the surface of ∼1.5. Thus, even under conditions when there is little or no dust in the SAL layer, dust can still be the dominant aerosol particle species in the boundary layer.

[13] Based on our findings, there was no systematic relationship between the thermodynamic sounding and dust vertical profile in Puerto Rico. The persistence of inflections and layers in the dust concentration implies weak vertical turbulent or convective mixing, indicating a deep vertical mixing process is not likely to be responsible for the dust in the MBL. This is particularly obvious on June 28 and July 3 when the MBL dust concentration is higher than the SAL dust concentration. Further, while the moderate water vapor mixing ratios in the low-level dust layers could be caused by the expected conditioning of the marine boundary layer, they cannot be responsible for mixing dust from the SAL to the MBL.

[14] With vertical mixing unable to explain such variability, the remaining mechanisms that could produce the unexpectedly high MBL dust concentrations are vertical differential advection, source region variations, or some combination of these. Certainly, differential advection occurs, but probably cannot explain the overwhelming shift in character of the dust vertical profile. We did find evidence that suggests that much of the variability in the vertical distribution of dust in the Caribbean can be attributed to atmospheric flow patterns at the coast of Africa. Consider Figure 2, the 23 Z soundings for June 23, June 29, and July 15 at Dakar, Senegal (14.74°N, 17.5°W) that correspond to the dust events in Puerto Rico on June 28, July 5 and July 21 respectively (in Figure 1). The July 15 sounding, corresponding with a ''typical'' dust event arriving at Puerto Rico on July 21, depicts a 2-km-deep monsoonal flow from the southwest at 5 m s^{-1} capped above by a SAL that reaches to 6 km with moderate easterlies. This pattern matches the conceptual model for dust transport in an elevated SAL and resulted in observed high mid-tropospheric concentrations of dust impacting Puerto Rico. In contrast, on June 23 the moist onshore monsoonal layer is weak, or nearly absent, and only a few hundreds of meters deep. Above this, there are at least two well-mixed layers with tops at 1.5 and 5.0 km, defined by near-constant potential temperature and mixing ratio, high dust concentrations and, typically, a continental origin. High dust concentrations at all levels below 5 km were subsequently observed in Puerto Rico on June 28. For the June 29 sounding (which was very similar to the July 5 case in Dakar as well), a transition begins with a very weak inversion at 950 mb. This flow pattern may have resulted in the more uniform vertical distribution found in the July 5 and 10 cases in Puerto Rico. After examining the Dakar sounding record for the summer of 2000, we found strong monsoonal flow did not develop until approximately 5–10 July. These dates matched our observed transition from ''well mixed'' to ''SAL'' transport.

[15] Dakar is not ideally located for this analysis, but it does demonstrate the tendencies along the African coast. This dependence of dust aerosolization and transport on the strength of the ''onshore'' monsoon flow has been observed before, although on much larger time scales. *Chaipello et al.* [1995] found that during the Northern Hemisphere winter months this near-surface onshore flow could weaken, thus allowing low level transport out to sea.

4. Discussion and Conclusions

[16] The vertical distribution of dust in the Caribbean was found to be highly variable during the PRIDE field campaign, with both ''typical SAL'' and lower-level transport of dust being observed. This variability is consistent with the findings of *Smirnov et al.* [2000], who found that the relationship between AOT and surface dust concentration at Barbados was highly variable. This variability was most recently observed by *Formenti et al.* [2001] reporting dust in both elevated ''SAL'' and planetary boundary layers for several days in March 1998 when dust was transported into the Amazon Basin. Interestingly, they found both patterns within 1 day of each other making any ''seasonal'' or a-priori estimations of the vertical profile of dust very uncertain. Thus, while the ''typical'' SAL transport pattern with dust concentrated aloft is common in the summer transport season, it is likely that African dust can dominate marine boundary layer aerosols.

[17] The presence of dust in the marine boundary layer at Puerto Rico was not correlated with any ''typical'' atmospheric sounding profile; in particular it did not correlate with the strength of the trade inversion in the Caribbean. However, atmospheric soundings at Dakar suggest that the vertical distribution of dust in the Caribbean is connected with the presence or absence of onshore flow and subsequent trade inversion in the planetary boundary layer on the coast of Africa.

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