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Satellite and in situ estimates of dust deposition in the tropical North Atlantic

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Abstract

The annual mean, seasonal cycle, and spatial distribution of dust deposition to the tropical North Atlantic Ocean is estimated for the 2000-2013 period using satellite retrievals of aerosol optical depth and rainfall and winds from an atmospheric reanalysis. It is found that annual mean deposition peaks in the eastern basin and decreases westward to the Caribbean, but remains nearly constant in a northeast-southwest band from Africa to northeastern South America due to a southwestward increase in wet deposition. Summed over the entire tropical North Atlantic, we find that 191 Tg of dust are deposited into the ocean each year on average, 118 Tg of which is deposited in boreal summer. These estimates are toward the upper range of values reported in previous studies. Indirect measurements of deposition from several moorings in the eastern and central basin generally agree with the spatial distribution and seasonality of deposition from the satellite/reanalysis technique.

Keywords: Dust deposition; tropical Atlantic; MODIS; PIRATA.

1. Introduction

The tropical North Atlantic Ocean is downwind from the Sahara and Sahel regions of Africa, which together are the earth's largest source of mineral dust (Prospero et al., 2002). About half of the dust that is transported westward from Africa is deposited into the tropical North Atlantic Ocean (Kaufman et al., 2005), where it modifies biogeochemistry and carbon export (Tagliabue et al., 2014). Recent studies also suggest that dust deposition in the Atlantic intertropical convergence zone (ITCZ) controls the latitudinal distribution of nitrogen fixation through its supply of iron and phosphorus to the ocean's mixed layer (Schosser et al., 2014). African dust that is transported across the Atlantic during boreal winter and spring provides essential nutrients for the Amazon rainforest (Swap et al., 1992).

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Despite its importance for ocean biogeochemistry and for understanding the atmospheric dust budget, there are large uncertainties in the amount of African dust that is deposited into the tropical Atlantic Ocean. Most previous basin-scale estimates rely on numerical model simulations and vary by a factor of two, from 143 Tg to 284 Tg (Kaufman et al, 2005).

In this study we estimate dust deposition to the tropical North Atlantic Ocean and Caribbean based on a 13-year record of satellite aerosol optical depth. Deposition is calculated at each satellite grid point, giving seasonal maps of the annual mean and seasonal variability. We also assess where the satellite-based method is likely to give the most reliable results. Finally, we compare the satellite-based estimates to more qualitative indirect estimates from an array of moorings in the central and eastern tropical North Atlantic and show that in general there is good agreement in the annual mean spatial structure.

2. Data and methods

We use daily aerosol optical depth and fine mode fraction from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS), available on a 1° grid from March 2000 through February 2013. Daily-averaged winds are available from the NCEP/NCAR reanalysis on a 2.5° grid, and daily precipitation was obtained from the Tropical Rainfall Measuring Mission (TRMM) satellite instrument on a 0.5° grid. The wind and rainfall data sets are available for the same period as MODIS and were interpolated to the 1° MODIS grid.

To calculate bulk (i.e., wet plus dry) deposition at each MODIS grid point, we follow the methodology of Kaufman et al, (2005), but with several modifications. First, in addition to the zonal divergence of dust transport, we consider meridional divergence and temporal changes in dust mass:

$$D = -\nabla \cdot (M\mathbf{v}) - \frac{\partial M}{\partial t}$$

Here *D* represents bulk surface deposition, *M* is the mass concentration (total mass of dust in the atmosphere per unit area), calculated from the dust optical depth (τ_{du}) following Kaufman et al. (2005), and $\boldsymbol{v}$ is the horizontal component of the wind at the level of the dust. In (1), deposition occurs when the sum of dust transport convergence (first term on the right) and the rate of change of dust mass with time (second term on the right) is positive.

We made several other modifications to the Kaufman et al. (2005) method. Based on the MODIS fine mode fraction averaged between 12°N-20°N during July-August 2000-2012, we found a fraction of fine aerosol for pure dust (f_{du}) of 0.3, smaller than reported by Kaufman et al. (2005). As dust is transported westward from Africa, large particles settle more rapidly than small particles (Maring et al., 2003). We therefore allow M/τ_{du} (and *M*, assuming that the light extinction efficiency is constant with particle radius) to decrease linearly by 10% from 16°W to 25°W and by an additional 15% between 25°W and 60°W. Recent studies show a strong seasonality in the average height of the dust layer (e.g., Generoso et al., 2008). Following their results, we allow the pressure levels at which $\boldsymbol{v}$ is calculated in (1) to vary seasonally. During June-September a pressure of 700 hPa is used. During October-February a pressure of 900 hPa is used, lower than in Kaufman et al. (2005).

In order to separate wet deposition from dry deposition, we use daily measurements of rain rate from TRMM. Missing values are filled with the daily climatological rain rate (1998-2012) at that grid point. For a given MODIS grid point and day, if rainfall exceeds the threshold of 0.02 mm hr^{-1} (0.5 mm for the day), then the deposition on that day at that grid point is classified as wet. This is likely an upper bound on wet deposition based on the assumption that all deposition on a given day with rainfall is wet deposition, even if it was not raining for the entire day.

Independent estimates of dry deposition are obtained from the dust accumulation biases in the surface shortwave radiation records from several Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) moorings in the tropical North Atlantic (Foltz et al., 2013). The negative shortwave biases caused by dust buildup are first converted to a dust aerosol optical depth using a lookup table and following Foltz et al. (2013). Dust mass concentration is then calculated from the resultant τ_{du} values, following Kaufman et al. (2005) with the modifications described above. The resultant daily time series of dust buildup (M_{buoy}) are interrupted by rainfall, which rinses the radiometer domes, and annual mooring servicing cruises, during which the radiometers with dust buildup are swapped out for new ones. At most mooring locations there are several months with continuous records of dust buildup, generally from November-January, after the rainy season has ended, until the start of the next rainy season in June-August.

The daily time series of M_{buoy} from each mooring is first smoothed with a 7-day running mean filter. To calculate annual mean deposition, the value of the smoothed M_{buoy} at the start of each calendar year is subtracted from the maximum value of the smoothed M_{buoy} within the same calendar year. This gives the maximum dust buildup (in g m^{-2}) for a given calendar year. The maximum dust buildup is divided by the length of time during which the buildup occurred in order to estimate the rate of deposition onto the radiometer. A similar technique is used to calculate seasonal deposition.

3. Results

In this section we first describe the annual mean fields of τ_{du} and winds, then present the annual mean and seasonal variability of deposition estimated from MODIS and from the PIRATA moorings. The annual mean τ_{du} shows a maximum of 0.4 centered at about 15°N off the coast of Africa and a westward decrease to 0.1 at the entrance to the Caribbean (Fig. 1a). There is also a ~5° southward shift in the latitude of maximum τ_{du} across the basin, consistent with the southward component of the trade winds and the concentration of dust lower in the atmosphere during boreal winter and spring. Annual mean dust deposition shows a similar southward shift in its maximum, from about 15°N off the coast of Africa to 10°N at 50°W (Fig. 1b). Dust deposition generally decreases westward, consistent with τ_{du}, but the decrease in deposition is less pronounced, especially between 30°W and 50°W. There is a sharp meridional gradient of deposition at the approximate latitude of the center of the ITCZ (8°N at 20°W and 5°N at 50°W), consistent with weaker winds and higher rainfall limiting dust transport and deposition to the south of the ITCZ.

There is a band of slightly negative values of deposition at 20°W between 12°N and 20°N that is caused by southward winds in the presence of southward-increasing τ_{du}, resulting in meridional divergence of dust mass (Fig. 1b). The dust mass divergence may be caused by our use of an oversimplified and meridionally uniform dust height. There is a larger region of negative deposition in the eastern basin between 0°-5°N that is also due to horizontal divergence of dust mass. Our basinwide estimates of dust deposition are therefore likely a lower bound on the true deposition since they include these nonphysical negative values.

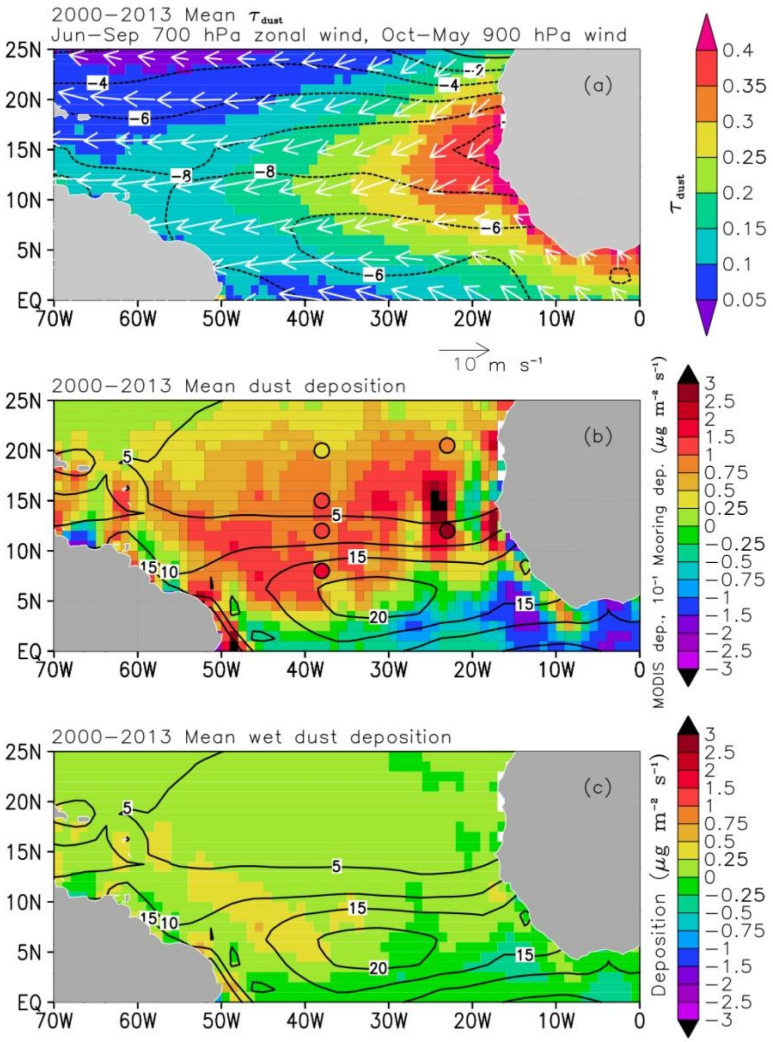

Fig. 1. Annual mean values for 2000-2013. (a) MODIS dust optical depth (shaded), NCEP reanalysis 900 hPa winds (arrows), and 700 hPa zonal wind (contours, m s^{-1}). (b) Bulk deposition estimated from MODIS (shaded) and from the PIRATA moorings (shaded circles). Note that the scale for the mooring estimates is a factor of ten smaller compared to the scale for the MODIS estimates. Contours are rainfall from TRMM (cm mo^{-1}). (c) Wet deposition estimated from MODIS (shaded) and rainfall (contours).

Deposition estimates from the PIRATA moorings are generally about a factor of ten lower than the satellite estimates (Fig. 1b). This is not surprising, since the mooring estimates generally cover only the first half of each year, are comprised entirely of dry deposition, and are based on the amount of dust that sticks to a curved dome. Nevertheless, the spatial pattern of deposition from the moorings agrees reasonably well with that from the MODIS analysis. Both analyses show the highest values in the eastern basin south of 20°N and lower values to the north and west. The similar spatial patterns between the mooring dry deposition and satellite bulk deposition suggest that dry deposition may dominate in the eastern and central tropical North Atlantic, consistent with the satellite-based results, which show very low values of wet deposition (generally less than 20% of the bulk deposition) in the eastern half of the tropical North Atlantic (Fig. 1c). Wet deposition reaches a maximum in the western basin between 5°N-15°N, where mean rainfall is high (>5 cm mo^{-1}) and bulk deposition rates are high (>1 μg m^{-2} s^{-1}).

There are pronounced seasonal variations in τ_{du} and winds in the tropical Atlantic, which lead to a strong seasonal cycle in deposition. The highest rates of dust deposition are concentrated between 5°N-15°N during boreal winter, spring, and fall, and between 10°N-25°N in the summer (Fig. 2). The dry deposition estimates from the PIRATA moorings generally agree with the seasonality found in the MODIS data (Fig. 2). The highest values of deposition move northward from 8°N-15°N during December-May to 15°N-20°N during June-August (Fig. 2a-c).

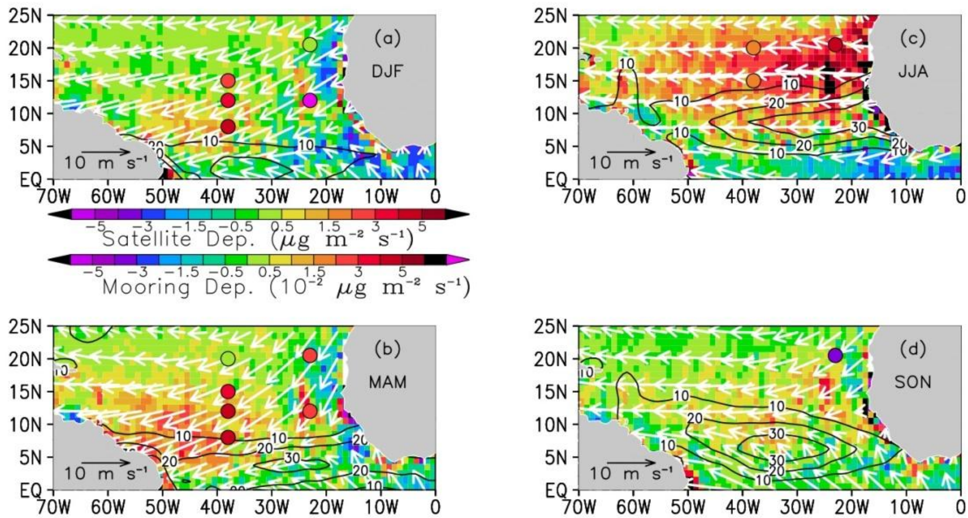

Fig. 2. Seasonal mean values for 2000-2013. (a) MODIS deposition (shaded), TRMM rainfall (contours, cm mo-1), 900 hPa winds (arrows), and PIRATA deposition (shaded circles) during December-February. Note that the scale for the mooring estimates is a factor of 100 smaller compared to the scale for the MODIS estimates. (b) Same as (a) except March-May. (c) Same as (a) except June-August and arrows are 700 hPa winds. (d) Same as (a) except September-November

Summed over the tropical North Atlantic Ocean (0°-25°N, 15°W-60°W), we find a strong seasonal cycle in bulk deposition, with a pronounced peak of 118 Tg in boreal summer, representing 62% of the annual deposition (Table 1). Bulk deposition is similar in boreal spring and winter, and these seasons combined account for 35% of the annual deposition. Total deposition in the tropical Atlantic is found to be 191 Tg, which is 36% larger than found by Kaufman et al. (2005) using MODIS τ_{du} and zonal winds. We find that wet deposition accounts for only 17% of the annual total in the tropical Atlantic. This low amount is surprising, especially since our very simple method of calculating wet deposition is expected to yield an upper bound. The median global wet deposition from AeroCom models is 28% of the total deposition, and this global total includes land areas where rainfall is very low (Huneeus et al., 2011).

Table 1. Dust deposition estimates from the MODIS technique, summed for the tropical North Atlantic (first column), Caribbean (second column), and the sum of both (third column). The 2000-2013 annual mean totals are shown for bulk (first row) and wet (second row) deposition and divided into seasons (third-sixth rows).

	Atlantic (0°-25°N)	Caribbean	Total
Annual bulk	**191 Tg**	**33 Tg**	**224 Tg**
Annual wet	32	8	40
DJF bulk	6	2	8
MAM bulk	38	13	51
JJA bulk	118	17	135
SON bulk	29	1	30

4. Summary

We estimated dust deposition to the tropical North Atlantic Ocean using MODIS satellite retrievals of dust optical depth and winds from an atmospheric reanalysis. In contrast to previous satellite-based estimates, which calculated only the total (wet plus dry) deposition along specific longitudes, we estimated deposition on a 1° grid and attempted to separate into wet and dry components based on satellite rainfall. Summed over the entire tropical North Atlantic, we found that 191 Tg of dust are deposited into the ocean each year on average during the 2000-2013 period.

The spatial variability of annual dust deposition from several PIRATA moorings generally agrees with that from the MODIS estimates, both showing maximum values near the Cape Verde islands, decreasing northward and westward. The seasonality also generally agrees, with the highest deposition rates located farther north in boreal summer compared to boreal winter and spring. It therefore may be possible to obtain more quantitative estimates of deposition from the moorings going back to the late 1990's with the addition of direct measurements of deposition at the mooring sites. With concurrent direct and indirect (i.e., from shortwave biases) measurements a correction could be applied to the indirect estimates to account for dust loss. Direct measurements at the mooring sites would also be useful for validating the MODIS-based estimates and for improving dust transport models.

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