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Key Points:
- About 28 Tg of Saharan dust is deposited into the Amazon yearly
- African dust plays an important role in preventing phosphorus depletion
- Ambiguity and inconsistency in model-observation comparison is clarified

Supporting Information:
- Tables S1 and S2

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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

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Abstract The productivity of the Amazon rainforest is constrained by the availability of nutrients, in particular phosphorus (P). Deposition of long-range transported African dust is recognized as a potentially important but poorly quantified source of phosphorus. This study provides a first multiyear satellite-based estimate of dust deposition into the Amazon Basin using three-dimensional (3-D) aerosol measurements over 2007–2013 from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). The 7 year average of dust deposition into the Amazon Basin is estimated to be 28 (8–48) Tg a^{-1} or 29 (8–50) kg ha^{-1} a^{-1}. The dust deposition shows significant interannual variation that is negatively correlated with the prior-year rainfall in the Sahel. The CALIOP-based multiyear mean estimate of dust deposition matches better with estimates from in situ measurements and model simulations than a previous satellite-based estimate does. The closer agreement benefits from a more realistic geographic definition of the Amazon Basin and inclusion of meridional dust transport calculation in addition to the 3-D nature of CALIOP aerosol measurements. The imported dust could provide about 0.022 (0.006–0.037) Tg P of phosphorus per year, equivalent to 23 (7–39) g P ha^{-1} a^{-1} to fertilize the Amazon rainforest. This out-of-basin phosphorus input is comparable to the hydrological loss of phosphorus from the basin, suggesting an important role of African dust in preventing phosphorus depletion on timescales of decades to centuries.

1. Introduction

The Amazon rainforest represents about half of the planet's remaining rainforests and is an important ecosystem that plays a crucial role in regulating the Earth's climate. Relatively small changes in the forest cover and productivity could have important implications for the carbon cycle, atmospheric circulations, the hydrology cycle, and climate from regional to global scales [*Shukla et al.*, 1990; *Nepstad et al.*, 2008; *Malhi et al.*, 2008]. Phosphorus (P) is the principal fertility factor influencing tree growth across the Amazon Basin [*Vitousek*, 1984; *Mercado et al.*, 2011]. However, 90% of soils in the Amazon Basin are P deficient [*Sanchez et al.*, 1982]. It has been suggested that long-term productivity of the Amazon rainforest depends highly on the atmospheric deposition of dust that may come from a distant ecosystem such as the Saharan desert [*Okin et al.*, 2004]. Although the presence of African dust in the Amazon Basin has long been observed [*Artaxo et al.*, 1990; *Talbot et al.*, 1990; *Formenti et al.*, 2001; *Schafer et al.*, 2008; *Ansmann et al.*, 2009; *Ben-Ami et al.*, 2010; *Baars et al.*, 2011, 2012], the dust deposition and associated P input are not yet well quantified. Recently, advanced satellite observations with routine sampling and large spatial and temporal coverage have become ideal for quantifying the intercontinental transport and deposition of aerosol [*Kaufman et al.*, 2005; *Yu et al.*, 2008, 2012a, 2013]. Substantial discrepancies still exist between measurements and models [e.g., *Swap et al.*, 1992; *Kaufman et al.*, 2005; *Bristow et al.*, 2010; *Ridley et al.*, 2012].

Factors contributing to the large discrepancies in the dust deposition are not fully understood or at least not adequately accounted for. There are several possible reasons for the large range of discrepancy between

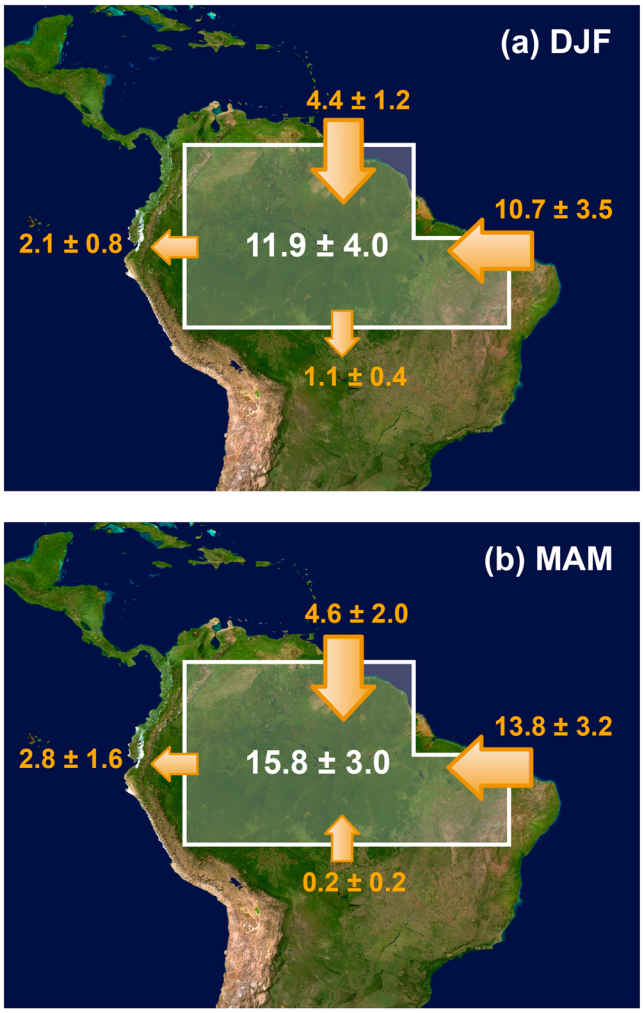

Figure 1. CALIOP-estimated seasonal dust mass fluxes (orange color, mean $\pm 1\sigma$, σ represents the standard deviation over the 7 years) across the boundaries of the Amazon Basin (white lines) and the estimated dust deposition (white color) in the basin: (a) DJF and (b) MAM. All numbers have a unit of Tg.

the different estimates of dust deposition into the Amazon Basin. First, each individual estimate is subject to specific uncertainties, some large. In addition, the intercomparisons have often been complicated by issues such as differences in geographical definition of the Amazon Basin, year of the assessment, and inclusion or exclusion of meridional transport.

The main objective of this study is to resolve the previous discrepancies and provide an alternative satellite-based estimate of dust deposition and phosphorus input into the Amazon Basin. We base our estimate on 3-D distributions of aerosols from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) from 2007 to 2013. Since June 2006, CALIOP has been measuring 3-D distributions of backscatter, extinction, and depolarization ratio of both clear-sky aerosol and above-cloud aerosol over nearly global scale [*Winker et al.*, 2013; *Yu et al.*, 2012b; *Yu and Zhang*, 2013; *Liu et al.*, 2015]. The previous standard for satellite estimates of dust deposition used the Moderate Resolution Imaging Spectroradiometer (MODIS) that provides only a two-dimensional view of the transport [*Kaufman et al.*, 2005]. By using 3-D measurements from CALIOP, the MODIS uncertainties can be reassessed or reduced. Another improvement over the single-year study of *Kaufman et al.* [2005] is the use of a multiyear data set. We also improve the dust deposition estimate by accounting for both zonal and meridional transport and defining the geographical region of the Amazon Basin more realistically. Note that *Kaufman et al.* [2005] neglected the meridional transport and included deposition into the nearby ocean by defining their domain as a rectangle. Both simplifications will introduce significant discrepancies in the estimates of seasonal and annual dust deposition into the Amazon Basin and require clarification to resolve the ambiguity and inconsistency in model-observation comparisons and the role of African dust in the biogeochemical cycle of the Amazon.

2. Methodology

We define the Amazon Basin as a region between 12°S and 8°N in latitude and between 75°W and 40°W (for the 12°S–2°S latitudinal segment) or 50°W (for the 2°S–8°N latitudinal segment) in longitude, as illustrated in Figure 1 (i.e., the white-line boundaries). The total area of the region is about 9.6×10^8 ha. This definition attempts to cover the major part of the Amazon Basin, while excluding the nearby ocean in the analysis, and without introducing too much complexity. We estimate the meridional dust mass flux at the latitudinal cross sections and the zonal flux at the longitudinal cross sections by using CALIOP measurements of the 3-D distribution of aerosol backscatter/extinction and depolarization at 532 nm (version 3, level 2) in both

clear-sky and above-cloud conditions. The dust mass flux in all-sky conditions was calculated as a weighted average of clear-sky and above-cloud dust mass flux with respective fraction of occurrence. While details of calculating dust mass fluxes with CALIOP measurements are described in *Yu et al.* [2015], a brief overview of the approach is given as follows.

We use CALIOP nighttime, high-quality data only and separate dust from nondust aerosol by using the CALIOP depolarization ratio (δ) measurements with a priori knowledge of characteristic depolarization ratios for dust and nondust particles. This step is necessary because a mixture of dust and tropical African smoke is often transported across the ocean to the Amazon Basin in boreal winter and spring [*Ansmann et al.*, 2009; *Baars et al.*, 2011; *Yang et al.*, 2013]. There is a range of δ values associated with dust and nondust aerosol. As discussed in *Yu et al.* [2015], we bound the range of dust fraction introduced by variability in δ and use an average of dust mass fluxes between the upper and lower bounds to represent the best estimate of dust transport and deposition. The difference between the best estimate and the bounds represents an uncertainty associated with the dust discrimination. The CALIOP-based estimate of dust mass flux is also subject to uncertainties associated with CALIOP extinction, vertical profile shape, dust mass extinction efficiency, and possible change of dust size distribution during the transport. The cumulative uncertainty of all these error sources has been estimated to be ±70%, near South America and the Caribbean Sea [*Yu et al.*, 2015]. Additional uncertainty may arise from the below-cloud dust missed by CALIOP and possible diurnal variations of dust transport, which, however, cannot be quantified because of the lack of reliable observations [*Yu et al.*, 2015].

Dust transport and deposition to the Amazon Basin is predominated by the trans-Atlantic transport in the northeasterly trade winds during boreal winter (December-January-February or DJF) and spring (March-April-May or MAM) [*Prospero et al.*, 1981; *Swap et al.*, 1992; *Prospero et al.*, 2014]. In boreal summer and fall when the Intertropical Convergence Zone moves northward, the majority of dust is transported by the easterly trade winds to the Caribbean Sea and North America [*Prospero et al.*, 1981, 2014]. Our analysis of CALIOP observations derives a 7 year average dust deposition into the Amazon of −0.22 Tg (ranging from −1.51 to +1.97 Tg) in boreal summer and fall. The negative deposition fluxes are not physical and could have resulted from a differentiation of small fluxes at the boundaries of the Amazon Basin. Thus, we assume the dust deposition into the Amazon Basin is negligible in boreal summer and fall, similar to *Swap et al.* [1992]. Subsequent discussion will be focused on the dust deposition in DJF and MAM.

3. Results and Discussion

3.1. CALIOP-Based Estimate of Dust Deposition Into the Amazon Basin

We calculate dust import to and export from the Amazon Basin in both zonal and meridional directions. The divergence of dust import and export mass fluxes is attributed to dust deposition into the Amazon Basin. Figure 1 shows the budget of CALIOP best estimate of seasonal dust transport (numbers in orange) and deposition (numbers in white) into the Amazon Basin. The numbers represent the 7 year average ± 1 standard deviation of the estimates. Dust fluxes in individual years are listed in Table S1 in the supporting information. In boreal winter, dust import from zonal (eastern boundary) and meridional (northern boundary) directions is 10.7 ± 3.5 Tg and 4.4 ± 1.2 Tg, respectively. In boreal spring, the corresponding zonal and meridional import of dust is 13.8 ± 3.2 Tg and 4.6 ± 2.0 Tg, respectively. Clearly, the meridional mass flux entering the basin from the northern boundaries accounts for 33–41% of the zonal mass flux through the eastern boundaries and cannot be neglected. A large majority of the dust import (e.g., 79–86%) is deposited in the basin. The dust deposition in the basin is 11.9 ± 4.0 Tg and 15.8 ± 3.0 Tg in DJF and MAM, respectively. On a basis of the 7 year average, the annual dust deposition into the Amazon Basin amounts to 27.7 Tg a^{-1} (equivalent to 28.9 kg ha^{-1} a^{-1}).

The multiyear CALIOP observations used in this study reveal interannual variation of dust deposition into the Amazon Basin. Figure 2a shows the CALIOP-based best estimate of dust deposition flux in DJF (blue bar) and MAM (red bar) in individual years. The gray error bar indicates the range of DJF + MAM combined dust deposition estimates introduced by uncertainty in separating dust from nondust aerosol. It shows that the year-to-year values can vary by as much as 29% of the 7 year mean. The dust deposition in DJF and MAM, combined, ranges from 14.3 to 20.9 Tg and 33.6 to 43.2 Tg, for the lower and upper bounds, respectively. The figure also shows that the relative contribution from DJF and MAM appears to be dependent on year.

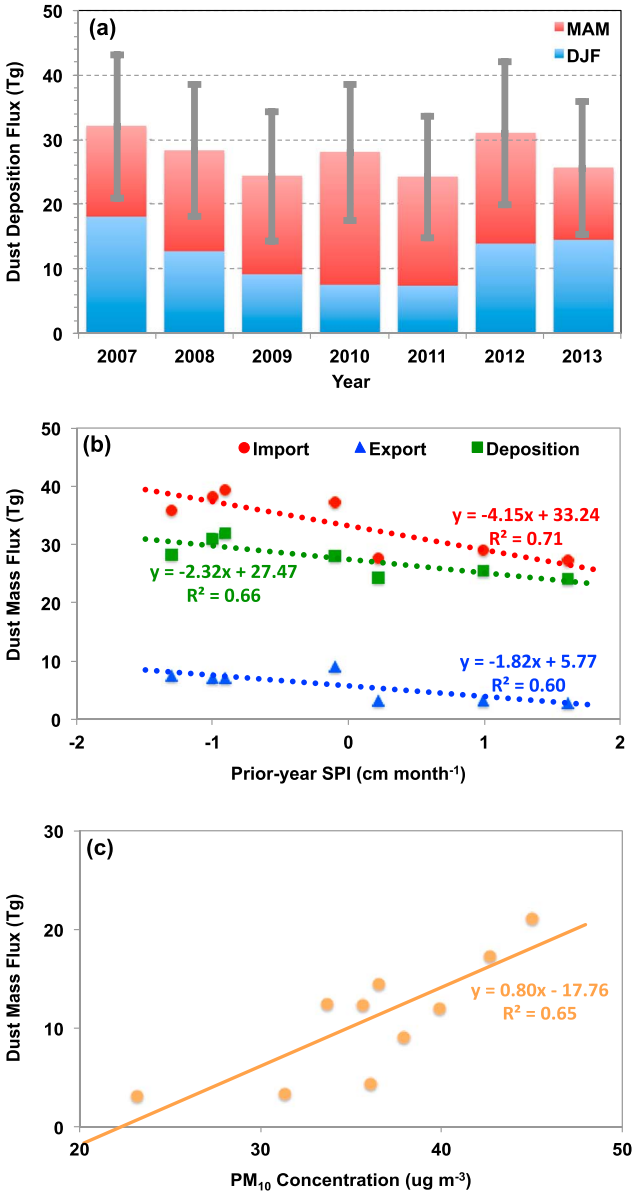

Figure 2. (a) CALIOP estimates of dust deposition (Tg) into the Amazon Basin. The wide stacked color (blue for DJF and red for MAM) bars represent mean dust deposition, while error bars indicate the lower bound and upper bound of DJF + MAM combined dust deposition associated with the dust discrimination schemes (refer to *Yu et al.* [2015]). On a basis of a 7 year average, the best estimate of dust deposition into the Amazon Basin amounts to 28 Tg for DJF and MAM combined. (b) Correlation of CALIOP-estimated DJF + MAM total dust import to, export from, and deposition into the Amazon Basin with prior-year Sahel Precipitation Index (SPI). (c) Correlation of CALIOP-estimated seasonal dust mass flux in zonal direction into the Amazon Basin with PM_{10} concentration measured at Cayenne (4.95°N, 52.31°W), French Guiana, over the period of 2007–2011.

In 2007 and 2013, the dust deposition in DJF was larger than that in MAM, contrary to the seasonal variation in the other years. Our analysis (Table S2 in the supporting information) suggests that this difference is mainly determined by dust emissions in the source regions.

The interannual variation of dust deposition is generally regulated by variations in African dust emissions, atmospheric circulations, and rainfall along the dust transport route [*Prospero and Lamb*, 2003; *Chin et al.*, 2014; *Yu et al.*, 2015]. *Yu et al.* [2015] found that the annual trans-Atlantic dust transport over the period of 2007–2013 has a statistically significant anticorrelation with the prior-year wet season rainfall anomaly in the Sahel or the so-called Sahel Precipitation Index (SPI) [*Janowiak*, 1988]. Similarly, we examined how the annual dust transport and deposition into the Amazon Basin correlate with the prior-year SPI, as shown in Figure 2b. Clearly, the annual dust transport and deposition are anticorrelated with the prior-year SPI, which is statistically significant at the 95% confidence level. For the dust import to the basin from the northern and eastern boundaries, the value of R^2 (R is correlation coefficient) is 0.71. The dust deposition into the basin and export from the basin show slightly weaker anticorrelation with SPI, with R^2 of 0.66 and 0.60, respectively. This may suggest that the variation of dust deposition into the Amazon Basin is largely associated with that of prior-year Sahel rainfall condition. We did not find statistically significant correlation between the estimated DJF + MAM dust deposition and the rainfall rate in the northern part of the Amazon Basin (2°S–8°N, 50°W–75°W), with $R = 0.426$ or $R^2 = 0.182$.

The seasonal mean dust import to the Amazon Basin estimated from CALIOP observations is correlated with surface particulate matter $(PM)_{10}$ measurements at Cayenne, French Guiana (4.95°N, 52.31°W) during 2007–2011 [*Prospero et al.*, 2014], as shown in Figure 2c. As discussed in *Prospero et al.* [2014], the PM_{10} level at Cayenne is a good measure of dust import into South America. The R^2 between CALIOP seasonal dust mass flux and PM_{10} concentration is 0.65, which is statistically significant at the 95% confidence level.

Table 1. Comparison of GOCART Simulated Dust Deposition (Tg) Into the Amazon Basin (White Boundaries in Figure 1a) With the CALIOP-Based Best Estimate of Dust Deposition[a]

Year	2007		2008		2009		2007–2009 Average	
Season	DJF	MAM	DJF	MAM	DJF	MAM	DJF	MAM
CALIOP	18.0 (11.2–24.8)	14.0 (9.7–18.4)	12.7 (7.6–17.8)	15.6 (10.5–20.7)	9.1 (5.0–13.2)	15.2 (9.3–21.2)	13.3 (7.9–18.6)	15.0 (8.9–20.1)
GOCART	12.6	10.4	7.3	10.9	4.8	9.6	8.2	10.3

[a]Shown in parentheses is the range of CALIOP estimates bounded by the dust discrimination scenarios (refer to *Yu et al.* [2015]).

In summary, on the basis of the 2007–2013 average, the CALIOP-based best estimate of dust deposition into the Amazon Basin is 28 Tg a^{-1}, ranging from 8 to 48 Tg a^{-1} when accounting for the estimated uncertainty of ± 70% [*Yu et al.*, 2015]. The interannual variation of dust deposition is anticorrelated with the prior-year wet season Sahel rainfall. The CALIOP-based estimate of dust import to the Amazon Basin is also well correlated with surface aerosol measurements at Cayenne. In the following we further compare the CALIOP-based estimate of dust deposition with simulation from the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model and other estimates in literature.

3.2. Comparisons of CALIOP-Based Dust Deposition Estimate With Models and Other Observations

The CALIOP-based estimate of dust deposition is compared with the GOCART model simulation in the same region for 2007–2009. The GOCART is a global chemical transport model that simulates major aerosol types including dust [*Chin et al.*, 2002]. A multidecadal (1980–2009) run was performed at a horizontal resolution of 2° in latitude by 2.5° in longitude [*Chin et al.*, 2014]. In GOCART, the dust deposition to the surface is calculated due to aerodynamic dry deposition, gravitational settling, and scavenging by large-scale and convective clouds with parameterized schemes [*Chin et al.*, 2002]. The GOCART model suggests that wet removal accounts for about 86% of the total dust deposition in the region during DJF and MAM. The GOCART model also reveals a high heterogeneity of dust deposition in the basin. The deposition north of 2°S accounts for 80–92% of the total deposition in the basin in DJF and MAM, because dust is injected into the basin from the northeast coast of South America and precipitation is much stronger in the northern part of the basin than the southern part.

Table 1 shows a comparison of the CALIOP-based estimates of seasonal dust deposition with the GOCART model simulations during 2007–2009. On a seasonal basis the GOCART-calculated dust deposition is 26–47% lower than the best estimate from the CALIOP observation. CALIOP and GOCART also show the same interannual variation during the 3 year period. On the basis of the 3 year average, dust deposition for DJF and MAM combined is 18.5 Tg from GOCART model, which is 35% lower than the CALIOP 2007–2009 average of 28.3 Tg. However, the GOCART model also simulates a dust deposition of 6.6 Tg in boreal summer and fall combined, when the CALIOP-derived estimate of dust deposition is nearly 0.

A comparison of annual dust deposition between the CALIOP-based estimate and those in the literature [*Swap et al.*, 1992; *Ridley et al.*, 2012] as well as GOCART [*Chin et al.*, 2014] and Weather Research and Forecasting model coupled with chemistry (WRF-Chem) [*Zhao et al.*, 2013] simulations is summarized in Table 2. We calculate the GOCART and WRF-Chem dust deposition into the same region as defined in Figure 1.

Table 2. Summary of Comparisons of CALIOP-Based Estimates of Annual Dust Deposition Into the Amazon Basin With Those in the Literature[a]

Source	Total Dust Deposition (Tg)	Dust Deposition Per Area (kg ha^{-1})	Averaging Region and Years	References
CALIOP	28 (8–48)	29 (8–50)	see Figure 1 for the defined region; 2007–2013 average	This study
MODIS	50	n/a	[20°S–10°N, 35°W–75°W]; 2001	*Kaufman et al.* [2005]
In situ observations	13 (9–19)	190	assuming all the imported dust is deposited in a small area of Central Amazon Basin; 1987	*Swap et al.* [1992]
GOCART model	26	27	same region as the CALIOP estimate; 1980–2009 average	This study and *Chin et al.* [2014]
WRF-Chem model	19	20	same region as the CALIOP estimate; 2011–2013 average	This study and *Zhao et al.* [2013]
GEOS-Chem model	17	n/a	10°S–10°N land only (similar to the CALIOP estimate); 2006–2008 average	*Ridley et al.* [2012]

[a]GEOS-Chem = Goddard Earth Observing System coupled with chemistry.

Apparently, the CALIOP-based estimate of 28 (8–48) Tg falls in between the MODIS-based estimate of 50 Tg [*Kaufman et al*., 2005] and those estimated from in situ observations and model simulations (13–26 Tg). However, the apparent discrepancies shown in the table should not be attributed to the uncertainties associated with individual methods or data, because such a comparison is complicated by differences in regions and years among the studies (see notes in the table).

We use the correlation between dust deposition and SPI (Figure 2b) to extrapolate the CALIOP-derived values back to the same years as previous studies listed in Table 2. The SPI values for 1986 (a year prior to the in situ observation in *Swap et al*. [1992]) and 2000 (a year prior to the MODIS estimate in *Kaufman et al*. [2005]) are −2.04 and −1.25, respectively. Applying the regression equation from Figure 2b, the dust depositions would have been 32 and 30 Tg in 1987 and 2001, respectively. These extrapolated values decrease the discrepancy between MODIS and CALIOP by only 9% and increase the discrepancy between the in situ estimate and CALIOP by 27%. Differences in years cannot explain the discrepancies in studies.

Can the definition of the Amazon Basin and the exclusion of meridional transport in *Kaufman et al*. [2005] explain the discrepancy in dust deposition? The estimate by *Kaufman et al*. [2005] was made in a region of [20°S–10°N, 35°W–75°W]. In contrast to that defined in Figure 1 and in other studies, this region includes a portion of tropical Atlantic Ocean just off the northeastern coast of South America where strong scavenging by intense rainfall could prevent a large amount of dust from reaching the Amazon Basin. In addition, the MODIS estimate considered the zonal transport of dust only, whereas other estimates accounted for both zonal and meridional transport.

Here we use the CALIOP observations to estimate the dust deposition in the same region as that used in *Kaufman et al*. [2005]. On a basis of the 7 year average applied to the rectangular domain defined in *Kaufman et al*. [2005], the CALIOP-derived net dust transport in the zonal direction alone is 49 Tg, which is nearly the same as the estimate of 50 Tg by *Kaufman et al*. [2005]. We also found that the CALIOP-derived meridional transport adds an additional 24 Tg of dust into the domain of *Kaufman et al*. [2005]. Thus, the total dust deposition, calculated from CALIOP, in the domain of *Kaufman et al*. [2005] amounts to 73 Tg, which is 160% larger than the 28 Tg estimated for the domain defined in Figure 1. The above practice underscores the importance of appropriately defining the basin and including the meridional transport. Improper assumptions, as per *Kaufman et al*. [2005], will overestimate the dust deposition, which could explain a significant portion of the discrepancies documented in literature.

In summary, the CALIOP-based estimate of dust deposition shows a better agreement with in situ measurements and model simulations than the MODIS-based estimate as reported in literature. The closer agreement benefits from a more realistic geographic definition of the Amazon Basin and an inclusion of meridional dust transport, in addition to the 3-D nature of CALIOP measurements.

3.3. Estimate of Phosphorus Input Associated With African Dust and Implications for Amazon Rainforest

Micronutrients such as phosphorus, carried by African dust, can have important implications for the biogeochemical cycle in the Amazon Basin. To estimate the amount of phosphorous associated with the dust deposition of 28 (8–48) Tg a^{-1}, we must obtain the mass concentration of phosphorus in the dust (C_{PD}). Observations at the Bodele depression yielded a C_{PD} of 780 ppm [*Bristow et al*., 2010], while those at Barbados and Miami gave a higher C_{PD} of 880 ppm [*Zamora et al*., 2013]. *Mahowald et al*. [2008] used C_{PD} of 720 ppm in their global model simulation. By using C_{PD} of 780 ppm, we estimate that on the basis of a 7 year average, yearly total P deposition into the Amazon Basin mounts to 0.022 (0.006–0.037) Tg P a^{-1} or equivalent to 23 (7–39) g P ha^{-1} a^{-1}. Given that the dust deposition is highly heterogeneous, phosphorus deposition should be substantially higher in the central Amazon Basin where most of dust deposition is expected. For comparison, *Swap et al*. [1992] estimated a range of 11–47 g P ha^{-1} a^{-1} in a much smaller study area of the central Amazon Basin. Note that our estimated P deposition is subjected to uncertainty associated with C_{PD}. It is possible that C_{PD} may have changed during the long-range transport. The issue could be investigated in the future by extracting dust and associated P from accumulating aerosol measurements in the Amazon Basin [*Artaxo et al*., 2002].

How significant is the P input associated with African dust in the context of the phosphorus cycle in the basin? *Vitousek and Sanford* [1986] summarized that the recycling of phosphorus through litterfall is 1400–4100 g P ha^{-1} a^{-1} in the Amazon Basin, which is 61–178 fold of our best estimate of phosphorus

input associated with dust deposition. The total atmospheric deposition resulting from dust and nondust sources was estimated to be 161–300 g P ha^{-1} a^{-1} [*Vitousek and Sanford*, 1986]. Our estimated P deposition associated with dust accounts for no more than 13% of the total atmospheric deposition. Primarily, biogenic aerosols and biomass burning smoke are thought to contribute the remaining atmospheric phosphorus deposition [*Artaxo et al*., 2002; *Mahowald et al*., 2005]. Therefore, the phosphorus associated with the dust is relatively small as compared with the recycling and the deposition of biogenic and smoke particles. On the other hand, our estimated phosphorus input associated with African dust is comparable to the estimated hydrological loss of 8–40 g P ha^{-1} a^{-1} [*Vitousek and Sanford*, 1986]. This suggests that African dust may have important implication for maintaining the health of Amazon rainforests over the long term. Without the phosphorus input from African dust, the hydrological loss would greatly deplete the soil phosphorus reservoir over a timescale of decades or centuries and affect the health and productivity of the Amazon rainforest.

Finally, we would like to note that the amount of dust needed to provide adequate phosphorus for maintaining the productivity of the Amazon rainforest remains unknown. To quantify the amount, we require a much better understanding of all major components of the phosphorus cycle (including the recycling through litterfall, atmospheric deposition of dust, smoke, and biological particles, and hydrological loss). Currently, our knowledge does not warrant a claim with high level of confidence that there exists a missing source of phosphorus for the Amazon Basin on the order of 50 Tg a^{-1} of African dust as claimed by *Kaufman et al*. [2005] or *Ridley et al*. [2012].

4. Concluding Remarks

This study provides the first multiyear satellite-based estimate of dust deposition into the Amazon Basin. We have estimated from the three-dimensional aerosol distribution derived from the CALIOP 7 year (2007–2013) record that on average 28 (8–48) Tg a^{-1} or 29 (8–50) kg ha^{-1} a^{-1} of dust is deposited into the Amazon Basin during the wet season (e.g., boreal winter and spring). On a seasonal basis, the estimated dust import to the Amazon Basin is well correlated with surface aerosol measurements during 2007–2011 in Cayenne, French Guiana. The dust deposition shows interannual variation of up to 29%, which is negatively correlated with the prior-year rainfall anomaly in the Sahel at the 95% confidence level.

The CALIOP-based multiyear mean estimate of dust deposition agrees better with estimates from in situ measurements and model simulations than the MODIS-based estimate [*Kaufman et al*., 2005] does. The closer agreement benefits from a more realistic geographic definition of the Amazon Basin and the inclusion of meridional dust transport, in addition to the 3-D nature of CALIOP aerosol measurements. These factors could explain a significant portion of the large discrepancies between measurements and models as reported in literature [*Swap et al*., 1992; *Kaufman et al*., 2005; *Ridley et al*., 2012].

We further estimated that the phosphorus (P) input associated with the dust deposition is 0.022 (0.006–0.037) Tg P a^{-1} or 23 (7–39) g P ha^{-1} a^{-1}. Although this phosphorus input originating from outside the basin is 1 to 2 orders of magnitude lower than the atmospheric deposition of smoke and biological particles and the phosphorus recycling via litterfall within the basin, it is comparable to the hydrological loss of phosphorus. This may suggest an important role of African dust in preventing phosphorus depletion on timescales of decades or centuries.

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