Atmospheric
Chemistry
and Physics
Discussions

Evaluating the Relative Importance of Northern African Mineral Dust Sources Using Remote Sensing

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Abstract. Mineral dust from the Sahara and Sahel provides the Amazon Basin with essential nutrients, although the process is still poorly understood. There is little understanding where the dust is coming from, and thus what the concentration of
10 nutrients in the dust is. This information, however, is vital to assess the impact it will have on the Amazon. This study analyses northern African dust sources of the boreal winter dust seasons between the years 2015-2017. It utilises high spatio-temporal resolution remote sensing data from SEVIRI, MODIS, VIIRS and Sentinel-2 to identify dust sources, classify them according to a geomorphic dust source scheme, and quantify the relative importance of source regions by calculating the total dust mass they produce. Results indicate that paleolakes emit the most dust, with the Bodélé Depression as the single largest dust source
15 region, however, that alluvial deposits also produce a substantial amount of dust. During the boreal winter dust seasons of 2015-2017, ~36% of the total dust mass emitted from northern Africa was associated to alluvial deposits, yet this geomorphic category has been relatively understudied to date. Furthermore, sand deposits were found to produce relatively little dust, in contrast to the results of other recent studies.

1 Introduction

20 Mineral dust is an important component of the climate system, affecting radiative forcing, cloud properties, and playing a key role in terrestrial, oceanic, and atmospheric biogeochemical exchanges (Harrison et al., 2001; Jickells et al., 2005; Mahowald et al., 2010). The Sahara and the Sahel are the world's largest dust source regions, emitting several hundred teragrams of mineral dust yearly (Ridley et al., 2012). Most of this dust is carried over large distances and transported west and southwest across the Atlantic Ocean (Chiapello et al., 1997). During boreal summertime dust is blown by the trade winds from northern
25 Africa towards the Caribbean, while during winter it takes a more southerly route towards the Amazon Basin. It has been suggested that this dust has a significant fertilizing effect on the nutrient deficient Amazonian rainforest soils (Swap et al., 1992; Yu et al., 2015). In order to better understand past, current, and future impacts of North African mineral dust on the Amazon Basin, the biogeochemical properties of the dust need to be determined. Recently it has been shown that these

properties differ significantly based on the geology and geomorphology of the terrestrial source (Gross et al., 2015, 2016), and it is therefore critical to identify dust sources and their geomorphic nature precisely.

Previous dust source identification studies have used geochemistry and mineralogy of dust samples, satellite remote sensing techniques, or back trajectory analysis (Schepanski et al., 2012; Scheuvens et al., 2013; Muhs et al., 2014). In the latter case,

5   performance of trajectory models is highly dependent on the initial conditions, and it is restricted by the quality of the input data (Gebhart et al., 2005). Tracing sources using the geochemistry and mineralogy of dust samples proves difficult for Saharan dust, as samples are sporadic in time and space, and transport affects measurements in poorly understood ways (Formenti et al., 2011). Satellite remote sensing on the other hand, provides high spatio-temporal data across the region, and has been found to be an effective method of identifying dust source areas (Prospero et al., 2002; Washington et al., 2003; Schepanski et al.,

10   2012). Notwithstanding this, many remote sensing techniques identify erroneous sources as they average both emission and transport (Prospero et al., 2002; Washington et al., 2003), and thus methods need to be adopted which only identify the site of dust emission (Schepanski et al., 2012; Ashpole & Washington, 2013).

While the major dust source areas within the Sahara and the Sahel have been identified using remote sensing (Prospero et al., 2002; Schepanski et al., 2009; Ginoux et al., 2012; Ashpole & Washington, 2013), less is known about the geomorphology of

15   these sources and their relative importance. Studies analysing the fertilization effect of dust on the Amazon focus primarily on the impact of paleolake Bodélé (Bristow et al., 2010; Yu et al., 2015) as this has been shown to be the most important source region (Koren et al., 2006; Ben-Ami et al., 2010). Latest estimates of phosphorous input into the Amazon are based solely on the phosphorous concentration in Bodélé dust (Yu et al., 2015), but this is unlikely to reflect the diversity of the surfaces producing dust.

20   The aim of this study is to identify wintertime dust sources, as only this dust is transported to the Amazon. The sources are classified according to the geomorphic dust source scheme developed by Bullard et al. (2011), after which the importance of the various dust sources is quantified, and it is calculated how much dust each region produces. This is achieved through a combination of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) dust red, green, blue (RGB) colour composite to identify sources, the Visible Infrared Imaging Radiometer Suite (VIIRS) dust RGB to accurately determine their location,

25   the Moderate-resolution imaging spectroradiometer (MODIS) aerosol optical depth product to quantify how much dust the sources produce, and the high spatial resolution (10 m) Sentinel-2 true colour composite to identify the geomorphology of each source. The study examines the dust storms of the 2015-2017 winter dust seasons. Both the number of individual dust sources of each geomorphological class, as well as the total dust mass emitted per class and dust source region are calculated.

2 Methodology

The study analyses northern African dust sources during boreal wintertime, defined as the area between the longitudes 20°W – 40°E and the latitudes 5°N – 40°N. The dust seasons analysed run between Dec 1st 2015 – Feb 29th 2016 and Dec 1st 2016 – Feb 28th 2017, following the wintertime dust months of Schepanski et al. (2009). Figure 1 provides a complete overview of the data and methodology.
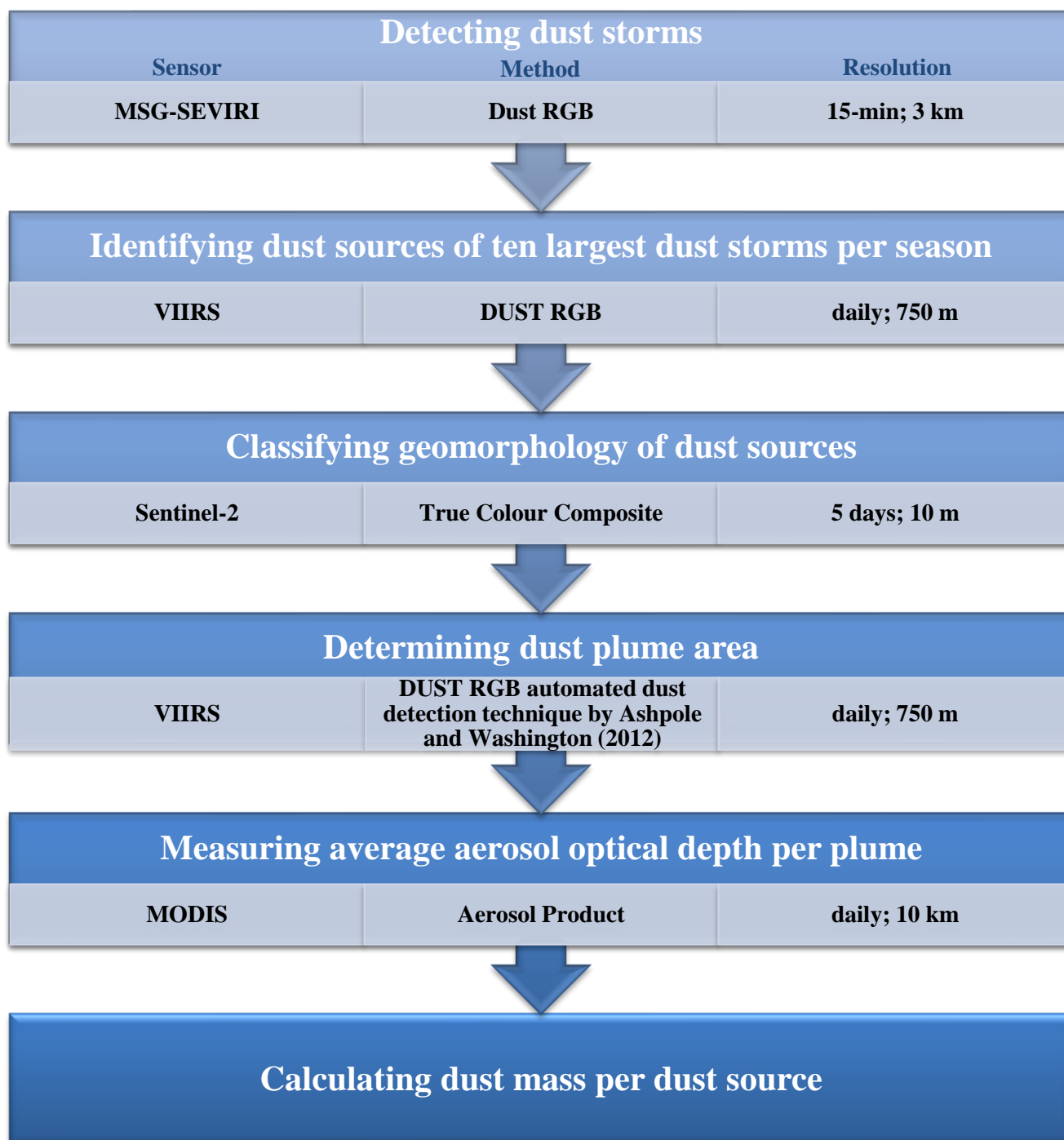
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Atmospheric
Chemistry
and Physics
Discussions

Detecting dust storms		
Sensor	**Method**	**Resolution**
MSG-SEVIRI	**Dust RGB**	**15-min; 3 km**

Identifying dust sources of ten largest dust storms per season		
VIIRS	**DUST RGB**	**daily; 750 m**

Classifying geomorphology of dust sources		
Sentinel-2	**True Colour Composite**	**5 days; 10 m**

Determining dust plume area		
VIIRS	**DUST RGB automated dust detection technique by Ashpole and Washington (2012)**	**daily; 750 m**

Measuring average aerosol optical depth per plume		
MODIS	**Aerosol Product**	**daily; 10 km**

Calculating dust mass per dust source

Figure 1: Overview of the methodology of the study. The remote sensing sensor used in each step is presented in the left column, the image processing method employed is shown in the middle column, and the resolution (temporal; spatial) is shown in the right column.

Atmospheric
Chemistry
and Physics
Discussions

2.1 Detecting dust storms

MSG-SEVRI was utilised to detect dust storms every 15 minutes at a spatial resolution of 3 km at nadir. The dust RGB method of Lensky and Rosenfeld (2008) was employed whereby infrared channels are utilised to produce an image in which dust is portrayed in a pink colour. To achieve this, the red band is allocated the brightness temperature difference (BTD) between

5   channels at 12 - 10.8 µm, green the BTD between channels at 10.8 - 8.7 µm, and blue the 10.8 µm channel. Processed SEVIRI dust RGB images were acquired from the database of the FENNEC project (FENNEC, 2017). By visually interpreting images, all dust events of the 2015-2017 boreal winter dust seasons were identified. Though the high temporal resolution of SEVIRI makes it suitable for observing dust storms (Schepanski 2009, 2012; Ashpole & Washington 2012), its low spatial resolution means it is less suited to determine the location and nature of the sources.

10   ## 2.2 Identifying dust sources

VIIRS was used to identify and map dust sources as it is currently the sensor with the highest spatial resolution that has a daily temporal resolution; it has 5 imaging-resolution bands (I-bands) at 375 m resolution, and 16 moderate-resolution bands (M-bands) at 750 m resolution. The same dust RGB method was employed using the infrared M-bands, centred at 8.55 µm, 10.76 µm, and 12.01 µm. Dust sources were identified manually using visual interpretation, by tracking the individual dust plumes

15   back to their first point of occurrence (illustrated in Figure 2). As this process is relatively labour intensive, this step was performed on only the ten largest dust storms (in spatial extent) of each dust season.
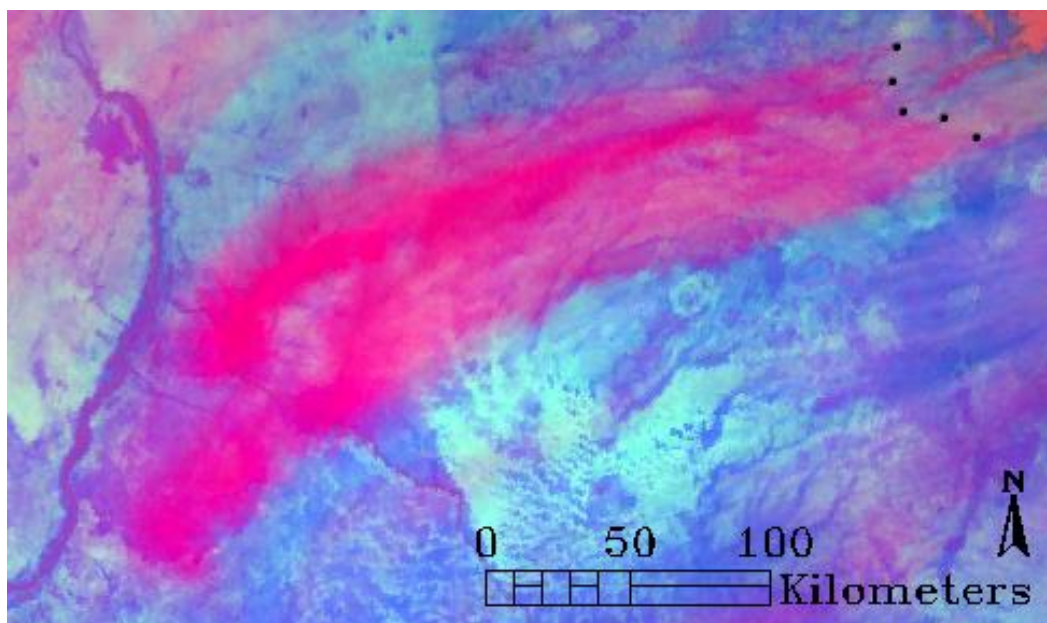
Figure 2: VIIRS Dust RGB showing dust being emitted northeast of the Sudanese Nile (lat: 18, lon: 35) on December 19, 2016. Dust

20   **source locations (black points) are identified by tracking dust plumes back to their first point of occurrence.**

2.3 Classifying geomorphology of dust sources

To determine the geomorphology of the individual dust sources, Sentinel-2 imagery was used. The sensor collects visible, near infrared, and shortwave infrared imagery at a spatial resolution of 10 – 60 meters, and a temporal resolution of 5 days. Using the 10-meter resolution true colour composites, it is possible to distinguish many geomorphic features within the imagery.

5 Cloud free, level 1c Sentinel-2 data was obtained for each of the dust source locations identified from the VIIRS data. Each point source was interpreted and allocated to one of the geomorphic classes described by Bullard et al. (2011). These classes are based on differences in surface characteristics governing their susceptibility of aeolian erosion, provided they met the criteria to be readily identifiable from remote sensing data. The classes from the scheme identified in this study are 'paleolakes', 'alluvial deposits', 'stony surfaces', and 'sand deposits'. Furthermore, the class 'anthropogenic' was added to the classification

10 scheme, defined as dust sources linked to urban areas, villages, roads, and agricultural lands. Drake et al. (2008) demonstrated that the geomorphic classification scheme could characterise dust sources in the Western Sahara region successfully. To account for the spatial resolution differences between VIIRS and Sentinel-2, point sources were classified as the most prominent feature and/or most common geomorphic class within 750 m of the point source.

2.4 Determining dust plume area

15 The dust plume area was calculated for all dust storms in the season using the automated dust detection technique developed by Ashpole and Washington (2012). In this method, the following thresholds are applied to the brightness temperatures (in Kelvin) of the 10.76, 12.01, and 8.55 μm channels of VIIRS imagery:

$$BT\ 10.76 \geq 285$$
$$BTD\ (12.01\text{-}10.76) \geq 0 \tag{1}$$
$$BTD\ (10.76\text{-}8.55) \leq 10$$

Background surface features that were incorrectly detected as dust were removed manually, after which dust plumes could be outlined and their size calculated. The methodology is objective, easily reproducible, fast, and was found to be consistent for

25 moderate-to-heavy dust storms occurring during daytime hours (Ashpole & Washington, 2012). The method was applied to VIIRS, rather than SEVIRI or MODIS, due to its higher resolution and its seamless continuation between swaths.

2.5 Measuring average aerosol optical depth per plume

In order to determine the concentration of dust within the dust plumes, average aerosol optical depth (AOD) per dust plume

30 was calculated. As the VIIRS AOD product was found to contain large data gaps, particularly over bright desert surfaces, the MODIS aerosol product (MOD04_L2) was employed. MODIS monitors AOD on a daily basis at a 10-km spatial resolution,

and combines the MODIS Dark Target (Kaufman et al., 1997; Levy et al., 2013) and MODIS Deep Blue (Hsu et al., 2004) algorithms. MODIS Dark Target uses the spectral radiances between 0.47 and 2.1 µm to measure AOD over oceans and dark land surfaces. MODIS Deep Blue is designed to analyse aerosols over bright-reflecting surfaces, such as deserts, utilizing measurements from the blue wavelengths (412 and 470 nm). The combined algorithms allow MODIS to record data across

5   North Africa consistently (Sayer et al., 2013). It should be noted that dust storm days between 19-27 February 2016 were omitted from this study due to a MODIS technical outage, during which the satellite did not log any data, and there was hence no MODIS AOD data available.

2.6 Calculating dust mass per dust source

Analysis of the dust source locations from the 10 largest dust storms in each dust season showed that a single geomorphological

10 source dominated in most areas. On the basis of this observation, 16 individual dust source regions were identified and mapped. For instance, regions of predominantly paleolake origin were the Bodélé, Bahr el Gazel, and Algeria, and those of predominantly alluvial deposit origin were the Ennedi, Sudan, North Aïr, and Tibesti. The South Aïr and El Eglab regions consisted of a substantial amount of both paleolake and alluvial dust sources in roughly equal amounts, therefore in dust mass calculations it was considered as 50% paleolake, 50% alluvial deposit. Each dust plume was then assigned a geomorphic class

15 based on the region it came from. The accuracy of this methodology was evaluated by randomly selecting three additional days, analysing the geomorphic class of each source, and determining what percentage of these dust sources coincided with that defined by the map of predominant dust geomorphologies.

The dust mass per source region was determined by combining the dust plume area data with the average MODIS AOD. The dust column concentration equation by Kaufman et al. (2005) was applied, whereby dust mass is calculated using the

20 relationship between plume size and average dust AOD at 550 µm:

$$M_{du} = 2.7A\tau_{du} \tag{2}$$

where M_{du} is dust mass, A is the dust plume area, and τ_{du} is the average AOD at 550 µm. The coefficient of 2.7 is derived through the extinction efficiency of 0.37 measured by Haywood et al. (2003), however a more recent review of mass extinction efficiency measurements by Ansmann et al. (2012) shows higher reported values ranging between 0.37- 0.57. An updated

25 Kaufman equation was derived using the extinction efficiency of 0.57, resulting in a coefficient of 1.75:

$$M_{du} = 1.75A\tau_{du} \tag{3}$$

Using equations 2 and 3, the dust mass range was calculated (i.e. eq. 3 for the lower limit, eq. 2 for the upper limit). Ben-Ami et al. (2010) demonstrated that the Kaufman equation could successfully be used to calculate dust mass over northern Africa, although it should be noted that the equation has an uncertainty of ±30% for AOD values between 0.2 and 0.4.

3 Results

5   A total of 3512 individual dust sources were identified (Fig. 3). The dust sources per geomorphological class are shown in Table 1; the vast majority were associated to alluvial deposits (51.11%) or paleolakes (42.85%). Sand deposits, including dune fields and sand sheets, only accounted for 3.93% of the dust storms. A few sources were linked to anthropogenic influences, such as villages, dirt roads, or agricultural fields. Moreover, 22 sources had no clear distinguishable features to place them in one of the geomorphic categories, and were thus labelled as 'unknown'.

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Table 1. Northern African mineral dust sources of the 2015-2017 winter dust seasons classified by geomorphology type.

DUST SOURCE GEOMORPHOLOGY TYPE	COUNT 15-16	%	COUNT 16-17	%	TOTAL COUNT	% OF TOTAL
Alluvial deposits	1293	53.47	502	45.89	1795	51.11
Paleolakes	992	41.03	513	46.89	1505	42.85
Sand deposits	82	3.39	56	5.12	138	3.93
Stony surfaces	19	0.79	15	1.37	34	0.97
Unknown	18	0.74	4	0.37	22	0.63
Anthropogenic	14	0.58	4	0.37	18	0.51
TOTAL	2418		1094		3512	

During the 2015-2017 winter dust season between 82.3 - 127.0 Tg of dust was emitted. The 2015-2016 dust season was significantly more dusty, producing approximately twice the amount of dust compared to the 2016-2017 dust season, which

15   is also reflected in the amount of individual dust sources identified per season in Table 1. The distribution of the dust over the various regions was, however, relatively similar in both seasons. Table 2 shows the full distribution of the emitted dust per dust source region, along with the frequency of emission, i.e. the percentage of days during which the region is an active dust source, and the predominant geomorphology. The Bodélé Depression is identified as the single largest source region, emitting 44.5% of the dust mass, and producing the densest dust plumes with an average AOD value of 0.92. The Bodélé,

20   Bahr el Gazel, and Ennedi regions were the most frequently emitting dust source regions, all of them emitting during more

Atmospheric
Chemistry
and Physics
Discussions

than half of the days of the wintertime dust season. Mauritania and South Niger were the least active regions, emitting dust on only 2 of the 172 days analysed.

Dust source regions of predominantly paleolake origin emitted approximately 64% of the total dust mass during the 2015-2017 winter dust seasons, compared to 36% for the dust regions governed by alluvial influence. The importance of paleolakes and alluvial deposits, however, fluctuated considerably. Figure 4 compares the influence of paleolakes versus alluvial deposits for the ten largest dust storms of the 2016-2017 winter dust season, which demonstrates this variability.

For the accuracy assessment, the geomorphological class of a further 163 dust sources were identified from the three randomly chosen days (29 Dec 2015, 21 Jan 2017, 8 Feb 2017). Of the 163 dust sources, 161 (98.77%) corresponded with the predominant geomorphology assigned to the region. The ten largest dust storms per season emitted 37.6% of the total dust mass.
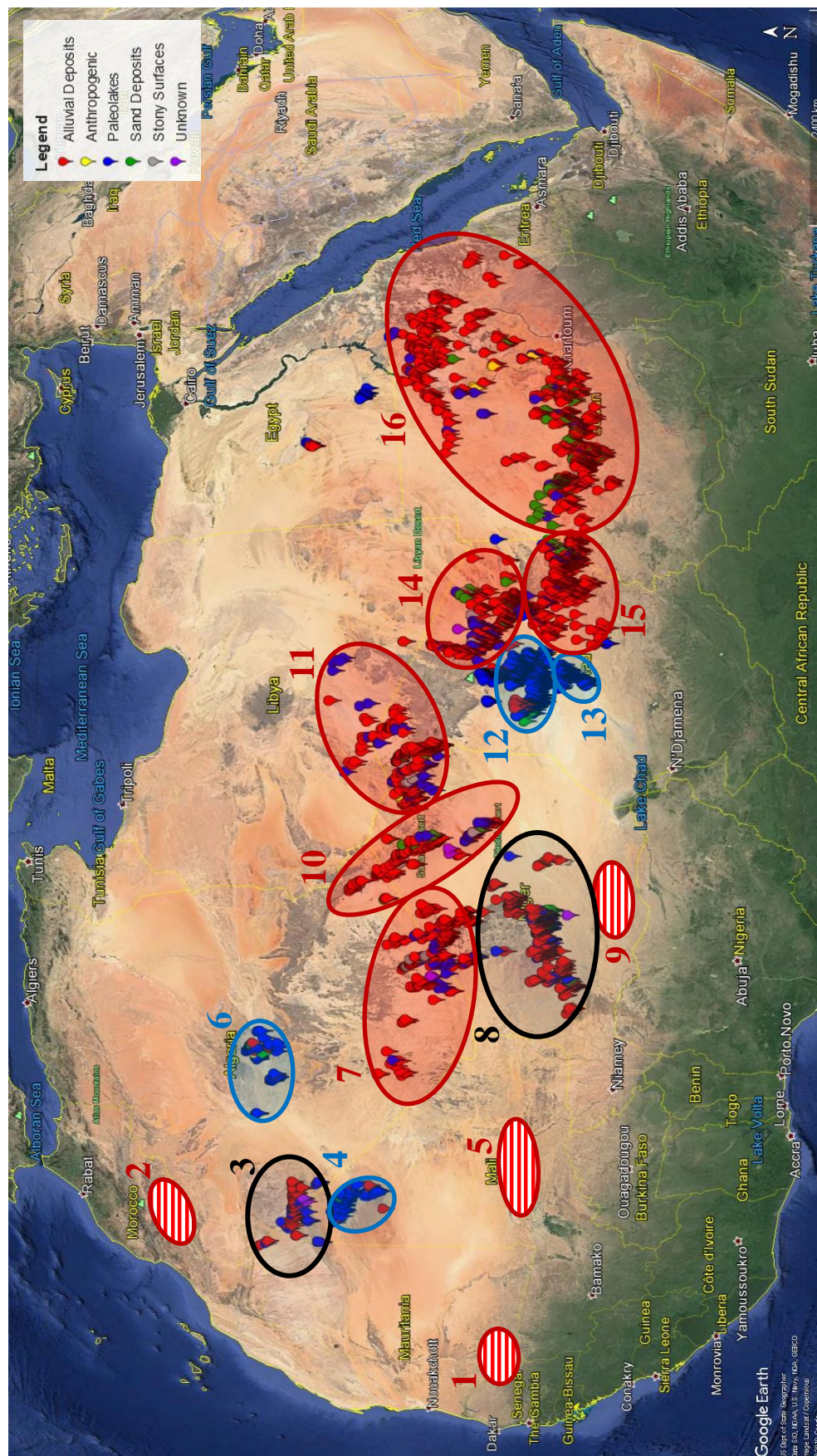
20 **Figure 3.** Geomorphology of the northern African mineral dust sources of the 2015-2017 boreal winter dust seasons. Coloured pins represent individual dust sources of the ten largest dust storms during the 2015-2017 winter dust seasons, with the colour signifying the geomorphic category of the dust source. The major dust source regions are outlined, with red regions containing predominantly alluvial deposit dust sources, blue regions containing predominantly paleolake dust sources, and black regions containing a mixture of alluvial deposit and paleolake dust sources. The striped regions were regions that emitted dust during the dust seasons, but did not emit during the ten largest dust storms of the 2015-2016 and 2016-2017 winter dust seasons and hence have no individual dust source locations attached to them. Source areas are numbered as follows: 1, Mauritania; 2, Draa River; 3, El Eglab; 4, 25 Northwest Mali; 5, Mid Mali; 6, Algeria; 7, North Air; 8, South Air; 9, South Niger; 10, Djado Plateau; 11, Tibesti; 12, Bodélé; 13, Bahr el Gazel; 14, Upper Bodélé; 15, Ennedi; 16, Sudan. Background Google Earth, imagery Landsat/Copernicus (2018).

Table 2. Total dust mass emitted per Saharan dust source region during the 2015-2017 winter dust seasons, alongside their predominant geomorphology and their frequency of emission.

	TG 15-16	TG 16-17	TG TOTAL	% OF TOTAL	FREQUENCY (% DAYS ACTIVE)	PREDOMINANT GEOMORPHOLOGY
Bodélé	24.7 - 38.1	11.9 - 18.4	36.6 - 56.5	44.5	67.4	Paleolake
Bahr el Gazel	5.9 - 9.2	2.8-4.3	8.7 - 13.5	10.6	55.2	Paleolake
South Air	5.0 - 7.8	3.3-5.0	8.3 - 12.8	10.1	43.6	Alluvial Deposit/ Paleolake
North Air	5.3-8.2	1.5-2.3	6.8 - 10.5	8.3	25.0	Alluvial Deposit
Sudan	4.6-7.0	1.6-2.5	6.2 - 9.5	7.5	36.6	Alluvial Deposit
Ennedi	2.7-4.2	2.1-3.2	4.8 - 7.4	5.8	54.7	Alluvial Deposit
Algeria	1.3-2.0	1.1-1.7	2.4 - 3.7	2.9	12.8	Paleolake
Tibesti	1.8-2.7	0.6-1.0	2.4 - 3.7	2.9	24.4	Alluvial Deposit
Djado Plateau	1.1-1.7	0.4-0.7	1.5 - 2.4	1.9	12.2	Alluvial Deposit
El Eglab	0.4-0.6	0.7-1.0	1.1 - 1.6	1.3	5.2	Alluvial Deposit/ Paleolake
Mid Mali	0.1-0.2	0.8-1.2	0.9 - 1.4	1.1	4.7	Alluvial Deposit
Upper Bodélé	0.6-0.9	0.2-0.4	0.8 - 1.3	1.0	22.7	Alluvial Deposit
Draa River	0.7-1.0	0	0.7 - 1.0	0.8	1.7	Alluvial Deposit
South Niger	0	0.5-0.8	0.5 - 0.8	0.6	1.2	Alluvial Deposit
Mauritania	0.3-0.5	0.1-0.1	0.4 - 0.6	0.5	1.2	Alluvial Deposit
Northwest Mali	0.1-0.2	0.1-0.1	0.2 - 0.3	0.2	2.3	Paleolake
TOTAL	54.6-84.3	27.7-42.7	**82.3 - 127.0**			
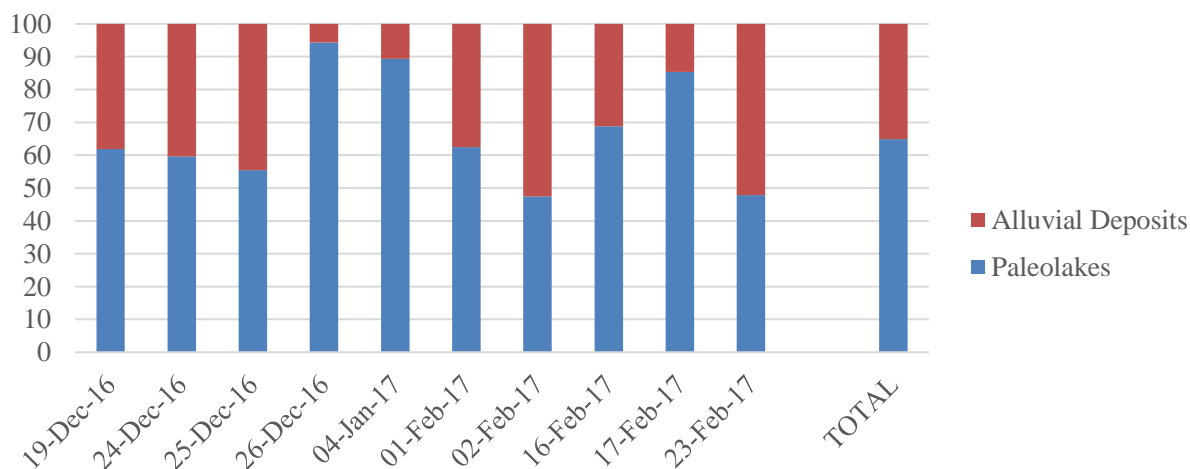
Figure 4. Contribution (in %) of paleolake dust sources versus alluvial deposit dust sources to total dust mass for the ten largest dust storm events of the 2016-2017 winter dust season.

4 Discussion

4.1 Paleolake and alluvial deposit dust sources

Our results indicate the importance of both paleolakes and alluvial deposits as African mineral dust sources. Alluvial deposits were found to deflate more often, while paleolakes produced more dust by emitting denser dust plumes. Dry lakebeds, most

5   notably the Bodélé Depression, are widely known to be preferential dust sources (Prospero et al., 2002; Tegen et al., 2002). Alluvial deposits, however, have been recognised to a much lesser extent in dust source studies, especially when compared to paleolakes (Bullard et al., 2011). Producing 51.11% of the individual dust plumes and representing ~36% of the total dust mass, alluvial deposits make a significant contribution to the dust burden. Despite this, the latest estimates of the fertilisation effect of dust on the Amazon by Yu et al. (2015) determine total phosphorus deposition into the Amazon (0.022 Tg per annum)

10   based solely on the phosphorous concentration in Bodélé dust, while not taking alluvial deposit dust sources into account. Given the fact that it has recently been shown that there are significant differences of bioavailable phosphorous content within dust from different source geomorphologies (Gross et al., 2015; 2016), and the evidence presented here of alluvial deposits being important sources, the accuracy of Yu et al.'s (2015) estimate can be questioned. In Namibia, Dansie et al. (2017) established that alluvial dust source sediments contained up to 43 times greater concentrations of bioavailable iron and enriched

15   N and P macronutrients compared to paleolake pan sediments. Further research into the actual differences in nutrient content of the different northern African dust sources and dust source geomorphologies is needed to improve the precision of fertilisation estimates. This is particularly the case for the underexamined alluvial source regions.

4.2 Sand dunes producing dust?

While paleolakes and alluvial deposits accounted for over 90% of the emitted dust, sand deposits only accounted for 3.93%.

20   This contradicts recent results by Crouvi et al. (2012), who found that active sand dunes were the most frequent dust sources within the Sahara. The discrepancy between the results presented here and those found by Crouvi et al. (2012) is most likely explained by the type of data used and the difference in their spatial resolution. Crouvi et al. (2012) mapped dust sources onto a coarse resolution (1° x 1°) grid, and compared them to a map of soils. When more than one soil type was present in a grid cell, Crouvi et al. (2012) assigned it to the geomorphic unit with the highest areal coverage. This carries a large bias towards

25   widespread sand sheets and dune fields, whereas for instance paleorivers and small to medium-sized paleolakes (which could be picked up with the high-resolution Sentinel-2 data utilised in this study) are underrepresented and easily overlooked. Another major difference between the studies is that Crouvi et al. (2012) classify the Bodélé region as sand dunes, whereas in this study it is classified as a paleolake. While dunes exist in the Bodélé Depression, they are commonly composed of fragments of lake sediments and the dunes themselves are subordinate in cover to lake sediment exposures (Bristow et al., 2009).

30   Furthermore, Crouvi et al. (2012) identified quartz-rich sand dune fields surrounding the Bodélé Depression as a major source of dust, however closer examination of the dust sources in this region, using high resolution data from VIIRS and Sentinel-2,

showed this was not the case. The higher resolution data used in this study has improved the accuracy of dust source identification, and suggests that sand dunes produce little dust in northern Africa during wintertime.

4.3 Location of dust sources

The majority of the locations of dust sources identified in this study correspond with previous studies such as Prospero et al.
(2002), Schepanski et al. (2007; 2009; 2012), Ginoux et al. (2012), and Knippertz and Todd (2012). However, one area that has not been widely recognised as a source region - despite representing ~7.5% of dust emitted -, is Sudan. In southern Sudan, a few of the sources lie within the Sahel, but most are located in the Sahara. While various studies have analysed Sahelian dust emissions (Klose et al., 2010; Bergametti et al., 2017; Kim et al., 2017), less is known about the importance of the Sahel compared to the Sahara. From our data, we find that the Sahelian dust sources account for a mere 5%, with the vast majority of wintertime dust sources being located in the Sahara. Of the Sahelian dust sources, 87% are alluvial. The lack of lacustrine dust sources in the Sahel may be due to higher rainfall leading to moisture accumulation in the lake basins, which in turn suppresses dust production. The inundation of ephemeral lakes has previously been observed to lower dust emissions in semi-arid regions (Mahowald et al., 2006).

5 Conclusion

This study provides a quantitative analysis of wintertime northern African mineral dust sources. It outlines a novel methodology in which high temporal resolution remote sensing data is combined with high spatial resolution data to analyse dust sources more accurately than previous dust source studies. The results show for the first time the strong importance of alluvial deposits, while simultaneously reaffirming the importance of paleolake sources. Sand deposits, on the other hand, are found to produce relatively little dust. The results concur with previous studies that the Bodélé Depression is the single largest dust source region, yet also highlight that there are lesser studied regions, such as Sudan, producing a substantial amount of dust. It furthermore stresses the significance of the Sahara over the Sahel regarding dust production, with 95% of dust sources emitting from the Sahara.

Author contributions

Conceptualisation and methodology of research established by all authors. Investigation and formal analysis carried out by N.L. Bakker, supervised by N. Drake and C. Bristow. Interpretation of results determined from discussions with all three authors. Original draft of manuscript written by N.L. Bakker, review and editing of manuscript by N. Drake and C. Bristow.

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Atmospheric
Chemistry
and Physics
Discussions

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