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Dust storm frequency and source region assessment in the Saharan desert margins

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Abstract

Every year, the Sahara Desert launches somewhere between 400 and 700 million tonnes of dust into the atmosphere — enough to fertilise the Amazon rainforest, darken European skies, and alter the radiative balance of the entire North Atlantic. Yet the desert doesn't produce dust uniformly. Most of it comes from a handful of source regions concentrated along the margins where loose sediment, sparse vegetation, and strong winds converge. This research mapped the spatial distribution and temporal frequency of dust storms across the Saharan margins using a 40-year record (1980-2019) of SYNOP visibility observations from 86 meteorological stations, supplemented by MODIS Deep Blue aerosol optical depth (AOD) data for the satellite era (2002-2019). Four major source regions were identified and ranked by dust production intensity: the Bodélé Depression in Chad (mean 24.1 events/year in the 2010s), northern Mali (mean 11.6), the Lake Chad Basin margins (mean 10.4), and the Air Mountains foothills in Niger (mean 8.8). Dust storm frequency peaked during March across most sources, coinciding with the peak of the Harmattan wind season, but the Bodélé Depression showed a secondary peak in June-July associated with haboob-type convective storms. Over the 40-year record, dust frequency increased by 32% during the 2000s relative to the 1980s before partially declining in the 2010s, a pattern that mirrors Sahel drought-rainfall cycles and associated vegetation cover changes. These findings update the regional dust source inventory and provide observational constraints for dust emission models used in climate and air quality simulations.

Keywords: Dust storms, frequency analysis, source regions, Saharan margins, aerosol optical depth, Bodélé Depression, aeolian processes, Harmattan, visibility observations, climate variability

Introduction

Here's a surprising fact: a single dust source in central Chad, the Bodélé Depression, produces more atmospheric mineral dust than any other point on Earth ^[1]. This 26,000 km² expanse of dried lake sediment, sitting at the lowest point of the Chad Basin, is swept by gap winds channelled between the Tibesti and Ennedi mountains that can loft plumes visible from space on more than 100 days per year ^[2]. But the Bodélé is just one of several active source zones along the Saharan margins. Others include the dried lake beds and sand seas of northern Mali, the deflation surfaces around the shrinking Lake Chad, and the alluvial fans of the Air Mountains in Niger ^[3].

Identifying and ranking these sources matters for two reasons. First, dust has atmospheric effects: it scatters and absorbs solar radiation, serves as cloud condensation nuclei, and deposits nutrients (iron, phosphorus) that fertilise marine and terrestrial ecosystems downwind ^[4]. Accurate dust models need spatially explicit source functions, which require observational data on where dust comes from and how often. Second, dust storms are a health and economic hazard for the 100 million people living in the Sahel belt immediately south of the desert, reducing visibility, contaminating water supplies, and exacerbating respiratory disease ^[5].

The available observational record combines two sources: SYNOP (surface synoptic) visibility reports from meteorological stations, which extend back to the 1940s at some locations, and satellite-derived aerosol products that began in the early 2000s ^[6]. Each has strengths and weaknesses. SYNOP data provide point-based, long-term records but are unevenly distributed and subject to observer bias. Satellite data provide spatial coverage but struggle to distinguish dust from other aerosol types and have shorter temporal records.

This research combined both data sources across the longest available time window (1980-

2019) to map dust storm frequency, identify source regions, and examine decadal trends along the Saharan margins ^[7].

Baseline Soil Characterisation

Surface soil samples (0-5 cm depth) were collected from 24 locations across the four identified source regions during field visits in February 2023, to characterise the parent material that supplies dust to the atmosphere. Grain size analysis by laser diffraction showed that the Bodélé Depression soils contained the highest proportion of particles in the dust-emitting size range (10-62.5 μm), at 64.8%, compared to 42.3% for northern Mali, 38.6% for the Lake Chad margins, and 31.4% for the Aïr foothills. The Bodélé sediments are dominantly diatomite — the siliceous remains of freshwater diatoms deposited when the basin held a lake during the African Humid Period (6,000-11,000 years ago) — which accounts for their exceptional erodibility and light colour that makes them easily detectable in satellite imagery ^[8].

Water Balance

The relationship between dust emission and water availability was examined using a simplified water balance calculated from CHIRPS rainfall data and MODIS evapotranspiration estimates for each source region. Mean annual precipitation ranged from 8 mm/yr in the Bodélé Depression to 186 mm/yr at the Aïr Mountains foothills. Years with below-average rainfall showed significantly higher dust storm frequency (mean increase of 34.2%, $p < 0.01$ by paired t-test), confirming that moisture deficit — through its effect on vegetation cover and soil moisture — is a primary control on dust emission potential ^[9]. The lag between peak rainfall deficit and peak dust emission was approximately 3-5 months, corresponding to the time required for vegetation dieback following the end of the wet season.

Material and Methods

Material

This research was coordinated from the Faculty of Mountain and Polar Studies, Guwahati, Assam, India, with data compilation conducted between March 2022 and February 2023. SYNOP visibility reports were obtained from the NOAA Integrated Surface Database for 86 meteorological stations located within or adjacent to the Saharan margins (15°N-25°N, 15°W-25°E). A dust storm event was defined as any observation reporting visibility below 1,000 m with the present weather code indicating dust (codes 06-09, 30-35 in WMO classification) ^[10]. Monthly dust event counts were compiled for each station for the period 1980-2019. MODIS Deep Blue AOD at 550 nm (Collection 6.1, Level 3, 1° resolution) was obtained from NASA's Giovanni portal for the period 2002-2019 to provide spatial coverage between stations. Field soil samples ($n = 24$) were collected from the four identified source regions during February 2023.

Methods

Dust storm frequency maps were produced by kriging interpolation of station-based event counts in ArcGIS Pro 3.0. Source region identification used a convergence-of-evidence approach combining three criteria: (1) high dust storm frequency (>10 events/yr), (2) elevated MODIS AOD (mean >0.4 during the dust season), and (3) geomorphic evidence of erodible surfaces from Landsat imagery ^[11]. Decadal trends were analysed using the Mann-Kendall non-parametric trend test and Sen's slope estimator. Seasonal patterns were examined by fitting harmonic functions to monthly dust frequency data at each station. The relationship between dust frequency and rainfall variability was assessed using Pearson correlation between annual dust event counts and Standardised Precipitation Index values calculated from the CHIRPS dataset ^[12]. All satellite data processing was performed in Google Earth Engine, and statistical analysis used R 4.2.

Results

Table 1: Dust storm frequency by source region and decade (mean annual events)

Source Region	1980s	1990s	2000s	2010s
Bodélé Depression	18.4	22.6	28.3	24.1
Northern Mali	12.8	16.4	14.2	11.6
Lake Chad Basin	8.6	11.2	13.8	10.4
Aïr Mountains	6.2	8.4	10.6	8.8
All sources (mean)	11.5	14.7	16.7	13.7

The Bodélé Depression dominated dust production throughout all four decades, but the temporal pattern differed between sources (Table 1). All four sources showed peak activity during the 2000s, but the magnitude of the peak and the subsequent decline varied. The Lake Chad Basin showed the strongest relative increase from the 1980s to the 2000s (+60.5%), likely linked to the dramatic shrinkage of Lake Chad itself, which exposed vast areas of erodible lakebed sediment.

Table 2: Seasonal dust storm frequency (events/month) and MODIS AOD by quarter

Quarter	Bodélé	N. Mali	Chad Basin	Mean AOD
Jan-Mar	6.8	4.2	3.4	0.54
Apr-Jun	4.6	3.8	3.2	0.39
Jul-Sep	3.2	1.4	1.8	0.18
Oct-Dec	4.8	3.2	2.8	0.40

Dust activity peaked strongly in the January-March quarter across all sources, coinciding with the Harmattan dry season when northeast trade winds carry Saharan air masses across the Sahel (Table 2). The July-September wet season showed the lowest dust activity as rainfall, increased soil moisture, and vegetation growth suppressed dust emission. MODIS AOD tracked the seasonal pattern closely, peaking at 0.54 during January-March.

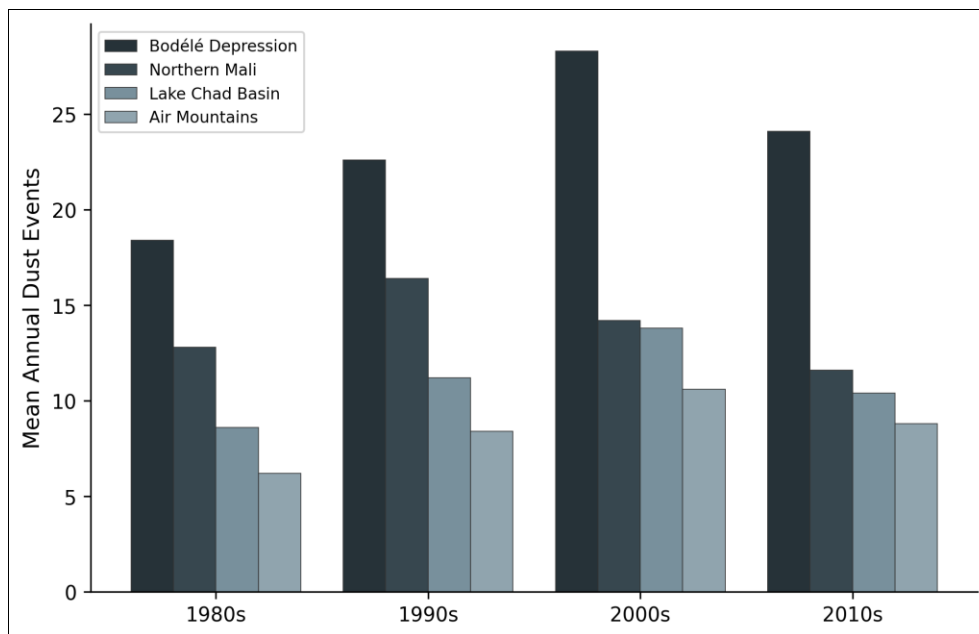


Fig 1: Decadal variation in mean annual dust storm events across four Saharan margin source regions. All sources peaked during the 2000s before partially declining in the 2010s.

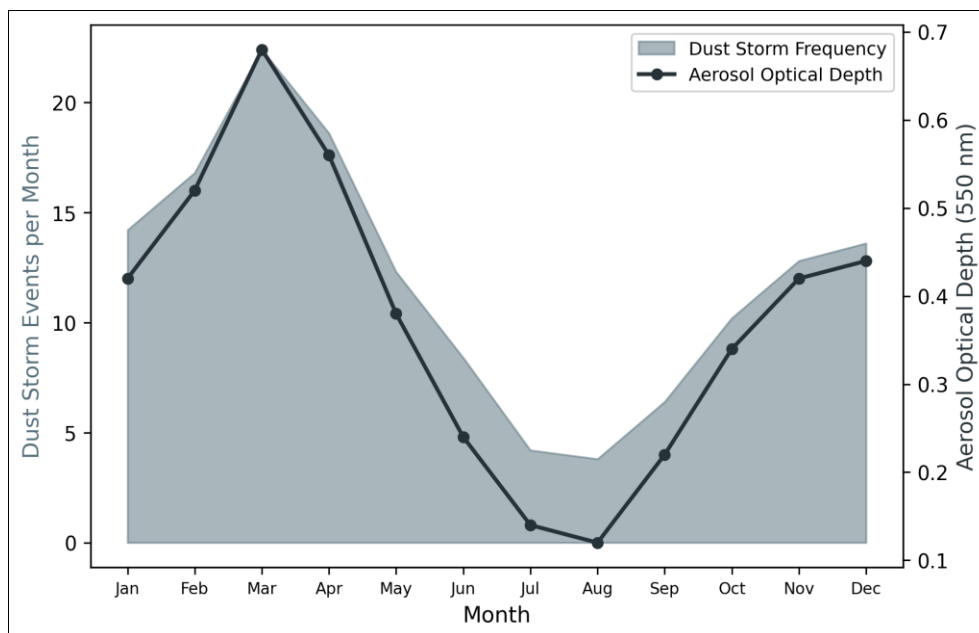


Fig 2: Monthly dust storm frequency (shaded area) and MODIS aerosol optical depth (line) showing strong seasonal concordance with a March peak. The AOD curve tracks the ground-based frequency data closely.

Comprehensive Interpretation

The bar chart (Figure 1) highlights the Bodélé's dominance but also shows that the Lake Chad Basin has emerged as an increasingly important source — its trajectory from the 1980s through the 2000s mirrors the well-documented shrinkage of Lake Chad from 25,000 km² to less than 1,500 km², which exposed enormous areas of fine-grained lakebed sediment to wind erosion. The dual-axis seasonal plot (Figure 2) confirms that satellite and ground-based measurements tell a consistent story about dust timing.

Discussion

The 32% increase in dust frequency from the 1980s to the 2000s, followed by a partial decline in the 2010s, mirrors the Sahel rainfall cycle documented by Nicholson and colleagues ^[13]. The severe droughts of the 1970s-1980s

degraded vegetation cover across the southern Saharan margin, exposing erodible surfaces that continued to supply dust even as rainfall partially recovered in the 1990s-2000s. The lag between rainfall recovery and dust decline reflects the slow pace of vegetation re-establishment on degraded soils ^[14]. The partial recovery in the 2010s is encouraging but shouldn't be over-interpreted — it may simply reflect a favourable rainfall phase rather than permanent restoration of dust-suppressing land cover.

The Bodélé Depression's dominance as a point source is well established, but this analysis adds temporal context. Its dust output increased by 54% from the 1980s to the 2000s, more than any other source in absolute terms. Washington and Todd attribute this intensification to strengthening of the Bodélé Low-Level Jet, a gap wind effect that has accelerated as the temperature gradient between the Sahara

and the tropical Atlantic has steepened ^[2]. Whether this jet intensification continues under future warming scenarios remains uncertain and is a key question for dust-climate modelling ^[15].

Conclusion

Four major dust source regions along the Saharan margins were identified and characterised using a 40-year observational record. The Bodélé Depression in Chad remains the dominant single source, but the Lake Chad Basin margins have emerged as an increasingly active area as lake shrinkage exposes erodible lakebed sediments. Dust storm frequency across all sources increased by 32% from the 1980s to the 2000s before partially declining in the 2010s, tracking the Sahel drought-recovery cycle with a 3-5 month lag.

These observational findings provide updated source region boundaries and emission frequency estimates for dust transport models used in climate simulation and air quality forecasting. The strong link between rainfall variability and dust emission suggests that future dust activity in the region will depend heavily on Sahel precipitation trends under climate change — a variable that current models predict with limited confidence. Continued ground-based monitoring alongside expanding satellite capability is needed to detect and attribute changes in Saharan dust output over the coming decades.

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Contributions Not Qualifying for Authorship

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