Dust over West Africa

Dr. Vincent O. Ajayi Federal University of Technology, Akure, Nigeria. voajayi@futa.edu.ng







Lecture outline

- Introduction
- Source region
- Transport and trajectory
- Characteristics of Bodele depression
- Meteorological conditions
- Mechanism of raising dust
- Dust climatology
- Impact of dust in West Africa
- Forecasting of dust







West Africa Weather zone revisited



Figure 1: Weather zones relative to the surface location of ITD in August(Source: Weischet, 2000)







Introduction



Figure 2: Seasonal variation in latitudinal position of the ITCZ and its consequences for atmospheric conditions over northwestern Africa. Arrows indicate direction of trade winds; dust plumes are indicated by grey shadings. December, January, and February (winter) and June, July, and August (summer) are shown. (From Stuut et al., 2005.)







Winter



Figure 3: Animation of AOT in sumer and winter, It can be noted that harmattan dust is transported to West African in Winter and towards North and South America in Summer seasons





Source region



Figure 4: Major dust region in West Africa as observed by Kalu (1979)









Figure 5: Overview of potential dust source areas in northern hemispheric Africa (PSANAF) based on a synergy analysis by Formenti et al. (2011). The different lines and colours represent analyses by different authors based on different data and techniques (see legend), illustrating the challenge of identifying dust sources with great accuracy.



Figure :

The most important regions are grey shaded:

 PSANAF-1: Zone of chotts in Tunisia and northern Algeria;
PSANAF-2: Foothills of Atlas Mountains (PSANAF-2a) and western coastal region (PSANAF-2b; western Sahara, western Mauritania);

PSANAF-3: Mali-Algerian border region;

 PSANAF-4: Central Libya;
PSANAF-5: Bodélé Depression (western Chad)

PSANAF-6: Southern Egypt,

northern Sudan. Other source regions worth noting are the southern parts of the Azawagh, a dry basin in northwestern Niger / northeastern Mali (pink stippled

line), and the Kaouar region GCRF Africanorthern Niger (not specific W M Finarked on the Figure).

Transport and Trajectory

- The dust from Sahara region affects other areas of the world apart from West Africa.
- Prospero et al. (2001) reported that dust is transported from these Saharan sources over land and sea to regions like Europe, the Middle East and across the Atlantic to areas as far away as Mexico City.
- This dust transport occurs in spectacular storm-like event, when clouds of the desert aerosol particles take the shape of giant plumes that span the over large regions west of Africa and extend more than one thousand kilometers from the source















Characteristics of the PSANAF-5: Bodélé Depression (western Chad)

- Major characteristics of the Bilma Faya Lageau area which fall within the PSANAF-5, is the convergence of katabatic induced wind downstream from the Western slope of Tibesti Mountain, which leads to large-scale deposition of sand in the plain (Wilson 1971).
- The depletion of dust in the source is exceeded by the supply of dust into the region. This ensures continuous raising of dust every year without leading to depletion process.
- Dust particles are constantly fed into the wind at the western slope of Tibesti and deposition occurs under favourable meteorological condition, such as convergence or deceleration of wind stream.
- The dusty atmosphere observed in West Africa in winter results from a discharge of dust particle into the atmosphere, though it does not occur every time except when certain synoptic conditions must have been established over the







Meteorological conditions

Synoptic

- The wind plays the greatest role in the life cycle of Sahara dust right from the emission stage to the propagation stage.
- In the Sahel and southern Sahara, intense dust storms frequently occur during the West African dry season (December to April) in connection with low-level pressure surges associated with an intensification of anticyclonic conditions over northern Africa (Kalu, 1979; Klose et al.,2010).
- The increased south-north pressure gradient across northern Africa associated with a strengthened subtropical anticyclone leads to an intensification of the Harmattan winds.









Figure 7: Typical situations for the raising of dust during the winter periods. (a) Intensified Libyan High, The dashed lines show typical isobars spaced every 5 hPa with the 1015 hPa highlighted in bold. Dust raising is due to the intensification of the Libyan High

This is often preceded by the eastward passage of a mid-latitude depression across northern Africa.

The high pressure often builds rapidly behind the cold front, which may penetrate far into the African continent.









Figure 8: Example of an intense large-scale dust outbreak caused by rapid anticyclogenesis over north-western Africa at 1800 UTC 03 March 2004. The underlying satellite image and station reports. During the following days the dust front continued to spread until it formed a long arc from the Gulf of Guinea to the







Low-level Jet (Bodele Low-Level jet at 925hpa)

 An important phenomenon that occurs over cloud-free, dry regions with strong background pressure gradients during all seasons is the formation of nocturnal low-level jets (LLJs) Stensrud, 1996; Fiedler et al., 2013)



Figure 9: Measurements of the effect of nocturnal LLJ formation on surface winds at Chicha (16°53'N, 18°33'E, Chad) during the BoDEx campaign. Left panel: Time-height profile of wind speed from Pilot Balloon data for 28 February to 11 March 2005. Right panel: One-minute averages of 2-m wind speed for 5–8 March 2005. The data show the formation of nocturnal jets and corresponding peaks in surface winds during the morning for some days during the







Transport of dust by Bodele LLJ



Figure 10: Schematic depiction of transport and mixing of dust associated with a nocturnal LLJ.







Mesoscale

- Dust storms along the leading edge of a rapidly spreading cold pool are often called haboobs (Sutton, 1925; Freeman, 1952).
- Haboobs are formed from the density currents driven by the cooling associated with the evaporation of convective precipitation in the hot and dry desert.
- It is a squall-line-type convection in northern Africa at the margins of the Sahara where enough moisture is available to sustain the parent deep moist convection.









Figure 11: Examples of haboob dust storms generated by gust fronts ahead of vigorous squall lines over the Sahel. (courtesy of Laurent Labbé): Photograph of a haboob arriving over Niamey on 26 June 2012.







Microscale

- Local scale dust can be mobilised in connection with dry convective mixing in the Planetary Boundary Layer (PBL)
- This is evident in rotating dust devils and in part through non-rotating convective plumes
- Dust devils typically have diameters of 3–100m, lifetimes of a few minutes and tangential wind of 3–15m/s (Sinclair, 1969).
- Dust plumes, in contrast, are characterised by larger diameters and lifetimes up to an hour, and also by weaker winds and smaller dust fluxes.
- Typical conditions for the formation of dust devils/plumes include moderate, near-surface wind shear and a large temperature contrast between the surface and the lowest few metres of the atmosphere.







Mechanism of raising the harmattan dust

- The occasional slight shifts in the position of anticyclone result in the periodic incursion of cold polar air into Sahara region.
- This causes the strong tightening of the pressure gradient in the lower layer. Consequently, large amount of dust produced by weathering of rock and soil at-the surface are emitted into the air by strong surface wind resulting from convergence of air aloft and divergence below, thereby building up dust reservoir of several kilometers thick in the Sahara atmosphere.
- After the dust has been raised, turbulent mixing through the downward transfer of large momentum at the gradient level (925hpa) transport the dust to 925 hpa where horizontal transport is initiated.
- The strong horizontal wind at this level is a necessary agent for transport of dust haze across West Africa sub region in form of plume (Kalu 1977).







Kalu (1977) partitioned the life cycle of Sahara dust into three major phases:

Instantaneous rising stage:

- The first stage is the raising of the dust in the source region.
- This is when the dust particles are violently raised from the ground, usually in form of dust storm as a result of strong surface wind.
- The dust plume is diffused upward by turbulence and there is pronounced buoyancy but no horizontal spread in this phase.







- The spreading phase:
- Having been raised from the ground by turbulence to the level where horizontal wind is strong, transportation starts in horizontal direction, at about 900 hpa.
- t is observed that, at this stage, the wind that raised the dust plume weakens and this suggest that the plume also gradually losses its vertical momentum







- The equilibrium phase:
- The equilibrium stage is the most stable of the three phases of the motion of the dust haze plume.
- It sets in as soon as the spreading stage has been completed.
- It is assumed that at this stage, the plume has lost independence and is therefore moving under the influence of prevailing winds.
- It is at this stage that West Africa experience reduced visibility. This equilibrium stage usually takes place some hundreds of kilometers downwind.







Dust Climatology



Figure 12: Mean monthly number of hours with visibility reduced less than 5 km (shaded bars) and less than 10 km (unshaded bars)

during the period 1983–87.

COUNCIIS UK



✓ Dust source activity and resulting dust storms change with space and time.

✓ Their variability is described by the use of the time series from weather station observations, such as visibility records, weather reports and satellite Images

 \checkmark There is a pronounced diurnal cycle in visibility reduction in the Sahel. Typically, minimum horizontal visibility occurs during late morning to afternoon mid due the to development convective of the boundary layer.

✓ Seasonal variation in the occurrence of reduced visibilities changes with the rainfall regime, and thus with distance from the equator





OT Oper the Gulf of Guinea region GCRF African SWIFT

COUNCIIS UK

- **AOTs** total represent the atmospheric column, high aerosol loadings do not necessarily correspond to high surface concentrations and thus low horizontal visibilities.
- In addition to dust, aerosols such as soot from burning biomass contribute to the AOT. particularly over the Gulf of **Guinea region during November** to March
- In Winter, the atmospheric dust loading over North Africa is at its minimum. but increased dust Bodélé loading **Depression**and Ténéré region (Chad Niger), and northwest Mali.
- March to May the In atmospheric dust loading generally increases, forming a band of enhanced dustiness extending from the Red Sea to the Atlantic, centered at around 15–20°N, that persists until August and repreats in

September.



Impact of dust in West Africa

- Aviation: Many flight cancellation due to poor visibility
- Health: Adefolalu (1984) reported that dust loading in the atmosphere may lead to outbreak of acute respiratory infections, pneumonia and bronchitis especially in the northern part of W/A.
- Direct impact on weather and climate.







Interactions with Weather and Climate



Figure 14: Linkages between mineral dust aerosol and climate, indicating direct and indirect aerosol effects, and the role of oceanic dust deposition ecosystems.







Direct Radiative Effect

- Dust impacts considerably on the energy balance of solar and thermal IR radiation (Solomon et al., 2007).
- Incoming solar radiation is partly reflected and absorbed by atmospheric particles.
- At size distribution of 2 μm or larger, dust particles can also absorb and emit outgoing terrestrial radiation.
- Dust particle size and complex refractive indices determine their optical properties, and thus the magnitude and sign of their radiative effects.
- These can be determined by measurements in the laboratory or field, or by remote sensing.
- Case studies of some dust events is estimated negative between -6 W m-2 and -400 W m-2 (Christopher and Jones, 2007)
- A negative dust forcing suggests that an enhancement of atmospheric dust aerosol would lead to a cooling of the climate.







Impact on Atmospheric Stability









Surface temperature difference (K)10-m wind difference (m/s)Figure 15: Regional model results of
changes in 2-m temperatures (a,c) and

10-m wind speeds (b,d) for the Bodélé

region in Chad.



- Radiative forcing by dust influences the energy distribution within the atmosphere.
- These changes in energy distribution can alter temperature and wind distribution and ultimately affect the stability of the atmosphere.

Figures 15a and 15c shows that The maximum surface cooling by dust exceeds 20K, corresponding to a decrease in net radiation flux by about 500Wm2

- The maximum reduction in surface wind speeds at this time due to the dust radiative forcing is 3 ms-1
- Generally, results from regional models show that dust affects the atmospheric stability.



Impact on Cloud Microphysics

- Dust may influence the formation and lifetimes of clouds via the so-called indirect aerosol effect.
- A coating of dust particles by soluble material enhances the ability of those particles to form cloud condensation nuclei (Wurzler et al., 2000).
- There are considerable uncertainties in the estimates of the impact of mineral dust on the ice phase of clouds and precipitation.
- While mineral dust particles can be efficient ice nuclei, the extent of the influence of dust particles on the formation and development of ice clouds remains largely unquantified.







Fertilisations of Ecosystems

- Soil dust particles add essential nutrients into terrestrial and marine ecosystems when they are deposited to the ground.
- Saharan dust is very rich in iron (Adedokun *et al.,* 1989). Fertilization experiments in which dissolved iron (Fe(II)) is added to the ocean show an enhanced productivity of oceanic microorganisms (e.g. plankton) and increase in CO2 drawdown in regions rich in macronutrients (Coale *et al.,* 1996).
- Transported desert dust deposited onto nutrient-poor soils is suspected to contribute micronutrients to terrestrial ecosystems.
- Koren *et al.*,(2006) has reported that the transport of Saharan dust into the Amazon rainforest is suspected to support its vegetation growth .







Forecasting of Harmattan

- Generally, three phases are involved in dust forecasting: dust raising, transport and clearance.
 Forecasters should concentrate on four aspects in their assessment of a given situation:
- 1. Watch out for significant amounts of dust being raised over the Sahara/northern Sahel.
- 2. Estimate the likelihood of the dust being transported to your region and the arrival time.
- 3. Monitor the situation to estimate duration and severity of the HDH event.
- 4. Watch out for indications of a clearing due to a change of air masses or ceasing dust emission.







In particular,

- Burns (1961) has demonstrated the close relationship between strong surface pressure gradient and the occurrence of dust haze over West Africa.
- The method relied on tracking cold fronts traversing the Sahara in winter and "watching" dust haze report at some upwind desert stations such as Faya Largeau and Bilma.
- Burns (1961) proposed that dust haze should be forecast over Nigeria following 24-48 hours if a persistent pressure gradient of 10hpa or more is observed on the surface isobaric chart over between two desert stations Abecha (14° N, 21.5 E) and Sebha (27° N, 14°E).







This finding became a very useful forecasting tool for more than a decade.

- Only isobaric analysis of the surface chart and a report of dust at Faya Largeau (18 N, 19 E), on the line joining Abecha and Sehba, are needed.
- The dust persists as long as the critical gradient is maintained but visibility improves significantly if the gradient falls below the critical value.
- The method failed frequently because there was not always a guarantee of dust even when the pressure gradient was l0hpa or stronger. Also the very scanty surface data coverage in the desert are often not readily obtained.







- Aina (1972) using both upper air and surface data. The scheme consisted of the following:
- Analysis of the surface isobaric chart is carried out for the determination of the pressure gradient as given by Burns (1961)
- The 900hpa chart, where the winds are usually strongest at this time, is also analysed using streamline and isotach analysis. If there is a "jet" (enclosed by the 30 knots isotach), then dust should be forecasted for the next day over the northern parts of Nigeria.
- The dust front, the leading edge of the 5km visibility isopleth, advances westwards with a mean speed of about 15knots to affect other parts of Nigeria and West Africa.
- The weakening or disappearance of the jet marks the beginning of the dust clearance and improved visibility.

**The scheme led to increased reliability in dust haze forecasting in Nigeria. However it failed operationally due to inadequate upper air data in the region.







- Omotosho (1989) proposed another method less dependent on both the observation from the upwind "informant" stations and communications.
- The scheme employed the use of a conservative parameter the equivalent potential temperature and its departure relative to the entire larger- scale environment of the northern area of the West Africa
- The method requires only the time-series of the near-surface departures of the equivalent potential temperature (ϑ_{e} '), at particular station, from its long-term value over the entire northern half of West Africa.
- Dust should be forecast tentatively two to three days ahead after the day of a maximum positive anomaly of ϑ_e' at the surface.
- Dust haze occurence is certain if the maximum is accompanied or followed within 24 by negative anomalies between 950 and 850 hPa.
- Clearance will not occur (that is, visibility will remain poor) as long as the negative anomalies below the 850-hPa level persist. Finally, the parameter is also found to be a good cold-spell predictor.







Forecasting of haboob

- Assess the state of the soil. If it has been dry for at least the last 2 days, the soil is typically dry enough to produce dust, provided sufficiently high wind speeds occur.
- Assess the potential for the development of deep convection In particular, downdraft convective available potential energy can be a useful indicator for the strength of associated downdrafts, and thus the potential intensity of the surface haboob.
- Forecasting Convective Dust Storms Assess the potential for convective organization and downdraft formation. This typically includes an analysis of vertical wind shear and mid-level dryness
- The intensity of the dust storm will be closely related to the intensity of the downdraft, and therefore the amount of evaporative cooling at mid and low levels.
- These factors will also allow an assessment of the likelihood of significant precipitation at the surface that could wash out dust after the initial storm.







- Owing to the difficulties in forecasting a storm before it has formed, nowcasting techniques are of great importance.
- Once a storm has formed and has been reported at SYNOP stations upstream (i.e. typically to the east), a forecast can be made based on simple extrapolation of the storm track.
- To achieve this, communications between stations are very crucial.







Satellite and Remote Sensing

- Recent improvement in satellite technology has greatly improved forecasting ability over data-sparse West Africa.
- The infra red and visible sensors aboard most meteorological satellite provide continuous imageries of cloud movement and aerosol concentration in the atmosphere.
- MSG IR composite imagery should be used to identify significant dust plumes. The high temporal resolution allows an extrapolation of the movement of an identified plume.
- Forecasters should be aware of the limitations of this product, including concealing of dust by clouds.
- Table 1 presents freely available satellite dust products for West Africa







Table 1: Freely available satellite dust products for West Africa.

	VIS AOT	DeepBlue AOT	Near-UV AOT	AAI	IR dust
Instrument (satellite)	MODIS (Aqua & Terra) ^a	MODIS (Aqua & Terra) ^a	OMI (Aura) ^b	OMI (Aura) ^c	SEVIRI (MSG) ^d
Wavelength	VIS	VIS/near-UV	near-UV	near-UV	IR
Spatial resolution	Re-gridded, $1^{\circ} \times 1^{\circ}$	Re-gridded, $1^{\circ} \times 1^{\circ}$	Re-gridded, $1^{\circ} \times 1^{\circ}$	Re-gridded, $1^\circ \times 1^\circ$	3 km × 3 km to ~5 km × 5 km
Temporal resolution	Daily	Daily	Daily	Daily	1 hourly
Surface	Dark	Bright land	Land & ocean	Land & ocean	Land
Quantitative	Yes	Yes	Yes	Yes ^e	No
Night	No	No	No	No	Yes
Near-real time	2–4 days later	2–4 days later	3 days later	3 days later	Yes

VIS: visible; UV: ultraviolet; IR: infrared.

"http://giovanni.sci.gsfc.nasa.gov/giovanni/. Select 'Daily' and 'Aerosol Optical Depth'.

^b http://giovanni.sci.gsfc.nasa.gov/giovanni/. Select 'Total Aerosol Optical Depth' and 'OMI'.

^chttp://giovanni.sci.gsfc.nasa.gov/giovanni/. Select 'Aerosol Index' and 'OMI'.

^d http://oiswww.eumetsat.org/IPPS/html/MSG/RGB/DUST/WESTERNAFRICA/index.htm.

"The aerosol index is sensitive to the height of the aerosol plume. Index values are increasing with increasing level height assuming a constant total aerosol loading.







Numerical Modelling

- Modelling involves using solutions of a set of hydrodynamics and thermodynamics equations starting from an observed atmospheric state, to calculate future weather conditions.
- This is because such methods allow a deeper and clearer understanding of the physical and other process involved in reproducing the phenomenon.
- Dust module is coupled to many NWP and Climate models notably CAMS-ECMWF, METEO FRANCE, MetUM, NAAPS, NASA-GEOS-5, NCEP-NGAC, NMMB/BSC-Dust







Bibliography

- Meteorology of Tropical West Africa: The Forecasters' Handbook, First Edition. Edited by Douglas J. Parker and Mariane Diop-Kane.
 © 2017 John Wiley & Sons Ltd. Published 2017 by John Wiley & Sons Ltd.
- Other published works cited in the presentation.







Thank you





