Dust emission and transport mechanisms in the central Sahara: Fennec ground-based observations from Bordj Badji Mokhtar, June 2011

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A detailed analysis of the first ever high-resolution ground-based dust observations in the remote central Sahara is presented from observations at Bordj Badji Mokhtar (BBM), taken during the Fennec project in June 2011. Detailed case studies are presented for three dust-producing mechanisms (cold pool outflows, low-level jets (LLJs), and dry convective plumes). The results confirm the importance of cold pools in dust emission and transport in the region. Forty-five percent of the dust over BBM is generated by local emission in cold pool outflows. Twenty-seven percent of the dust is advected rather than locally emitted dust; on three occasions, it is advected over 500 km to BBM by cold pool outflows. Dust that has been in long-range transport to the area within such cold pool outflows is found to carry larger particles and be responsible for higher dust loadings than fresh uplift. LLJs are of tertiary importance in the partitioning, responsible for 14% dust over BBM. Dry convective plumes are identifiable in the data but produce much less significant quantities of dust, approximately 2% of the June total. The cube of wind speed has a stronger correlation with dust emission than wind speed. The correlation is strongest (at 95% confidence) for LLJ-induced emission (0.88), followed by locally emitting cold pools (0.78).

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1. Introduction

The Sahara Desert is the dustiest place on Earth [Prospero et al., 2002; Washington et al., 2003]. Atmospheric dust has an important effect on the radiation budget [e.g., Haywood et al., 2005], global biogeochemical cycles [e.g., Mahowald et al., 2010], atmospheric circulation [e.g., Stanelle et al., 2010], and ocean circulation [e.g., Evan et al., 2011], as well as being a hazard to transportation and human health. The atmospheric mechanism responsible for dust emission in the Bodélé depression in Chad, a largely winter and spring time source, has been shown to be a strong low-level jet (LLJ) identifiable even in long-term mean wind fields [Washington and Todd, 2005; Washington et al., 2006]. By contrast, boreal summer central Saharan dust emission, which dominates the global atmospheric dust burden [Engelstaedter et al., 2006], is thought to be the result of several atmospheric mechanisms acting over multiple dust sources. Mechanisms include (i) the mixing down of momentum from low-level jets toward the surface after sunrise [e.g., Schepanski et al., 2009], (ii) high winds and turbulence at the leading edge of cold pool outflows [e.g., Emmel et al., 2010], and (iii) dust devils and dry convective plumes [e.g., Ansmann et al., 2009]. However, although there has been ground-based work in Tamanrasset, Hoggar Mountains, Algeria [Cuesta et al., 2008], much of what we know about the mechanisms of dust emission in the central Sahara has been inferred from satellite analysis [e.g., Schepanski et al., 2009] and numerical model simulations [e.g., Marsham et al., 2011]. Progress in understanding summer central Saharan dust emission has been hampered by a paucity of high-quality ground-based observations.

1.1. The Fennec Project

The Fennec program [Washington et al., 2012] was designed to gain observations from the data-sparse region of the central Sahara. Fennec includes three observational components: airborne (J. B. McQuaid et al., Overview and insights from airborne observations over the Sahara during Fennec 2011 and 2012, manuscript in preparation, 2013), satellite [Banks et al., 2013], and ground-based. The ground-based component comprises a network of remote automatic weather stations [Hobby et al., 2013] and two supersites: Zouerate, Mauritania [Todd et al., 2013] and Bordj Badji Mokhtar (BBM) on the Algerian-Mali border [Marsham et al., 2013]. BBM is within a few kilometers of...
the mean center of summertime dust loadings as estimated from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) data [Asphole and Washington, 2012]. Key aims of the Fennec program include the identification of mechanisms associated with dust emission and determining the contribution of these mechanisms to the total dust burden in the central Sahara.

1.2. Atmospheric Dust Emission Mechanisms

There are several different atmospheric dust emission mechanisms that operate in the Sahara, ranging from the scale of tens of meters to thousands of kilometers. The operation of those pertinent to this study are briefly summarized below.

1.2.1. Cold Pool Outflows

Cold pool outflows form from downdrafts of moist convection when evaporating or sublimating precipitation cools the air in the subcloud layer, allowing it to sink to the surface, particularly if the environment is dry adiabatic [e.g., Miller et al., 2008]. As the sinking air approaches the surface, it spreads away from the parent storm in a density current or outflow. Turbulence and high winds at the leading edge of the outflow (the gust front) can raise substantial “walls” of dust [Flamant et al., 2007; Knippertz et al., 2007; Miller et al., 2008; Williams et al., 2009; Emmel et al., 2010; Solomos et al., 2012], especially where the threshold velocity for sediment entrainment is low. Dust storms caused by cold pool outflows are frequently called “haboobs.” If a density current propagates into a zone of strong static stability such as a nocturnal inversion it can initiate a bore ahead of the current [e.g., Smith, 1988; Fulton et al., 1990; S. E. Koch et al., 1991]. The typical signature of a passing bore is a short-lived pressure rise, increase in wind speed and shift in wind direction. Unlike during a density current, there is no decrease in surface temperature; pure bores do not transport mass [Simpson, 1997; Kingsmill and Crook, 2003].

1.2.2. Low-Level Jets

LLJs frequently form in desert regions after sunset when turbulent heating dies down and winds aloft become decoupled from the surface. In conditions of a moderate or strong pressure gradient the flow can then become geostrophic above the nocturnal inversion [e.g., Blackadar, 1957; Knippertz and Todd, 2012]. After sunrise, turbulent mixing begins to increase and momentum from the LLJ can be mixed down to the surface [e.g., Washington et al., 2006; Todd et al., 2008]. LLJs can be found in the Hamattan [Washington and Todd, 2005] and monsoon flow [Parker et al., 2005]. Satellite-based work suggests that they play a dominant role in dust emission across the Sahara [Schepanski et al., 2009].

1.2.3. Dry Convective Plumes and Dust Devils

On the smallest scale, dry convective plumes and dust devils lead to dust emission. Under dry conditions with intense surface heating, localized turbulent circulations can develop producing short-lived plumes or vortices associated with dust lofting [Sinclair, 1969; Kaimal and Bussinger, 1970; J. Koch and Renno, 2005; Balme and Greeley, 2006; Ansmann et al., 2009]. Dust devils are rotating vortices, with a mean diameter of 7 m and heights from a few meters to over 1 km [Balme and Greeley, 2006]. Dry convective plumes are non-rotating updrafts, with diameter ~100 m [Ansmann et al., 2009]. Dry convective plumes observed in the Saharan summer reach heights of 1–2 km in Tamanrasset, Algeria [Cuesta et al., 2008] and <1 km in Ouazarzate, Morocco [Ansmann et al., 2009].

1.2.4. Monsoon Surges

Penetration of the West African Monsoon (WAM) into the Sahara can raise dust emission as it acts as an intrusive surge, with strong wind speeds occurring at the leading edge of the monsoon flow [Bou Karam et al., 2008]. WAM surges behave like large-scale density currents, but since they also transport moisture into very hot regions they can promote deep moist convection and subsequent density currents within the monsoon flow itself [Bou Karam et al., 2008]. Indeed, it is not always easy to separate the two [Marsham et al., 2013].

This paper presents a detailed analysis of summer dust production from observational data in the heart of the central Sahara during the Fennec Intensive Observation Period (IOP) of June 2011. June was chosen since the satellite-derived absorbing aerosol index from the Total Ozone Mapping Spectrometer and Ozone Monitoring Instrument demonstrates that June is the dustiest month in the central Sahara [e.g., Engelstaedter et al., 2006]. The aims of this paper are to (1) document the main dust outbreaks during the 2011 Fennec IOP at Bordj Badji Mokhtar, (2) identify the mechanisms associated with dust production and establish their relative importance, and (3) document the characteristics of the key dust-producing mechanisms and their relationship with wind speed for dust emission. The paper is structured as follows. Section 2 describes the location of the observations, the instrumentation, and additional data employed. Sections 3 to 6 describe the detection and attribution of dust events and their characteristics. Section 7 presents a selection of detailed case studies. Sections 8–10 provide interpretation of the dust mechanisms in relation to aims 2 and 3. The conclusions are presented in section 11.

2. Data

This section describes observational data analyzed in this paper, notably from the Fennec supersite at BBM, and supporting satellite and numerical model products.

2.1. The Bordj Badji Mokhtar Supersite During the Fennec 2011 IOP

The existing synoptic station of Bordj Badji Mokhtar (21.38°N, 0.92°E; WMO ID: 60686; altitude 420 m above sea level) was chosen as the location for Fennec supersite 1. It is located in southwestern Algeria, near the border with Mali. BBM was heavily instrumented for almost the entire duration of June 2011, the first Fennec (IOP). Marsham et al. [2013] provide an overview of the meteorology over BBM for the period. The instrumentation consisted of a HALO Photonics Streamline 1.55 μm Doppler lidar, a Scintec MFAS phased array sodar, a Cinem sun photometer, a vacuum pump aerosol sampler, an inverse nephelometer (670 nm) and a real-time absorption reflectometer (both at 2 m), Vaisala RS92 GPS radiosondes (launched at 3-hourly to 6-hourly intervals), and a 15 m mast (the “flux tower”) instrumented with 20 Hz sonic anemometers at 10 m and 15 m. At 2 m on the mast, pressure measurements and passively ventilated measurements of temperature and humidity were taken. A separate 2 m mast was used to support a Kipp and Zonen CNR4 radiometer. Filters from the aerosol sampler are still being
analyzed, and the data are not presented in this paper. There are individual periods when observations are missing: these are mentioned in the text and in the captions, where possible including the most likely explanation for the data gaps.

[12] Instrument measurement precision is as follows: nephelometer scattering \( \times 10^4 \text{m}^{-1} \), relative humidity \( \pm 2\% \), temperature \( \pm 0.3 \text{C} \), pressure \( \pm 0.5 \text{hPa} \), and anemometer wind speed \( \pm 0.1 \text{m/s} \). Wind speeds are reported at 10 m above ground level (agl) unless otherwise stated. The Doppler measurement precision of the lidar is \( \leq 10 \text{cm} \) in the boundary layer [Pearson et al., 2009]; its minimum range is 75 m agl. A standard lidar inversion technique, the Klett-Fernald method, is employed to obtain the aerosol backscatter coefficient profile [Fernald et al., 1972; Klett, 1981; Fernald, 1984]. Lidar horizontal wind speed measurements are derived using a modified velocity-azimuth display algorithm [Browning and Wexler, 1968; Banta et al., 2002] and have a precision of \( \pm 0.1 \text{m/s} \). Aerosol Optical Thickness (AOT) is reported at 500 nm, and the \( \alpha \) is calculated from 440 and 675 nm. Both AOT and \( \alpha \) are level 1.5 (cloud-screened). AOT is accurate to \( \pm 0.01 \). The sun photometer formed part of the Aerosol Robotic Network (AERONET) project [Holben et al., 1998] during its deployment. Unless otherwise stated, times are all in UTC.

### 2.2. Satellite and Numerical Model Data

[13] False color imagery from SEVIRI on board the Meteosat Second Generation satellite at 0°N, 0°E [Lensky and Rosenfeld, 2008] is used to help identify deep cloud and dust. Colors map onto features as follows: deep cumulonimbus, dark red; thick water clouds, gold; clouds with small particles, green; thin cirrus, black; desert dust, pink; surface quartz sand, light blue/gray. The Cloud-Aerosol Lidar with Orthogonal Polarization [Winker et al., 2003] on board the CALIPSO satellite is used to provide information on aerosol profiles. Operational fields (18 h UTC initialization) from the UK Met Office Africa Limited Area Model (LAM), 12 km resolution, are used to provide a regional context for interpretation of the supersite data.

### 3. Detection and Attribution of Dust Events at BBM

[14] The time series of nephelometer scattering (Figure 1a) during June 2011 was used to identify dust event periods. Since this is the sampling base, from now onward the IOP will be defined as the period when nephelometer scattering data are available (i.e., from 2020 h on 5 June to the end of 30 June). Nephelometer scattering at 670 nm can be used as a proxy for dustiness since (i) dust scatters visible light [e.g., Redmond et al., 2010] and (ii) mineral dust is the dominant aerosol in the region, especially in summer [Herman et al., 1997; Engelstaedter et al., 2006]. Ground-based nephelometer scattering has also been used previously as a criterion for dust event identification [Marrane et al., 2002]. At 2 m height, the nephelometer scattering will identify both local emission and also advection [Marsham et al., 2013]. Any period where nephelometer scattering was \( > 2 \times 10^{-4} \text{m}^{-1} \) was designated a “dust event”; below this threshold, it proved very difficult to unambiguously determine any individual events. Thirty-two
individual events were identified in this way. The peak nephelometer scattering of each event was then used to rank them by strength. Ranking was not performed using the lidar data since in situations when the lidar beam is strongly attenuated, column-integrated lidar measurements will not give a true representation of the strength of an event. The sun photometer was not used to create a ranking since it provides no nocturnal data and therefore misses many dust events (10/32 events started between sunset and sunrise).

Each of the 32 dust events were attributed to their most likely causal mechanism (Figure 1c). This was done using all available observations made at BBM, SEVIRI false color composites, and Africa LAM fields, using existing literature as a guide for attribution. Lines of ground-based evidence to help attribution include the following: (i) sudden changes in humidity, temperature, and pressure to identify cold pool outflows [e.g., Miller et al., 2008; Emmel et al., 2010]; (ii) timing of events: LLJs likely to lead to dust emission in the mid-late morning, dry convective plumes most likely to occur in the afternoon when surface temperatures are highest; (iii) structure in lidar backscatter profile: a raised “nose” is likely to be the leading edge of a haboob [e.g., Solomos et al., 2012], a narrow spire of raised backscatter is likely to be from a dry convective plume [e.g., Cuesta et al., 2008]; and (iv) timing of wind speed changes: a progressive change is likely to be associated with momentum mix-down from a LLJ [e.g., Washington et al., 2006], whereas a sudden spike is likely due to the passing of a cold pool front [e.g., Miller et al., 2008] or dry convective plume if the prior winds are <7 m/s [Ansman et al., 2009].

Lines of satellite evidence for attribution include presence of deep convection and possibly arcus clouds for cold pool outflows [Knippertz et al., 2007] and identification of dust storm origin by backtracking 15 min SEVIRI time steps. Additionally, Africa LAM fields provide important continental-scale context, although cold pools will not be represented since the resolution (12 km) is too low and convection is parameterized [Marsham et al., 2011; Solomos et al., 2012]. An “automated” approach to determine the dust production mechanism in each case was considered but not used since most time series (especially the flux tower measurements) have several gaps (explained in the captions, e.g., on 13, 17, 21, and 29 June). Key observations for the strongest dust events during the IOP including wind speeds, Ångström exponents, AOT, SEVIRI, event duration, and nephelometer scattering are given in Table 1.

4. Distinguishing Local Emission From Dust Advection

Distinguishing local dust emission from dust advection over the site is difficult to do with the instrumental setup available (section 2.1). AOT, lidar backscatter, and nephelometer scattering at 2 m provide measurements of dustiness, as distinct from dust emission. Ångström exponents are sometimes used to help distinguish emission from advection [e.g., Knippertz et al., 2009], but here it is difficult since (i) so many events occur at night when the sun photometer is not operational (section 3) (ii) it is not clear that at BBM low Ångström exponents imply local emission (discussed in section 9). Marsham et al. [2013] use uplift potential, the wind-dependent component of the Marticorena and Bergametti [1995] dust uplift parameterization, to separate emission from advection at BBM. However, they still report uncertainty regarding the wind speed threshold for emission.

Here, we propose a local emission threshold based on a dust event which, of all the events during the IOP, shows the strongest evidence for local dust emission. This evidence is (i) changes in wind speed correspond closely to changes in 2 m nephelometer scattering (Figure 2a), (ii) the increases in 2 m nephelometer scattering lead lidar backscatter (which only measures above 75 m) by up to 2 h (Figure 2b), and (iii) the mid-morning timing of the wind speed increase suggests that it represents local LLJ momentum mixing down to the surface. During this event (ranked 12th dustiest of the IOP), the relationship between wind speed and nephelometer scattering shows a clear threshold at 8 m/s. Below 8 m/s, nephelometer scattering is low and has a narrow range between $3 \times 10^{-4}$ m$^{-1}$ and $4.5 \times 10^{-4}$ m$^{-1}$. Above 8 m/s, although there is some variability, the general trend is a substantial increase in nephelometer scattering up to $13 \times 10^{-4}$ m$^{-1}$ (Figure 2c).

The choice of an 8 m/s threshold for emission is similar to other work: Marticorena et al. [1997] and Callot et al. [2000] suggest a 7.5 m/s threshold for the 1° box containing BBM (also for winds at 10 m height). In order to take into account related studies and the fact that some dust events may contain a mixture of advected and locally emitted dust, we propose a range as follows: advected dust, wind speed $\leq$ 6 m/s (the lowest threshold in the range chosen by Marsham et al. [2013]); mixture of advected and emitted dust, 6 < wind speed $\leq$ 8 m/s; locally emitted dust, wind speed $>=$ 8 m/s (Table 2).

5. Estimating Dust Storm Heights

Estimating the height of dust storms at BBM during the IOP proved problematic since on many occasions (particularly during cold pool outflows) the lidar signal was strongly attenuated. Since AOT values were so high, there was little the inversion procedure could do about this. Williams et al. [2009] report haboob dust top heights in Niamey, Niger, for 12 late summer cases to vary from 2000 to 5000 m with a mean of 3500 m, substantially lower than suggested by the lidar data at BBM. This may be partly because Niamey is further away from the main summer dust source regions than BBM [Scheepanski et al., 2007; Ashpole and Washington, 2012]. But as the attenuation of the lidar backscatter makes determination of the heights from this data set difficult, we suggest the depth of the convective boundary layer (CBL) as a guide for maximum dust plume height. Within the CBL, dust will be mixed fairly rapidly. The top of the CBL is defined as the height at which potential temperature (derived from the radiosondes) begins to increase with height. However, this proxy is only strictly valid for events which are caused by local emission, when the dust will for a short time at least not be elevated/penetrate into the Saharan residual layer [Cuesta et al., 2009; Messager et al., 2010]. This proxy is not valid for dust some way behind the leading edge of cold pools which can be lifted above the CBL [Flamant et al., 2007; Bou Karam et al., 2008]. However, attenuation limitations notwithstanding, this particular scenario does not appear to have occurred at BBM during the IOP. CBL heights, where identifiable, are included in
| Date      | Overall Nephelometer Rank | Nephelometer Rank by Mechanism | Advection/ Emission/ Mixture? | Dust Identified on SEVIRI? | 440–675 nm Ångstrom (z) Event Average | 500 nm AOT Peak (Event Average) | Duration (h) | Peak nephelometer Scattering ($\times 10^4 m^{-1}$) | Wind Speed (m/s) at Peak Nephelometer Scattering | Minimum Dust Layer Thickness (m) (Time Observed) | CBL Height (m) (Time Observed) |
|-----------|---------------------------|---------------------------------|-----------------------------|---------------------------|----------------------------------------|---------------------------------|-------------|------------------------------------------------|------------------------------------------------|-----------------------------------------------|---------------------------|
| 29th 2200h| 1                         | 1                               | Emis                        | Y                         | N/A                                    | N/A                             | 6.8         | 107                                           | 17.5                                           | 300 (21 h)                                    | N/A (21 h)                |
| 17th 1700h| 3                         | 2                               | Emis                        | Y                         | N/A                                    | N/A                             | 9.8         | 38                                            | 11                                             | 800 (21 h)                                    | N/A (21 h)                |
| 13th 0530h| 4                         | 3                               | Adv                         | Y                         | –0.01                                  | 4.4 (3.3)                       | 11.7        | 36.5                                          | 6                                              | 300 (9 h)                                     | 400 (9 h)                |
| 20th 2300h| 5                         | 4                               | Mix                         | Y                         | 0.00                                   | 3.5 (2.5)                       | 20          | 27                                            | 7                                              | 500 (12 h on 21st)                           | 800 (12 h on 21st)        |
| 21st 1900h| 6                         | 5                               | Mix Under cloud             | Y                         | –0.03                                  | 3.3 (2.2)                       | 11          | 25                                            | 2.5                                             | 500 (12 h)                                    | 800 (12 h)                |
| 17th 0600h| 7                         | 6                               | Adv                         | Y                         | –0.03                                  | 3.3 (2.2)                       | 11          | 25                                            | 2.5                                             | 500 (12 h)                                    | 800 (12 h)                |
| 29th 0730h| 2                         | 1                               | Emis                        | 3 h late and not that pink | N                                      | 2.6 (2.3)                       | 13.4        | 55                                            | 19                                             | 700 (12 h)                                    | 900 (12 h)                |
| 26th 0600h| 12                        | 2                               | Emis                        | N                         | 0.33                                   | 1.2 (0.9)                       | 8.2         | 13                                            | 15.5                                           | 400 (9 h)                                     | 400 (9 h)                |
| 18th 0700h| 17                        | 3                               | Emis                        | no signal in background dust | 0.05                                   | 2.2 (1.7)                       | 9.1         | 7                                             | 8.5                                             | 500 (12 h)                                    | 1000 (12 h)               |
| 25th 0700h| 22                        | 4                               | Emis                        | N                         | 0.19                                   | 1.9 (1.4)                       | 8.8         | 6                                             | 11                                             | 600 (12 h)                                    | 1600 (12 h)               |
| 16th 0700h| 25                        | 5                               | Emis                        | 3 h late and not that pink | 0.25                                   | 0.8 (0.8)                       | 6           | 4.5                                           | 15                                             | 400 (9 h)                                     | N/A (9 h)                |
| 24th 1600h| 11                        | 1                               | Emis                        | N/A                        | 0.11                                   | 1.2 (1.2)                       | 1.2         | 19                                            | 11                                             | 1300 (16 h)                                   | 3600 (15 h)               |
| 27th 1500h| 19                        | 2                               | Emis                        | N/A                        | 0.17                                   | 1.2 (1.2)                       | 2           | 6.5                                           | 11.5                                           | 800 (16 h)                                    | 4400 (15 h)               |
| 23rd 1600h| 20                        | 3                               | Emis                        | N/A                        | 0.08                                   | 1.3 (1.2)                       | 2           | 6                                             | 11                                             | 1000 (17 h)                                   | 4600 (15 h)               |
| 22nd 1800h| 21                        | 4                               | Emis                        | N/A                        | 1.1                                    | 6                                 | 10          | 10                                           | 10                                              | 1000 (18 h)                                   | 4600 (18 h)               |

Cold pool outflows

Low-level jets

Dry convective plumes

The ranking/identification process is discussed in section 3. For discussion of categorization of dust as advected/emitted/mixed and thresholds, see section 4. Ångstrom exponents presented are averaged over the course of each event. Both event peak AOTs and event-averaged AOTs are shown. Dust layer thickness statistics are based on the height of the $10^{-4} m^{-1} sr^{-1}$ lidar backscatter contour and are likely to be conservative, especially in cases of attenuation. For discussion of dust layer heights, see section 5. CBL = convective boundary layer, top height is diagnosed from radiosondes (defined as height at which potential temperature begins to increase with height). N/A = not available, N/I = not identifiable.
Table 1, together with a gauge for the absolute minimum dust layer thickness, the height of the $10^{-5} \text{m}^{-1} \text{sr}^{-1}$ lidar backscatter contour. This will be particularly conservative in cases of strong attenuation, as discussed.

[21] The CALIPSO space-borne lidar can be used to gauge dust plume heights. However, CALIPSO data are not available on 4 June or 6–14 June 2011. Of the remaining days, there is only one case (early morning of 18 June) for which the satellite passes close enough to BBM and at the right time to gauge dust plume height. On this case, thick dust is detected to 2000 m above the surface (not shown). Wind speeds of between 4 and 8 m/s at the time of the overpass suggest that it is dust remaining from the strong emission event of the previous night (see section 7.2.2).

6. Dust Detection by SEVIRI

[22] The false color SEVIRI satellite dust detection algorithm [Lensky and Rosenfeld, 2008] is used frequently to identify dust over the North African region, both for nowcasting and for research [Schepanski et al., 2007; Knippertz, 2008; Marsham et al., 2008; Bou Karam et al., 2010; Knippertz and Todd, 2010; Ashpole and Washington, 2012; Marsham et al., 2013]. Central to the appeal of SEVIRI is the very high temporal resolution of the data (15 min), which allows qualitative inspection of emission sources and inference of mechanisms. In the case of the central Sahara, the performance of SEVIRI has been difficult to assess owing to the paucity of comparatively high-quality ground-based observations. In the case of data from BBM, SEVIRI is more reliable in identifying cold pools than LLJs (Table 1). With sufficient moisture, cold pool outflows can generate a line of arc clouds along the leading edge [e.g., Knippertz et al., 2007]. Five of the six haboobs listed are detectable in SEVIRI, but one event is not as the area is covered by cloud. Of the five strongest LLJ events at BBM in June 2011, none is clearly detectable using SEVIRI (Table 1). Two are not identifiable at all, one is not detectable against the background dust, and two are detected 3 h after the lidar on the ground detects them and do not show up strongly as the cold pool events. One possible reason for the missed SEVIRI detection of the LLJs is that the dust generated by the breakdown of the LLJ does not penetrate deep enough into the atmosphere to be identified by the algorithm, although precise dust heights are difficult to establish (section 5 and Table 1).

[23] As demonstrated by Brindley et al. [2012], SEVIRI detection can also fail if a surface temperature inversion is present in the early hours of the morning. This is the case at 0600 h on the LLJ days of 16 and 29 June for example. This would also explain why, during the 13 and 17 June cold pool events which arrive at BBM at roughly 0600 h, the SEVIRI images do not appear bright pink until the late morning, 2–3 h after the dust maximum in the lidar backscatter and after the inversion has been broken. On 13 June, the 0600 h surface inversion is about 2°C (Figure 7h); on 17 June, it is about 5°C (Figure 5h). Since many cold pool outflows arrive at BBM in the late afternoon or early evening (Figure 1c), when a temperature inversion is not present or only beginning to develop, they tend to be detected more easily by the algorithm.

[24] If the SEVIRI algorithm has difficulty detecting LLJ-induced emission in other regions of the Sahara, analyses based on SEVIRI may be under-representing

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**Table 2.** Wind Thresholds Used to Discriminate Between Local Dust Emission and Dust Advection

| Type                          | Threshold       |
|-------------------------------|-----------------|
| Local emission                | Wind speed $\geq$ 8 m/s |
| Advected dust                 | Wind speed $\leq$ 6 m/s |
| Mixture of advected and emitted dust | 6 $<$ Wind speed $< 8$ m/s |

*Wind speed is at 10 m height. See section 4 for full details.*
the importance of LLJs for Saharan dust uplift. There is therefore a possibility that results such as those of Schepanski et al. [2009], which already point to the importance of low-level jet breakdown as a dust emission mechanism, are conservative.

7. Analysis of Dust Mechanisms at BBM During the IOP

[25] In this section, the three principal dust mechanisms in operation at BBM (cold pool outflows, low-level jets, and dry convective plumes) are analyzed in turn. Each subsection contains a selection of case studies followed by a discussion of notable characteristics.

7.1. Cold Pool Outflows

[26] A total of 20 cold pool outflow events were identified over BBM during the IOP: nine containing mostly advected dust and 11 generating local emission or at least containing a mixture of local and advected dust (see section 4 and Table 2 for how the distinction is defined). This is a high number of such events: for comparison, Todd et al. [2013] report only four cold pools reaching Fennec supersite 2 at Zouerate, western Mauritania, during the June 2011 IOP, and Cuesta et al. [2008] report only eight cold pools between May and September 2006 at Tamanrasset, southern Algeria. In the former case, this small number is probably mainly due to the long distance between Zouerate and both monsoon and Atlas convection; in the latter case, it is likely because the rock/gravel soil at Tamanrasset is too coarse to permit much local emission [Callot et al., 2000; Cuesta et al., 2008]; therefore, for the most part, only advected dust contributes.

[27] The dustiest four cold pool outflow events during the Fennec IOP (as ranked by the nephelometer time series, Table 1 and Figure 1) are presented here.

7.1.1. 29 June 2011, 2100 h

[28] By far the largest peak in the nephelometer scattering time series \(10^7 \times 10^{-4} \text{ m}^{-1}\), almost twice as high as the next highest peak at 0730 h the same day; Table 1) is the haboob event beginning at 2100 h on 29 June. On the evening of 29 June, BBM is just to the south of the center of the Saharan Heat Low (SHL). The center is very well defined, with the highest 925 hPa temperatures \(>39.5^\circ C\) and lowest geopotential heights \(<730 \text{ hPa}\) almost exactly colocated (Figure 3c). The SHL location is between the June and July mean presented by Lavaysse et al. [2009], as expected for a date so late in June. SEVIRI shows deep convection developing to the SW of the Hoggar Mountains in southern Algeria from midday on 29 June. The moisture for this convection is provided by a monsoon surge which arrives in the morning (Figure 4h and see also Marsham et al. [2013]); the surge is likely promoted by the strong SHL center to the north of BBM. At 1830 h, a density current/dust front begins to propagate westward away from the convective system, with its leading edge marked by a thin band of cloud. These may be arc clouds, which have been observed at the leading edge of density currents propagating downslope from the Atlas Mountains [Knippertz et al., 2007]. The arc cloud/haboob front passes over BBM at 2130 h (Figure 4f), in excellent agreement with the lidar and nephelometer observations (Figure 4a).

[29] At 2130 h, 10 m winds show a sharp surge from 6 m/s to almost 22 m/s then steadily decrease until midnight with fluctuations between 9 m/s and 20 m/s (Figure 4c). These wind speeds are more than strong enough for local dust emission. Vertical winds \((w)\) also show a strong jump at 2130 h, from roughly \(\pm 1 \text{ m/s}\) to \(\pm 3 \text{ m/s}\) (Figure 4e). The hourly mean vertical winds during the event are all negative (net downward component). With the passing of the front, relative humidity shows a rapid drop and rise of 2%, corresponding to a fluctuation in dew point temperature of 2.9°C (from 18.6°C to 15.7°C). This is followed by a slightly more gradual decrease to a plateau at 32% (not shown). Recorded temperatures show...
the same structure: a rapid drop and rise of 2.5°C followed by a slightly more gradual decrease to plateau at 32°C. At 2130 h, there is also a sharp decrease in pressure of 1 hPa, and wind direction rapidly changes by 50° from roughly 200° (SSW) to roughly 150° (SSE) (Figure 4g). There are no Cimel sun photometer measurements of the cold pool since it passes at night.

7.1.2. 17 June 2011, 0600 h

The haboob that occurs on the morning of 17 June has the seventh highest peak in nephelometer scattering of the IOP (Table 1), $25 \times 10^{-4} \text{m}^{-2}$ at 1020 h. SEVIRI shows that the dust arrives at BBM as part of a cold pool outflow, which is spawned from a mesoscale convective complex (MCC).
over western Niger. The density current begins to propagate northwestward from the MCC at 1800 h on 16 June, and the front arrives at BBM at 0600 h on 17 June (Figures 5a and 5g), covering 500 km in 12 h with an average speed of 11.6 m/s. SEVIRI-based estimates of propagation indicate that the current slows down as expected as it progresses:

between 1800 h and 2100 h, the leading edge average speed is 18.1 m/s; between 0300 h and 0600 h, this reduces to 10.5 m/s.

[31] Near 0500 h, 1 h before the dust arrival at BBM, there are two spikes in 10 m wind speed (11.5 and 8.2 m/s, Figure 5c) accompanied by two jumps in pressure with a
sudden 0.8 hPa drop in between (Figure 5d). Ten-meter wind direction (Figure 5f) at 0500 h is southeasterly (the direction from which SEVIRI shows the density current to propagate), in contrast to the northerlies and northeasterlies that occur before and after. The mentioned changes are short lived (wind speed subsides after 15 min) and are not followed by a near-surface temperature decrease (Figure 5). As such, they fulfill the typical criteria used to define a bore (section 1.2.1), suggesting that one precedes the density current which brings the dust to BBM.

[32] At 0600 h at BBM, there is a clear jump in lidar backscatter values from $10^{-5.5} \text{ m}^{-1} \text{ sr}^{-1}$ to $10^{-4.25} \text{ m}^{-1} \text{ sr}^{-1}$ above 400 m agl (Figure 5a). Flux tower data was not recorded from 0600 h to 0800 h, possibly due to strong winds in the gust front damaging the instrumentation, but this cannot be verified since the only other wind observations are from the local station at 0600 h (before dust is detected at the surface) which record a speed of only 4.1 m/s. The haboob arrives at BBM with a raised nose, the structure of the lidar backscatter suggesting it is tilted toward the direction of the propagation (Figure 5a). The nephelometer scattering data supports this hypothesis, as nephelometer scattering values (at 2 m agl, Figure 5a) only begin to increase half an hour after the dust is seen in the lidar backscatter, once the main body of the current arrives. Combined with SEVIRI-based estimates of the leading edge propagation between 0600 h and 0630 h, this suggests that the nose has a horizontal extent of 9.9 km.

[33] The increase in scattering from 0800 h onward is coincident with a steady increase in the magnitude of the 10 m vertical wind (not shown). The minimum dust layer thickness is 500 m at 1200 h, 300 m below the CBL height of 800 m (Figure 5a and Table 1). The dust storm is also represented in the AOT (peak of 3.3 at 1330 h, Figure 5c). There are no AOT data before 1330 h on 17 June, and since the lidar and nephelometer peak several hours before 1330 h, it is likely that at its thickest, the AOT was greater than 3.3, making it a very major dust storm.

[34] Throughout the passage of the density current over BBM (i.e., until roughly 1700 h), 10 m horizontal wind speeds are low, fluctuating mainly between 1 and 7 m/s (Figure 5c). At the time of peak nephelometer scattering, wind speed is only 2.5 m/s (Table 1). This suggests that the dust is mostly advected (section 4 and Table 2). Angstrom exponents for this event are all below 0 where recorded and as low as −0.04 (Figure 1d), which implies large particle sizes. These Angstrom exponents are the lowest of the 2011 IOP. This is somewhat surprising since large particle sizes are usually more dominant in freshly emitted rather than transported dust (in this case, transported some 500 km; discussed further in section 9).

7.1.3. 17 June 2011, 1700 h

[35] The third largest peak in the nephelometer time series for June 2011 (Table 1) was associated with a cold pool outflow that reached BBM at approximately 2140 h on 17 June (Figure 5a). Nephelometer scattering peaks at $38 \times 10^{-4} \text{ m}^{-1}$ at 2300 h. This density current was proceeded by two others, at 0600 h (discussed in section 7.1.2) and at 1700 h (Figure 5a). The 1700 h and 2140 h haboobs are described together since SEVIRI imagery suggests that both originate from the same convective cell and, unlike the 0600 h event, wind speeds in both cases are suggestive of local emission (Figure 5c). The arrival of the 1700 h cold pool outflow appears to disrupt the boundary layer structure: at 1500 h, the CBL height is 3200 m, but at 1800 h (still before sunset), a fluctuating stable layer is present up to 2000 m, possibly caused by the cold pool (Figure 6). Above 2000 m, the air is well mixed to 4000 m, still growing into the residual layer, later in the afternoon than commonly observed in the Sahara [Cuesta et al. 2009]. At 2140 h, lidar backscatter shows a sharp transition from a dusty column up to at least 900 m agl, caused by the 1700 h haboob, to a much shallower but thicker dust layer (Figure 5c), which suggests that the backscatter after 2140 h is high enough to attenuate the lidar signal.

[36] SEVIRI shows that the density current emanates from an MCC that evolves to the south west of the Hoggar, in a similar way to the 29 June evening cold pool (section 7.1.1). The convection is evident from 1500 h onward, where it develops over an extensive dust layer. The convection is likely promoted by the very high temperatures to the southwest of the Hoggar, over 39.5°C at 925 hPa (Figure 3a). Geopotential heights over the region show that the SHL is not as intense as later in the month, however (compare Figure 3c). Cloud is present over BBM from 1700 h onward. A haboob front emerges from the MCC at 2015 h and propagates southwestward. The satellite imagery shows the front crossing BBM at approximately 2130 h (not shown), in very good agreement with the ground-based data. The density current then propagates radially out from BBM over a distance of approximately 300 km during the following 8 h.

[37] At 2140 h, 10 m wind speeds jump from 6 m/s to over 17 m/s (Figure 5c) and vertical winds from ±0.5 m/s to ±3.5 m/s (Figure 5b). This is likely to be the signature of the gust front. Wind speeds then fluctuate between 8 and 16 m/s until midnight. These speeds are high enough for local dust emission (Table 2). As on the evening of 29 June, hourly mean vertical winds during the event are all downward. The sodar (not shown) measured wind speeds >15 m/s for all but the lowest 50 m of the atmosphere after 2200 h. On 18 June, 10 m wind speeds decrease from 10 m/s at midnight to 3.5 m/s at 0300 h (Figure 8c). The nephelometer scattering follows this decreasing trend very closely, which is further evidence that the emission was local.
Wind direction at 10 m during the passing of the density current was steady and southeasterly (Figure 5f). Between 2130 h and 2200 h, the period within which the current front passed BBM, wind direction changed from southerly to southeasterly. There are no sharp changes in pressure in this period (Figure 5d); no coincident temperature or relative humidity data are available from the flux tower.

It is interesting that this cold pool event, the third strongest dust event over BBM in June 2011, followed another very strong haboob earlier the same day (see section 7.1.1 above). Density currents are known to initiate convection under certain conditions, even far away from their origin [e.g., Thorpe et al., 1982; Carbone et al., 1990; Moncrieff and Liu, 1999] and convection can then initiate new density currents. It is possible that the density current which arrived at BBM at 0600 h helped promote the convection that began at 1500 h by enhancing lifting of air: the morning density current propagated from the southeast, and prevailing winds were northeasterly. This positive feedback will be discussed further in section 7.1.5.

### 7.1.4. 13 June 2011, 0530 h

The cold pool outflow that arrived at BBM on 13 June at 0530 h was the fourth largest event in the nephelometer time series (Table 1). It is similar to the 17 June event (section 7.1.2). Nephelometer scattering peaks at $37 \times 10^{-4} \text{ m}^{-1}$ at 1120 h (Figure 7a). The earliest CIMEL AOT available on the day, at 1240 h is 4.4 (Figure 7c), a remarkably high value (although it may be cloud contaminated: the lidar detects no clouds but a dust/cloud mix is present over the BBM region in SEVIRI, not shown). The cold pool was spawned from deep convection to the east of the Algeria-Niger-Mali triple point. It is visible in the SEVIRI imagery from about 1930 h on 12 June. The dust/arc front is most clearly visible at 2130 h (Figure 7e). The front propagates westward toward the triple point and then veers northwesterly. Its arrival is very clear in the BBM lidar backscatter (Figure 7a). The LAM 925 hPa wind vectors (Figure 7g) suggest that the current propagates against a headwind, and, as on 17 June, the elevated “nose” (reaching at least 700 m agl) arrives first, and the nephelometer scattering only begins to increase an hour later, at 0630 h. At 0900 h, the minimum dust layer thickness is 300 m, slightly below the CBL height of 400 m (Figure 7a and Table 1). The average (SEVIRI-derived) propagation speed of the current from 1900 h to 0530 h is 16.2 m/s, 4.6 m/s faster than the current on 17 June.

At 0220 h, 3 h 10 min before the arrival of the haboob at BBM, surface pressure increases by 0.5 hPa followed by a marked spike in 10 m wind speed, up to over 17 m/s (Figure 7). At the same time, the 10 m vertical wind component shows an increase from roughly ±1 m/s to $-3.5 < w < 2.5$ m/s (Figure 7d). Similar values are seen in the lidar-derived vertical wind, up to 2800 m agl (Figure 7b). This suggests that, as on the morning of 17 June, the density current may be preceded by a bore. Twenty minutes after the initial pressure increase, coincident sudden spikes in temperature (increase of 5.5°C) and relative humidity (increase of 5%) are observed (Figure 7f), the latter corresponding to a change in dew point temperature of 7.2°C (from 17.4°C to 24.6°C). The hourly mean w component at 10 m is strongly downward at the time (Figure 7d). Radiosondes show that the temperature inversion below 100 m agl is stronger at 0000 h than at 0600 h (Figure 7h). These findings all suggest mixing down of warm air at 0240 h, possibly caused by a bore, as can happen when one breaks a temperature inversion [Clarke et al., 1981].

After the passing of the nose of the density current, 10 m wind speeds are low. Between 0600 h and 0800 h, they decrease from 5.5 m/s to 3 m/s, then from 0800 h to 1100 h increase to 6 m/s (Figure 7c). This suggests, as on 17 June, that the dust passing over BBM behind the leading edge is transported, not emitted. Again like 17 June, Ångstrom exponents (measured at 1240 h and 1340 h) are very low (−0.01, Table 1), suggesting that the dust particles are very large (see section 9). No measurements are available from the flux tower from 1100 h to 2000 h, probably due to the voltage regulators overheating. At 1800 h, the time of a nephelometer scattering spike to $11 \times 10^{-4} \text{ m}^{-1}$, local station wind speed is 11.3 m/s and dew point 8°C.

### 7.1.5. Notable Cold Pool Outflow Characteristics

In several cold pool outflow cases, the lidar backscatter (which is only available above 75 m agl) leads the 2 m agl nephelometer observations by up to several hours. A simple explanation for this is the elevated leading edge (or nose) of the cold pool outflows. A raised density current nose has been observed in other studies [e.g., Sun et al., 2002]: as a density current propagates, surface drug slows down propagation speeds near the surface, and an elevated nose develops. In the case of some events (e.g., 13 June, section 7.1.4), the ambient winds may also have contributed to the elevation of the nose. Liu and Moncrieff [1996] have shown using a numerical model that flow against the propagation direction of density currents, as in this case, raises the nose. However, on the morning of 17 June, this raised nose is estimated to have a horizontal extent of 9.9 km (section 7.1.1), which seems rather extensive.

An alternative explanation for such an extensive apparent “nose” is that the density current propagated above a stable nocturnal layer. This may have been the case on 17 June. However, since an elevated density current cannot produce dust uplift, the density current must have propagated along the surface before arriving at BBM, and before a nocturnal temperature inversion began to develop. At some later time, the current (now with dust mixed within it) was raised above a strengthening surface inversion, possibly by isentropic upgliding, as it propagated northward. At levels above the surface, wind speeds are likely to be higher: this may explain why the current could carry such large particles within it (Angstrom exponents all below 0; Table 1 and Figure 1d). There are no observational data to intercept these features between western Niger and BBM, but the propagation of a moist and dusty feature, with a clear leading edge, from NW Niger toward BBM is evident in SEVIRI (see Figure 5g).

Between 0600 h and 0900 h, as the surface temperature inversion at BBM was eroded, the density current and the dust within it mixed down to the surface. There is some evidence to support this. Between 0000 h and 0600 h, the 3-hourly radiosonde launches show a strong (−5°C) temperature inversion between the surface and 200 m agl (Figure 5h). A comparison of the 2 m temperatures on 17 June with the June 2011 composite temperatures (Figure 5e) shows that before 0230 h BBM 2 m temperatures are colder than usual, at 1 standard deviation
below the June mean, and after 0230 h cool even more rapidly, becoming 5°C colder than the June mean at 0500 h. Under these conditions, it is possible that the “cold pool” could in fact be less dense than the surface and therefore propagate toward BBM above the cold nocturnal surface layer [Marsham 2012, personal communication]. Indeed, at 0600 h, the temperature of the dusty elevated density current (the layer between 400 and 800 m agl, Figure 5a) is 28.5–31.5°C (Figure 5h), and the 2 m temperature under the inversion is colder, 26.5°C (Figure 5e). As solar heating warms the surface, 2 m temperatures begin to increase, the temperature inversion begins to erode, and from 0600 h onward the dusty current mixes down to the surface.

Figure 7. Dust events of 13 June 2011 at BBM: two cold pools: from 0500 h and from 2000 h. (a) Lidar backscatter (contours) and nephelometer scattering (line). (b) Lidar vertical wind (positive upward). (c) 10 m wind speed (black), nephelometer scattering (green), and 500 nm AOT (red bars). (d) 10 m vertical wind (positive upward, lines show hourly mean). (e) 12 June 2130 SEVIRI dust detection algorithm image centered on BBM, with the dust front marked in green. (f) 2 m temperature, relative humidity, and pressure. (g) 0600 h Africa LAM wind vectors (925 hPa). (h) Radiosonde temperature profiles. Flux tower data (i.e., 10 m wind speed, vertical component; 2 m temperature, pressure, and relative humidity) are missing from 1030 to 2000 h. This is likely due to the voltage regulators of the tower overheating. Humidity and temperature are missing from 2200 to 2400 h.
Elevated cold pools have been shown in both theoretical and laboratory measurements, where such currents are known as intrusions [Simpson, 1997], occurring when a layer of intermediate density flows along the interface between a more and less dense layer of fluid, in this case, the nocturnal surface layer and the residual layer. Fluctuations evident in temperature, wind, and pressure (e.g., near 0500 h on 17 June, Figure 5) match the kind of features documented by Liu and Moncrieff [1996] in their 2-D numerical model.

Several of the case studies describe events where cold pools follow each other in succession. On 9/12 occasions, cold pools that occur in the morning or persist through the night into the morning are followed by another in the afternoon. Additionally, on three out of three occasions, cold pools that start in the evening are followed by a new cold pool in the morning. It is plausible that there is a “positive feedback” of cold pool formation: cold pools which propagate into an area initiate convection, which leads to an increase in convection and, potentially, the issuing of a feedback mechanism at BBM, as in the northwestern SHL region [Todd et al., 2008] since the surge acts as a density current.

The morning of 29 June saw the second highest peak (Figure 8a). In the early morning, this is due to a strong haboob that occurred the prior evening (see section 7.1.3 above); however, there is also evidence of a weak low-level jet breakdown contribution to the dust loading later in the morning. The event is the third dustiest LLJ of the IOP but only 17th overall (Table 1).

The morning of 18 June has high dust concentrations recorded in both the nephelometer scattering and lidar backscatter (Figure 8a). In the early morning, this is due to a strong haboob that occurred the prior evening (see section 7.1.3 above); however, there is also evidence of a weak low-level jet breakdown contribution to the dust loading later in the morning. The event is the third dustiest LLJ of the IOP but only 17th overall (Table 1).

At 0800 h, nephelometer scattering increases very closely in line with the 10 m wind speeds (Figure 8c), peaking at 0930 h at a modest $7 \times 10^{-4} \text{m}^{-1}$, unsurprising given that the wind speeds only just reach 10 m/s. As wind speeds begin to decline, so does the scattering: the match between the wind speeds and the scattering also suggest that this is almost certainly local emission. The vertical wind component shows a gradual increase from 0700 h (averaging about $\pm 1 \text{m/s}$) to 0900 h (averaging $+2.7$ and $-2.2 \text{m/s}$); in
this period and for the rest of the morning, the hourly mean vertical wind is upward (Figure 8e). AOTs during the event are high but not extreme for BBM: averaging 1.7 Ångstrom exponents average 0.05 (Table 1).

[55] Arrival of mixed-down LLJ winds are clear in the lidar data between 0856 h and 0926 h (Figures 8b and 8d), coincident with the increase in 10 m wind speeds. Degeneration of the nocturnal inversion is apparent when the 0600 h and 0900 h radiosonde temperature profiles are compared (Figure 8h). The reason dust emission is modest is likely because the LLJ is itself weak; lidar profiles (not shown) show that wind speed in the core declines from 18 m/s at midnight to 12 m/s by 0700 h.

[56] As on 29 June, the LLJ is embedded in the monsoon flow: observed wind directions at 10 m height are southwesterly from 0500 h to 1200 h (Figure 8f); Africa LAM 925 hPa wind directions are southwesterly over BBM during the morning (Figure 8g), and a moist monsoon tongue is
apparent in the model specific humidity field over southern Algeria (not shown). Consistent with these features, the model shows that BBM is very close to the intertropical discontinuity on the morning of 18 June.

7.2.3. The Monsoon and Low-Level Jets

[57] The nephelometer scattering time series (Figure 1) shows that, prior to 13 June, there is little dust at BBM. Marsham et al. [2013] demonstrate that the dusty period from 13 June is coincident with monsoon influence at BBM. The WAM can promote dust emission in the region directly or indirectly. Indirectly, the WAM promotes dust emission by encouraging deep convection, promoting cold pool outflows and haboobs [Flamant et al., 2007; Marsham et al., 2008]. Directly, the monsoon flow can lead to dust emission as it acts as an intrusive surge [Bou Karam et al., 2008] or when LLJs are embedded within the flow [Parker et al., 2005].

[58] Of the 12 strongest LLJs to occur over BBM, the Africa LAM suggests that nine were embedded in the monsoon flow. Only two of the 12 strongest jets were embedded in the Harmattan flow. The remaining LLJ was an extension of a strong Atlantic inflow. Coupled with the importance of cold pool outflows, this clearly shows the primacy of the monsoon in promoting dust emission in the region.

7.3. Dry Convective Plumes

[59] A case study of the dustiest dry convective plume is presented here. The others (Figure 1c) developed in a very similar fashion. All of the dry convective plumes detected occurred in the second half of June 2011. This is consistent with the higher surface temperatures and deeper boundary layer heights found at BBM after 13 June 2011, 600–450 hPa compared to 700 hPa prior to 13 June [Marsham et al., 2013], linked on the synoptic scale to the westward displacement of the SHL [Marsham et al., 2013; Todd et al., 2013].

7.3.1. 24 June 2011, 1600 h

[60] On 24 June, BBM is within the center of the SHL (Figure 3b). The 925 hPa temperatures exceed 38°C at 1800 h, although the heat maximum and pressure minimum are not as strongly colocated or as intense as on 29 June (compare Figure 3c). Nonetheless, the CBL is deep, 3.6 km at 1500 h and 4 km at 1800 h (Figure 9). At 1600 h, there is a very sudden spike in the nephelometer scattering, lidar backscatter, and 10 m wind speed (Figures 10a and 10c). This dust event is ranked 11th in the nephelometer time series, at 19°C and 4 m/s (Table 1). There are several features which suggest that this event is a dry convective plume. These are

Figure 9. Radiosonde-derived potential temperature profiles from BBM, afternoon of 24 June 2011.

Figure 10. Dust events of 24 June 2011 at BBM: a dry convective plume (16 h) and cold pool (from 18 h). (a) lidar backscatter (contours) and nephelometer scattering (line). (b) 10 m vertical wind (positive upward, lines show hourly mean). (c) 10 m wind speed (black), nephelometer scattering (green), and 500 nm AOT (red bars). (d) 2 m temperature, relative humidity, and pressure. Lidar data are unavailable from 0330 to 0530 h.
also promote dust uplift.

Tamanrasset plume period (not shown), as also observed for a case in 5000 m agl present over BBM during the dry convective very fast. Lidar backscatter and SEVIRI show clouds at

promote dust plumes since hot air from the surface can rise

pro

2.3

(Figure 10d), corresponding to a drop in dew point of 7.3.2. Dry Convective Plume Characteristics

in temperature of 3

55 m of ascent, the 1500 h radiosonde recorded a decrease

near-surface temperature pro

erage CBL height of 4.7 km at 1800 h. Although a detailed

wind speed, lidar, and nephelometer changes. The plume

the following: (i) wind speed rise from 1 m/s to 21 m/s in just

20 min (Figure 10c), (ii) vertical wind component reaches

over +4 m/s (Figure 10b), (iii) drop in pressure of 1 hPa (a

“pressure well,” Figure 10d), and (iv) concurrent timing of

wind speed, lidar, and nephelometer changes. The plume

lasts just over an hour and is at least 1.3 km in height

(Figure 10a and Table 1), although the CBL height at 1500 h is 3.6 km. This is similar to observations by Cuesta et al. [2008] from Tamanrasset in June/July 2006, who record dry convective dust plume heights of 1–2 km, despite an average CBL height of 4.7 km at 1800 h. Although a detailed near-surface temperature profile is unavailable, in its first 55 m of ascent, the 1500 h radiosonde recorded a decrease in temperature of 3°C, a strong super-adiabatic temperature profile. Super-adiabatic temperature profiles near the surface promote dust plumes since hot air from the surface can rise very fast. Lidar backscatter and SEVIRI show clouds at 5000 m agl present over BBM during the dry convective plume period (not shown), as also observed for a case in Tamanrasset [Cuesta et al., 2008]. Clouds may reduce surface temperatures, but the related convective updrafts could also promote dust uplift.

[61] Coincident with the plume are drops in temperature and relative humidity of 2°C and 2%, respectively (Figure 10d), corresponding to a drop in dew point of 2.3°C from 27.3 to 25°C. This suggests that there is subsidence surrounding the plume.

7.3.2. Dry Convective Plume Characteristics

[62] BBM dry convective plume evolution is broadly consistent with previous studies. Height estimates are similar to lidar observations of dust plumes from Ouarzazate, Morocco, where most convective plumes reached <1 km [Ansmann et al., 2009]. Also consistent with theory and with the measurements of Ansmann et al. [2009] are (i) the low (2–7 m/s) prior wind speeds necessary for the plumes to develop (these were 1–7 m/s in the hour preceding the plume on 24 June) and (ii) the high wind speeds within the plumes (up to 21 m/s on 24 June).

[63] The formation of a dry convective plume on 22 June following a dusty cold pool (Figure 1c) suggests that a prior optical depth <0.3 is not necessary for plume development, as suggested by Ansmann et al. [2009]. This may be because temperatures were still hot enough for the plume to form (~42°C at 2 m), despite the high background dust loadings (AOT > 2 at 1600 h, Figure 1b).

[64] Although no dust devils were explicitly identified in the BBM data, this is not to say that they do not occur in the region. Because of their narrow diameter (~7 m) and duration of only a few minutes [e.g., Balme and Greeley, 2006], it is possible that several passed nearby the site but not over the lidar or past the flux tower. A network of instrumentation over a grid (rather than just one instance of each instrument) is more likely to have detected them.

8. Relative Importance of Dust Mechanisms (Partitioning)

[65] Fennec data provide the first opportunity to quantify the characteristics of the dust layer during the central Saharan summer. The data also provide the opportunity to partition the dust burden between the different generating mechanisms (Figure 11). The Figure considers all 32 dust events of the IOP and also the background dust, i.e., periods when nephelometer scattering is less than 2 × 10−4 m−1 (see section 3). Four dust-producing mechanisms are distinguished: local cold pool emission; cold pool dust advection (i.e., cold pools with wind speeds ≤6 m/s, section 4); LLJ-induced emission and dry convective plumes.

[66] Partitioning is done in two different ways which provide complementary information. The first method (red bars of Figure 11) considers the duration of dust events. The duration of each dust event is distinguished (section 3), and for each mechanism separately (i.e., LLJs, dry convective plumes etc.), the summation of the dust event durations is calculated. Since the duration of the IOP, representing 100%, is known, the percentage of time that any mechanism is in operation can be calculated. The red residual represents the percentage of time that nephelometer scattering is below 2 × 10−4 m−1, which is the threshold value chosen between background dust and dust events (section 4). The second way partitioning is done is by nephelometer scattering (blue bars of Figure 11). The sum of the nephelometer scattering during each dust event is calculated (one “sum” for each event). For each dust mechanism separately, the total of the sums of the nephelometer scattering is calculated. Since the total nephelometer scattering during the IOP, representing 100%, is known, the percentage of scattering that occurs during the operation of any mechanism can be calculated. The blue residual represents the total nephelometer scattering during periods which are not designated as dust events (section 3). Since the whole duration of the IOP is represented, the values of the blue and red columns each add up to 100.
Dry convective plume.

At 2 m height, and 670 nm wavelength. Thirty-one events
speed is measured at 10 m height, nephelometer scattering
tween the different atmospheric mechanisms (top). Wind
Table 3.) Three different symbols are used to differentiate be-
(Associated correlation coef-
Figure 12. Scatter plot showing peak nephelometer scatter-
ing (× 10^4 m⁻¹) for individual dust events as a function of
wind speed at the time of the peak scattering (wspeedp). 
(Combined correlation coefficients are presented in
Three different symbols are used to differentiate between
the different atmospheric mechanisms (top). Wind speed is measured at 10 m height, nephelometer scattering at 2 m height, and 670 nm wavelength. Thirty-one events are presented; wind measurements were unavailable for one dry convective plume.

Locally emitting cold pool outflows are the most important
dust emission mechanism during the IOP, responsible
for 45.0% nephelometer scattering. Advected dust in cold
pools occurs marginally more frequently (18.4% of the
time compared to 17.1% of the time), but dust in these cold pools
is responsible for less nephelometer scattering, 26.9%.
Nonetheless, cold pool dust advection is the second largest contributor to the dust burden. Together, both types of cold
pool are responsible for 71.9% of the nephelometer scattering
at BBM. LLJ-induced emission is responsible for just 13.9% 
nephelometer scattering and dry convective plumes only
1.6%. This is an order of magnitude less than the global estimate of 35% by Koch and Renno (2005). Dust events are
actually not present over BBM 51.2% of the time, but the percentage of nephelometer scattering that occurs in this
period is only 12.5%; this is the contribution of the “background” dust loading. Nonetheless, this is close to the LLJ
contribution of 13.9%.

Marsham et al. [2013] also present a partitioning of
dust events at BBM, primarily based on uplift potential (see
section 4). These uplift potential results also show the domi-
nance of cold pool outflows and the secondary importance of
LLJs. Their results with regard to nephelometer scattering are
slightly different to those presented here, however. Marsham et al. [2013] suggest that both cold pool outflows and LLJs
are responsible for 33% nephelometer scattering (compare
Figure 11). However, the authors define LLJ periods simply
as those between 0600 h and 1200 h UTC. This is likely to
overestimate their contribution: frequently, LLJs do not lead
to dust uplift at BBM (e.g., 28 June, Figure 1c) and on several
occasions between 0600 h and 1200 h UTC, cold pool out-
flows are responsible for dust (e.g., 13 June, section 7.1.4; 
see also Figure 1c). Cold pool contributions between 0600 h and 1200 h UTC not only explain why the LLJ contribu-
tions to nephelometer scattering in the present paper are
lower than Marsham et al. [2013] but also why cold pool
contributions presented here are higher. Additionally, since
Marsham et al. [2013] use uplift potential as a sampling base, they do not explicitly consider scattering due to dust
advected in low wind conditions, which is significant
(26.9%, Figure 11). This paper also builds upon the initial
partitioning results of Marsham et al. [2013] by including a
dry convective plume category.

Monsoon surges are not identified explicitly in
Figure 11. This is because they are difficult to unambiguously identify [Marsham et al., 2013]: they can share charac-
teristics of both LLJs and cold pool outflows [see also Bou
Karam et al., 2008]. However, Marsham et al. [2013] do
suggest that monsoon surges produce or at least contribute
to dust at BBM on two particular occasions: the early morn-
ing of 25 June and the late morning to mid-afternoon of 29
June. In Figure 11, the former event is included as advected
cold pool dust and the latter as a LLJ (see also discussion in
section 7.2.1 above). However, if they are treated separately,
the early morning event of 25 June is responsible for 2.7% of
IOP nephelometer scattering, and the afternoon event of 29
June is responsible for 7.2%, a significant fraction. Thus
monsoon surges could be responsible for 9.9% nephelometer scattering during the IOP.

The high relative importance of cold pools during the
IOP at BBM is unsurprising given its location: monsoon-relat-
ded deep convection frequently reaches the southern fringes of the Sahara in summer [Sultan and Janicot, 2003; Cuesta
et al., 2010]. Although the meteorological processes at
BBM are not representative of the Sahara as a whole (partic-
ularly further north, away from monsoon influence), it is im-
portant to recall that BBM is very close to the global dust
maximum in summer [e.g., Ashpole and Washington, 2012]; therefore, it remains likely that cold pool outflows are a significant contributor to the dust maximum.

9. Ångstrom Exponent and Dust Advection

The Ångstrom exponent is the exponent used when
calculating the dependence of extinction on wavelength. It
has the useful property of varying with particle size: z is typi-
cally larger for smaller particles, and usually < 0.5 for coarse
windblown dust [Redmond et al., 2010]. The z time series
from BBM is shown in Figure 1d. Ångstrom exponents for
all the events listed in Table 1 are below 0.4, a criterion used
by Huneeus et al. [2010] in the definition of a station as
“dusty” (the other criterion is that monthly average of AOT
is over 0.2, which is certainly the case). What is intriguing,
however, is that the lowest z (as low as −0.04, Figure 1d),
dictating the presence of very coarse particles in the atmo-
spheric column, occur on days when the dust is transported
over BBM rather than emitted. This is somewhat counterin-
tuitive, as it is expected that transported large particles will
fall out of the column early due to gravitational settling,
while fresh emission under high wind speeds should lead to
a greater number of larger particles in the column. However,
this is similar to the results of Cuesta et al. [2008], who found that the lowest Ångstrom Exponent values (z = 0.17, standard deviation ±0.08) in Tamarasset
in 2006 occurred during the late May to mid-June period
when long-range dust transport was most frequent. The three
events of June 2011 with the lowest z values are density cur-
rents spawned by mesoscale convective complexes over
Table 3. Correlation Coefficients Between wspdp and Peak Nephelometer Scattering*

|               | All Events | Cold Pool Outflow | LLJ-Induced Plume | Dry Convective Plume |
|---------------|------------|-------------------|-------------------|----------------------|
| Number of events |            | wspdp > 6 m/s | wspdp < 6 m/s     |              |
| r (wspdp, peak nephelometer scattering) | 0.44 | 0.55 | 0.64 | 0.16 | 0.77 | 0.16 |
| r (wspdp, peak nephelometer scattering) | 0.60 | 0.74 | 0.78 | 0.13 | 0.88 | 0.14 |

*wspdp = Wind speed observed at the time of peak nephelometer scattering. All dust events observed during the IOP except one dry convective plume (15 June) when no wind speed measurements were available. Correlation coefficients are calculated for all events (left column) and also separately for each category of dust mechanism (other columns). Correlations are similarly calculated for wspdp. Italicized correlations are significant at 95% confidence. For full details, see section 10. Figure 12 presents a visual representation of wspdp relationship with peak nephelometer scattering.

11. Summary and Discussion

[73] To further examine the relationship between wind speed and dust production, the peak nephelometer scattering for each of the dust events during the IOP is plotted as a function of the wind speed at the time of the scattering peak, wspdp (Figure 12). Thirty-one events are plotted, including those defined as advected dust (wspdp ≥ 6 m/s), local emission (wspdp ≥ 8 m/s), and mixed emission and advection (6 m/s < wspdp < 8 m/s). See section 4 for discussion of emission thresholds. wspdp is chosen as the independent variable so that the independent and dependent variables are coincident in time. It can be seen from Figure 12 that dust that is not locally emitted (i.e., wspdp < 8 m/s) is responsible for relatively high nephelometer scattering values. Indeed, in four of these cases, peak nephelometer scattering is over 20 × 10^{-3} m^{-1}, which is never the case for dry convective plumes and only the case for one LLJ.

[74] The correlation between wspdp and peak nephelometer scattering for all events is not particularly strong, r = 0.44 (p < 0.05; Table 3). This is unsurprising given that 12 of the events are not considered to represent purely locally emitted dust. More telling are the correlation coefficients obtained when the calculations are done separately for each dust mechanism. The correlation is highest for LLJs, r = 0.77 (p < 0.05; Table 3). Cold pool outflows with wspdp > 6 m/s (i.e., excluding purely advected dust) come second, r = 0.64 (p < 0.05; Table 3). Unsurprisingly, the correlation for advected dust is low and statistically insignificant, r = -0.16 (p > 0.05). The correlation for dry convective plumes is surprisingly low, r = 0.16, but caution should be taken in interpreting this result since the sample size, four events, is low and r is statistically insignificant (p > 0.05).

[75] Research dating back to [Bagnold, 1941] suggests that in many cases the relationship between emission and the cube of wind speed is stronger than that with wind speed alone. This also appears to be the case with these results (Table 3). Taking wspdp results in stronger correlations with peak nephelometer scattering for all cases, except those where a relationship is not expected anyway (purely advected dust) or where the correlation with wspdp is not statistically significant either (purely advected dust and dry convective plumes). The correlation with wspdp is highest for LLJ-induced emission (r = 0.88, p < 0.05) followed by cold pool outflows with wspdp > 6 m/s (r = 0.78, p < 0.05).

11. Summary and Discussion

[73] This paper has presented the first detailed descriptions of dust production mechanisms from observations near the center of the Saharan heat low, in the June dust maximum region. Three aims were outlined in section 1: (1) document the main dust outbreaks in June 2011 at Bordj Badji Mokhtar, (2) identify the mechanisms associated with dust production and establish their relative importance, and (3) document the characteristics of the key dust-producing mechanisms and their relationship with wind speed for dust emission.

[75] A total of 32 individual dust events were identified during the June 2011 IOP (Figure 1c). Three main mechanisms led to dust over BBM: cold pool outflows, low-level jets, and dry convective plumes. They have been identified and documented primarily from the ground-based observations but also with the aid of satellite products where necessary. Monsoon surges are also potentially important, but since they can share cold pool or LLJ characteristics, their contribution is difficult to isolate unambiguously.

[76] Cold pool outflows are the most important mechanism for dust over BBM (Figure 11). Their contribution can be split between locally emitting outflows (45% nephelometer scattering) and advected dust (27%). LLJs come third (14% nephelometer scattering) followed by dry convective plumes (2%). Using a partitioning based on uplift potential (see section 4), Marsham et al. [2013] also found that cold pool outflows were the most important dust production mechanism at BBM during the IOP. Their partitioning based on nephelometer scattering however assigned equal importance to LLJs and cold pool outflows (33% each); this difference with the present findings can likely be explained by the decision of Marsham et al. [2013] to take scattering between 0600 and 1200 h to be caused by LLJ emission, whereas frequently in this period cold pool outflows produced dust (Figure 1c). This study extends the partitioning work of Marsham et al. [2013] by including advected dust and dry convective plumes.
The meteorological observations during the dust events are broadly consistent with modeling work and observations from other parts of the Sahara but with some interesting differences. Cold pool outflows at BBM are typically associated with sudden air temperature changes of the order 2–2.5°C (usually increases in the early morning and decreases at other times), fluctuations in pressure of between 0.4 and 1 hPa, sudden increases in wind speeds of 9–16 m/s, rapid increases of the vertical wind component of between 1.3 and 2.5 m/s, changes in relative humidity of around 2%, changes (positive and negative) in dew point from 2.8 to 7.2°C, and rapid switches in wind direction. In their climatology of density currents in the Atlas foothills, Emmel et al. [2010] note, for example, a mean temperature decrease of 2.3°C, dew point temperature increase of 5.4°C, and wind speed increase of 8.2 m/s, in good agreement with these results. Many of these rapid changes as the gust front passes also match modeling work, even in two dimensions [e.g., Liu and Moncierff, 1996]. The changes are not as extreme as those at the outflow fronts observed by Miller et al. [2008] in the Arabian Peninsula, who report an idealized “ensemble” pressure rise of 2 hPa, air temperature drop of 7°C, and relative humidity increase of 15%.

It appears that density currents promote further convection and new outflows, as reported by several authors [e.g., Weckwerth and Wakimoto, 1992; Moncierff and Liu, 1999; Tompkins, 2001]. Several also appear to be preceded by bore-like phenomena as has been shown in laboratory experiments [e.g., Simpson, 1997] and recorded in observations [e.g., Koch et al., 1991]. Where reasonable estimates of the average propagation speed of density currents can be made (based on SEVIRI), these are faster than their counterparts in the Atlas foothills: 12 m/s and 16 m/s compared with (based on SEVIRI), these are faster than their counterparts average propagation speed of density currents can be made. The propagation speed is, however, within the range of that computed for the three case studies reported by Miller et al. [2008] in the Arabian Peninsula (10.5–18 m/s).

Low-level jet-induced emission appears to conform to the classic “jet breakdown” theory and observations from other parts of the Sahara [Blackadar, 1957; Washington et al., 2006]. The degeneration of the surface temperature inversion and the propagation of wind speeds toward the surface after sunrise are clear in the lidar wind profiles and radiosonde measurements. There is frequently a strong correspondence between the wind speed curve on these mornings and the nephelometer scattering and lidar backscatter (e.g., Figures 2 and 8c). More details on the LLJ emission process at BBM are in C. J. T. Allen and R. Washington (The low level jet dust emission mechanism in the central Sahara, manuscript in preparation, 2013).

The intensive measurements at BBM in June 2011 detected five dry convective plumes. Similar to other observational studies, a super-adiabatic temperature gradient at low levels is often present; there is a 1 hPa pressure well during the strongest plumes, and very large and rapid increases in wind speed are observed after a period of very low wind (an increase of 21 m/s on one occasion). In contrast to the work of Ansmann et al. [2009], low AOT prior to the plume does not appear to be a prerequisite for formation, possibly because temperatures at BBM are still very high at the time of formation (~42°C at 2 m). Convective plumes are only responsible for 2% of the dustiness during the IOP.

The current work presents some unexpected results when it comes to long-range dust advection and particle size. Cold pool outflows advected from Niger had very large AOTs, with peaks from 3.3 to 4.4 (Table 1). These density currents also carried very large particles, with Ångström exponents as low as ~0.4 (Figure 1d and Table 1). Indeed, the largest particles found over BBM were associated with advected dust behind the leading edge rather than local emission. Cuesta et al. [2008] also report the lowest Ångström exponents at Tamanrasset to be in advected dust, and the long-range advection potential of density currents is highlighted in Miller et al. [2008]. Advedt dust in cold pool outflows was responsible for 27% nephelometer scattering during the IOP.

For locally emitting dust events, the cube of wind speed has a closer relationship with nephelometer scattering than wind speed alone. The correlation with the cube of wind speed is 0.88 for LLJ-induced emission and 0.77 for emission caused by cold pool outflows (both at 95% confidence, Table 3). This is in agreement with long-held ideas regarding the cube of wind speed as an important control on emission (dating from Bagnold [1941]), reflected in commonly used parameterization schemes such as Marticorena and Bergametti [1995].

North Africa is of global importance for dust emission in boreal summer [e.g., Ginoux et al., 2012]. Given the primary of cold pool outflows and monsoon-embedded LLJs observed over BBM, there is strong incentive for research to improve model representation of moist processes and to use explicit convection where possible, as this appears to significantly improve representation of dust storms in the region [e.g., Marsham et al., 2011; Kocha et al., 2012].

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