The low-level jet dust emission mechanism in the central Sahara: Observations from Bordj-Badji Mokhtar during the June 2011 Fennec Intensive Observation Period

Christopher J. T. Allen1 and Richard Washington1

1Climate Research Lab, Oxford University Centre for the Environment, Oxford, UK

Abstract This paper presents the first detailed analysis of low-level jets (LLJs) in the central Sahara from ground-based observations at Bordj-Badji Mokhtar, Algeria, and addresses their operation as a dust emission mechanism. On LLJ mornings, composite wind speeds in the core (300 m aboveground level) reach 13.5 m s\(^{-1}\) at 0400. Surface temperatures increase from 0545 (30 min after sunrise), and jet decay begins around 0600. Ten meter winds lag those in the core by 5 h; peak 10 m wind speed, 7.5 m s\(^{-1}\), occurs at 0900. Only the deepest and strongest LLJs lead to dust emission. At 0600, these five LLJs have core wind speeds ≥16 m s\(^{-1}\), below-core wind shear ≥0.6 m s\(^{-1}\)/30 m, and wind shear between the core and 500 m above the core ≤−1.8 m s\(^{-1}\). On these occasions, momentum mixes down from the LLJ after surface heating, leading to emission. On nondusty LLJ mornings, the convective boundary layer is 100 m shallower, and the LLJ is too weak to provide enough momentum to be mixed down for emission. LLJs are most frequently embedded in the monsoon flow or in the Harmattan; there is a clear association with the Saharan Heat Low. ERA-Interim reanalysis underestimates both Harmattan and monsoon LLJ core winds (by 4 m s\(^{-1}\) and 6 m s\(^{-1}\), respectively). The Met Office Africa Limited Area Model underestimates Harmattan LLJ core winds by only 0.2 m s\(^{-1}\). Monsoon LLJ core winds, however, are underestimated by 8.5 m s\(^{-1}\). Surface winds at 0900 are underestimated in both cases by up to 6 m s\(^{-1}\).

1. Introduction

Mineral aerosol, or dust, is being increasingly studied because of its effects on the atmospheric radiation budget [e.g., Haywood et al., 2005; García et al., 2012], subsequent changes in atmospheric and ocean circulation [e.g., Tompkins et al., 2005; Stanelle et al., 2010; Evan et al., 2011; Solomon et al., 2012], modification of biogeochemical processes [e.g., Mahowald et al., 2010], and impacts on human health [e.g., de Longueville et al., 2012; Dukić et al., 2012]. In the Sahara desert, mechanisms which are known to lead to dust emission include cold pool outflows [e.g., Marsham et al., 2008; Emmel et al., 2010; Allen et al., 2013], dry convective plumes [e.g., Ansmann et al., 2009], monsoon surges [e.g., Bou Karam et al., 2008; Cuesta et al., 2010], and low-level jets (LLJs) [e.g., Washington and Todd, 2005; Washington et al., 2006a].

Dust emission from the Bodélé Depression, the dustiest place on Earth, is caused by the strong (20 m s\(^{-1}\)) and persistent Bodélé low-level jet (LLJ) [Washington and Todd, 2005; Washington et al., 2006a]. LLJs are thought to lead to dust emission over much wider areas of the Sahara [e.g., Schepanski et al., 2009; Fiedler et al., 2013], but the lack of observational data in the region, particularly before the Fennec project [Washington et al., 2012], has meant that there is a need for more direct evidence to examine the link between LLJs and dust emission. This paper uses high-resolution Fennec observations from the remote central Sahara to examine current LLJ dust emission understanding and draws upon high-resolution numerical model data to investigate the wider spatial context.

Much of the current work on LLJs stems from the ideas of Blackadar [1957] who proposed that LLJs can form over flat terrain after sunset, when the frictional force caused by turbulent mixing in the boundary layer is removed and the flow near the top of the boundary layer effectively becomes decoupled from the surface. If the background pressure gradient is strong enough, the flow accelerates and undergoes an inertial oscillation, with a period of 2\(\pi/f\), where \(f\) is the Coriolis parameter. In cloud-free desert regions,
where nocturnal radiative cooling is intense, the conditions for the development of such jets are particularly favorable. Some numerical (large eddy simulation) modeling has successfully generated LLJs due to inertial oscillations [e.g., Basu et al., 2008], and an exact analytical solution to the Blackadar model has also been demonstrated [Shapiro and Fedorovich, 2010]. The model has been extended to include frictional effects within the nocturnal boundary layer [van de Wiel et al., 2010]. In many model simulations and observations, at locations as wide ranging as Chad [Washington et al., 2006a], the Netherlands [van de Wiel et al., 2010], Niger [Madougou et al., 2012], Mali [Bain et al., 2010], and the Weddell Sea [Andreas et al., 2000], the core of the jet is found a few hundred meters above the ground, although LLJs with core heights of ~100 m or less have also been documented [Banta et al., 2002]. Marsham et al. [2013] show that a nocturnal LLJ was a common feature at Fennec supersite 1 in the central Sahara in June 2011, detectable in the mean diurnal cycle of near-surface and boundary layer winds, with peak winds at around 300 m. The mix-down of momentum from a LLJ to the surface is the process that leads to dust emission. This has been documented in detail for the Bodélé LLJ from observations [Washington et al., 2006a] and regional climate model (RCM) simulations [Todd et al., 2008]. After sunrise, turbulent mixing induced by surface heating increases and momentum from the jet is mixed down toward the surface [e.g., Lothon et al., 2008]. Surface wind speeds begin to increase, and if they surpass the local emission threshold, dust uplift takes place. There is a lag of several hours between the peak wind speed in the LLJ (just before sunrise) and peak wind speed at the surface. On dusty days during the Bodélé Dust Experiment (BoDex) in spring 2005, composite wind speeds (i.e., wind speeds averaged for dusty days) at the surface were maintained above 10 m s⁻¹ from 0600 to 1300 UTC [Washington et al., 2006a]. At Fennec supersite 2 in the western Sahara, this lagged relationship is complicated by the Atlantic inflow, resulting in a much slower LLJ breakdown [Todd et al., 2013]. LLJs have also been documented to raise dust in other parts of the central and western Sahara [e.g., Cuesta et al., 2008; Knippertz, 2008; Schepanski et al., 2009]. Using ERA-Interim reanalysis [Dee et al., 2011] and an offline dust model, Fiedler et al. [2013] estimate that 15% dust in the North African annual and spatial mean is caused by mix-down of LLJ momentum to the surface. In the Bodélé Depression, this figure is up to 60%. One reason the Bodélé LLJ is particularly strong and persistent is that the northeasterly Harmattan flow is channeled between two mountain chains, the Tibesti and Ennedi. RCM sensitivity experiments show that without this topography, 925 hPa winds during a strong deflation event are 30% slower than with topography [Washington et al., 2006b]. However, it has been argued that LLJs occur frequently in areas of the Sahara with little orography [Schepanski et al., 2009] and can occur in the monsoon flow [Parker et al., 2005] as well as north of the intertropical discontinuity (ITD) [Bou Karam et al., 2009].

Given the potential importance of LLJs as a dust mechanism in the central Sahara and given the observational data available for the first time from Fennec, the key questions posed by this paper are the following: (i) What are the observed characteristics of the LLJ in the central Sahara at Bordj-Badji Mokhtar (BBM) in summer? (ii) How well are LLJs at BBM represented by the Met Office Africa Limited Area Model and ERA-Interim reanalysis? (iii) Under what synoptic and local conditions is LLJ development favorable? (iv) What are the characteristics of LLJs associated with dust emission? (v) Is dust emission consistent with the mix-down of momentum from the jet core?

Section 2 describes the location of the observations, the instrumentation, and additional data and methods employed. Section 3 presents the June 2011 composite LLJ, surface wind speeds, and temperature from the Fennec supersite 1. Section 4 develops a LLJ detection scheme and an index of LLJ strength. Section 5 explains the spatial orientation of the LLJs and assesses model performance at simulating LLJ profiles. Section 6 addresses the synoptic and local conditions for LLJ development. Section 7 attends to the relationship between LLJs and dust emission. Section 8 discusses evidence for low-level oscillations and a discussion and conclusions are presented in section 9.

2. Data and Methods

2.1. The Bordj-Badji Mokhtar Supersite During the Fennec Project

The Fennec project [Washington et al., 2012] is the first project to instrument the remote central Sahara and provide detailed airborne and ground-based observations of central Saharan atmospheric dynamics, dust, and radiation. Fennec supersite 1 is located in southwest Algeria at the existing synoptic station of BBM on
the border with Mali (21.38°N, 0.92°E; altitude 420 m above sea level; World Meteorological Organization ID 60686). It is very close to the boreal summer global climatological dust maximum [e.g., Ashpole and Washington, 2012], which makes it an unparalleled location to study central Saharan dust emission. Ashpole and Washington [2013] identify 15 major source regions of dust in the central Sahara. BBM is within one of these. Additionally, they identify major sources ≈100 km to the NW, ≈300 km to the WSW, ≈200 km to the SSW, and ≈200 km to the ESE. The ITD frequently lies over BBM in summer, making it an excellent site from which to sample LLJs in both the southwesterly monsoon flow and the northeasterly Harmattan.

During the first Fennec Intensive Observation Period (IOP) in June 2011, BBM was heavily instrumented. June was chosen since the satellite-derived absorbing aerosol index from the Total Ozone Mapping Spectrometer shows that June is the dustiest month in the central Sahara [e.g., Engelstaedter et al., 2006]. The instrumentation included a Halo Photonics Streamline 1.55 μm Doppler lidar, a Scintec MFAS phased array sodar, a Cimel Sun photometer, an inverse nephelometer (670 nm, fixed at 2 m height), 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. Pressure, visibility, and passively ventilated measurements of temperature and humidity were taken at 2 m. Unless otherwise stated, all times reported are in UTC. Marsham et al. [2013] provide a comprehensive overview of the meteorology and Allen et al. [2013] provide a detailed analysis of the dust events during the IOP. There was no rain at BBM during the IOP.

Instrument measurement precision is as follows: nephelometer scattering ±10⁻⁷ m⁻¹, relative humidity ±2%, temperature ±0.3°C, pressure ±0.5 hPa, and anemometer wind speed ±0.1 m s⁻¹. The Doppler measurement precision of the lidar is ±10 cm⁻¹ in the boundary layer [Pearson et al., 2009]. A standard lidar inversion technique 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 ±0.1 m s⁻¹. Minimum lidar range is 75 m above ground level (agl) although the lowest lidar wind measurements are taken at 90 m agl. The vertical resolution of the measurements is 30 m. Lidar horizontal wind speed profiles were taken twice an hour; unless otherwise stated, these two profiles are averaged to obtain hourly resolution. Lidar data were obtained from 3 June 2011 to the end of the month.

Aerosol optical thickness is reported at 500 nm (AOT₅₀₀) and is level 1.5 (cloud-screened). AOT is accurate to ±0.01. The Sun photometer formed part of the Aerosol Robotic Network (AERONET) project [Holben et al., 1998] during deployment. AOT availability is not continuous: Where there are gaps, this is not because AOT₅₀₀ is zero but because either (i) no AOT measurements were taken (e.g., night) or (ii) AOT measurements were removed as part of the level 1.5 cloud-screening process. Radiosondes were launched at 3- or 6-hourly intervals, from 8 June 2011 to the end of the month. Reproducibility (standard deviation of differences in twin soundings) of radiosonde measurements is as follows: temperature 0.2°C, humidity 2% RH, and pressure 0.5 hPa. The positioning uncertainty of the radiosonde GPS in the horizontal is 10 m. There are some periods with missing data; where relevant, these are highlighted in the text and in the captions with an explanation given where possible.

### 2.2. Satellite and Numerical Model Data

The presence of deep cloud and dust over the wider Saharan region is identified using false color imagery from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the Meteosat Second Generation satellite at 0°N, 0°E [Lensky and Rosenfeld, 2008]. Additionally, a SEVIRI cloud mask product (available from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) website) is also used.

A configuration of the UK Met Office Unified Model [Walters et al., 2011], the Africa Limited Area Model (LAM), is used to provide a regional context and for comparison with observations. Africa LAM horizontal resolution is 12 km. There are 70 levels in the vertical. The lowest level is at 10 m; levels are terrain following in the lower troposphere. The boundary layer scheme is described by Lock et al. [2000] with modifications as in Lock [2001] and Brown et al. [2008]. It is a first-order turbulence closure that mixes adiabatically conserved variables. In stable boundary layers and in the free troposphere, a local Richardson number scheme [Smith, 1990] is used with the stable stability dependence given over land by the "long tail" function. In unstable boundary layers, diffusion coefficients (K profiles) are specified functions of height through the boundary layer, related to the strength of the turbulence forcing. Two K profiles are used, one for surface sources of turbulence (surface...
heating and wind shear) and one for cloud top sources (radiative and evaporative cooling) [Walters et al., 2011]. The LAM is driven by the Met Office Global Model (the Unified Model in its numerical weather prediction configuration), which assimilates data globally using Hybrid Incremental 4D-Var. Boundary conditions are applied in a 10-point rim around the edge of the LAM domain. Sea surface temperatures are held constant during runs. The LAM simulations ran to T + 54 h. There were two forecast runs per day (at 06 Z and 18 Z) but only data from the 18 Z forecast are available. The LAM fields presented here are T + 12 (18 Z initialization, valid at 0600).

European Centre for Medium Range Weather Forecasts ERA-Interim reanalysis (ERAI) [Dee et al., 2011] is presented for comparison with the LAM in section 5.2. ERAI has a 6-hourly temporal resolution, horizontal resolution of 0.75° (roughly 83 km in the central Sahara), and 60 levels in the vertical, which are terrain following in the lower troposphere. A K diffusion scheme is used to parameterize turbulent transport in the stable boundary layer [Bechtold et al., 2008].

The LAM was chosen as the primary model tool for several reasons: (i) Automatic weather station (AWS) measurements from Fennec AWS across remote Mauritania and Algeria were assimilated [Hobby et al., 2012]; (ii) 12 km is very high spatial resolution; (iii) LAM simulation of Harmattan LLJs at BBM is excellent and substantially better than ERAI (see section 5.2); and (iv) an objective of the Fennec project is to better understand and improve Met Office numerical weather prediction tools in the Sahara.

2.3. Momentum Calculations

Most studies of LLJs in the Sahara use wind speed as a proxy for momentum. The Fennec instrumentation at BBM, however, allowed direct calculations of momentum to be made for the atmospheric column above the supersite. Wind velocity at 30 m intervals through the atmosphere was obtained from the lidar, at hourly time steps. The mass of each 30 × 1 × 1 m column of air was derived from its density, which was calculated from radiosonde observations at every 30 m height interval. With the velocity and mass of each 30 m column known, momentum could be calculated. When sonde launches were 3 hourly, the hourly lidar velocity profiles were used together with mass calculations from the (temporally) closest sonde launch to obtain hourly momentum profiles. When sonde launches were 6 hourly, momentum profiles were not estimated for intermediate hours. For the 0600 radiosonde launches (the launch time when the LLJ was strongest), balloon horizontal deviations from the launch point were never more than 9 km (by 2000 m agl) and only 1.0 km by 300 m agl (the mean height of the wind speed maximum). Momentum at 10 m agl was calculated using measurements taken on the flux tower.

2.4. Assessment of Dust-Producing Mechanisms

Assessment of the dust conditions (section 7) was accomplished following the approach of Allen et al. [2013]. This is a multiplatform approach that includes the SEVIRI dust detection algorithm; lidar backscatter and wind speed profiles; nephelometer scattering; 2 m temperature, pressure, and relative humidity; 10 m wind direction and speed; sodar wind speed; and Africa LAM simulations. The approach is able to separate different dust production mechanisms and distinguish between advected and locally emitted dust. See sections 3 and 4 of Allen et al. [2013] for full details.

3. Composite LLJ, Near-Surface Wind Speeds, and Temperature

The following two sections address key question 1: What are the observed characteristics of the LLJ in the central Sahara at BBM in summer?

3.1. Composite LLJ Wind Profile and Daily Variability

The composite wind speed profile for 3–30 June 2011 clearly shows that the LLJ is detectable in the mean diurnal cycle over BBM (lidar wind data, Figure 1). From 0000 to 0700, the core of the jet is found close to 300 m agl (Figure 1; 300 m ≈ 935 hPa). (Henceforth, “core” will be used to refer to the height of the LLJ wind speed maximum.) The LLJ begins to develop after sunset (1839 h on 15 June). Peak mean LLJ wind speed, 12 m s⁻¹ in the composite, occurs from 0300 to 0500 (Table 1). After sunrise (0513 h on 15 June), the jet decays and the height of the wind speed maximum increases (Figure 1 and Table 1).

Although the composite shows a clear LLJ structure (Figure 1), there is significant day-to-day variability in the wind speed profiles in the nocturnal and morning hours over the course of the month. Between 0400 and
0500, when the composite LLJ is at its peak wind speed, wind speed maxima on different days of June 2011 range from 4.7 m s\(^{-1}\) to 23 m s\(^{-1}\) (Figure 2). Several of the profiles do not display the characteristic LLJ shape, with the height of the wind speed maxima below 2000 m agl ranging from 90 m to 1680 m (Figure 2). There is similarly large variability in the wind speed profiles at other nocturnal and morning hours (not shown). In section 4, it will be shown that not all of these profiles are LLJs.

3.2. Composite 10 m Wind Speed

Composite wind speeds (6–30 June, 10 m agl) decline gradually from 02–03 h to 06–07 h (Figure 3a and Table 1). Between 06–07 h and 07–08 h, there is a relatively large jump in 10 m wind speed, from 5.1 m s\(^{-1}\) to 6.0 m s\(^{-1}\). Composite wind speeds continue to increase until 09–10 h, when they peak at 7 m s\(^{-1}\). This peak is 5 h behind the composite LLJ peak (Table 1). Such a lagged relationship was also found in the Bodélé, where composite surface wind speeds for the BoDEx period also peaked from 09 to 10 h but were higher (9 m s\(^{-1}\)) [Washington et al., 2006a]. The composite 10 m wind has large standard deviations (always larger than any change in mean wind speed from any hour to the next). The peak composite wind speed of the diurnal cycle at 09–10 h is only 7.0 m s\(^{-1}\) but has a standard deviation of 3.0 m s\(^{-1}\). It is likely that the large variability of the LLJ contributes to the large variability of the 10 m wind speed in the late morning.

3.3. Composite 2 m Temperature

Composite 2 m temperature (6–30 June) follows the expected diurnal cycle, peaking at 42.5°C at 1500 (Figure 3b). The standard deviations are larger in the evening and early morning than at other times. This is likely due in part to the effect of cold pool outflows that are most frequent at these times [see Allen et al. [2013] and Marsham et al. [2013] for details of these events] and to the influence of the monsoon flow, which intrudes farthest north at night but displays significant daily variability [Parker et al., 2005; Marsham et al., 2013]. Temperatures begin to increase again at 0545. The LLJ begins to decay from this point onward (Figure 1) and 10 m wind speeds start to increase from 0700 onward (Figure 3a). Taken together, the timings of these three features (2 m temperature, LLJ speed, and 10 m wind speed) are consistent with the theory that turbulent mixing soon after sunrise mixes down momentum from the LLJ toward the surface.

Table 1. June 2011 Composite Wind Statistics for Morning Hours at BBM

| Time (UTC) | Peak Wind Speed (m/s) (Composite) | Height Above Ground Level of Peak Wind Speed | Wind Speed at 10 m Height (Composite) |
|------------|----------------------------------|---------------------------------------------|---------------------------------------|
| 00–01      | 10.2                             | 300 m                                       | 5.6                                   |
| 01–02      | 10.2                             | 190 m                                       | 5.6                                   |
| 02–03      | 11.4                             | 250 m                                       | 6.3                                   |
| 03–04      | 12.0                             | 300 m                                       | 6.0                                   |
| 04–05      | 12.0                             | 300 m                                       | 5.5                                   |
| 05–06      | 11.6                             | 300 m                                       | 5.3                                   |
| 06–07      | 11.3                             | 290 m                                       | 5.1                                   |
| 07–08      | 11.4                             | 300 m                                       | 6.0                                   |
| 08–09      | 10.2                             | 480 m                                       | 6.8                                   |
| 09–10      | 9.0                              | 600 m                                       | 7.0                                   |

*Wind speeds shown are from the lidar instrument except for those at 10 m height which are measured on the flux tower. All available measurements are averaged across the indicated time intervals. The time period for the composite is 3–30 June 2011. Ten meter wind speeds for hours after 1000 are shown in Figure 3a.
Given the large daily variability in wind profiles discussed in section 3.1, it is important to be able to objectively identify mornings on which LLJs occurred. There are no universally accepted criteria for identifying LLJs [Kallistratova and Kouznetsov, 2012; Nunalee and Basu, 2013]. Schepanski et al. [2009] and Fiedler et al. [2013] have developed LLJ detection schemes for the Sahara from ERA-40 and ERAI reanalysis data, respectively. Although ERAI is the newer version of the product, it still likely underestimates the morning LLJ strength [Fiedler et al., 2013] and, in the nocturnal boundary layer, simulates artificially smooth changes in meteorological variables with height [Sandu et al., 2013]. Given these problems, and given the existence of the high-quality Fennec observational data set for BBM, we optimize the Fiedler et al. [2013] detection method to LLJ values based on thresholds from observations at BBM rather than those which are appropriate for reanalysis data. We later show that application of the original Fiedler et al. [2013] criteria to the observational data would be unsuitable given the differences between ERAI reanalysis and the observed (section 5.2) and that adoption of the Fiedler et al. [2013] detection criteria would miss 3/5 of the LLJs which lead to dust emission at BBM (section 7.1).

The LLJ identification criteria were developed and applied to the 06–07 h lidar wind speed profiles. This period was chosen for three reasons. (i) It is a period when shear is still present in the LLJ profile (Figure 1) but the jet is close to breakdown: the strength of the LLJ from 06 to 07 h is expected to have a close relationship with dust emission, which is a key focus of this paper. (ii) It is an hour commonly used for model outputs, allowing for easy model-observation comparison. (iii) It opens the possibility of future comparison with 0600 radiosoundings across West Africa.

LLJ detection is executed in four steps. First, the wind speed maximum below 600 m agl is identified. This is much lower than 1500 m which is used by Fiedler et al. [2013]. It is chosen based on the composite wind profiles (Figure 1) and in order to avoid detecting elevated wind speed maxima which occur on some mornings. These elevated maxima can occur together with or without LLJs and...
Table 2. Day-to-Day Variability in 06–07 h Wind Profiles at BBM, June 2011a

| Date | Wind Speed Max (m s⁻¹) | Height of Wind Speed Max (m agl) | Above-Core Wind Shear (m s⁻¹) | Below-Core Wind Shear (m s⁻¹/30 m) | LLJ? | Low-Level Jet Index (LLJi; m² s⁻²) | Cold Pool Present in the Morning? | LLJ Leads to Dust Emission? |
|------|------------------------|---------------------------------|-------------------------------|-----------------------------------|------|---------------------------------|---------------------------------|-------------------------------|
| 4    | 4.3                    | 90                             | −1.4                          | N/A                               | N/A  | N/A                             | N                               | N/A                           |
| 7    | 6.4                    | 300                            | −1.8                          | 0.5                               | N/A  | N/A                             | N                               | N/A                           |
| 19   | 5.5                    | 90                             | −4                            | N/A                               | N/A  | Y                               | N                               | N/A                           |
| 27   | 10.6                   | 180                            | −1.1                          | 0.5                               | N/A  | N/A                             | N                               | N/A                           |
| 6    | 7.3                    | 270                            | +2.2                          | 0.2                               | N/A  | N/A                             | N                               | N/A                           |
| 24   | 12                     | 150                            | −0.8                          | 0.5                               | N/A  | N/A                             | N                               | N/A                           |
| 17   | 10.8                   | 210                            | −1.7                          | 0.5                               | N/A  | N/A                             | Y                               | N/A                           |

aMeasurements are from the lidar instrument, averaged between 06 and 07 h. Wind speed maxima are reported for observations below 600 m agl. “Above-core wind shear” is the wind shear between the LLJ core (i.e., the height of the wind speed maximum) and 500 m above the core. Below-core wind shear is calculated between the LLJ core and 90 m agl (the lowest available measurement) and is shown per 30 m height interval to be comparable. No measurements are available prior to 3 June. For details on how events are classified as LLJs, see section 4. Within each subsection, events are ranked by low-level jet index (LLJi, low to high). For the definition of the LLJi, see section 4.1. Figure 6 summarizes the LLJ detection scheme graphically. For further details on the distinction between LLJs that lead to dust emission and those that do not, see section 7.

bWhen the wind speed maxima themselves are at 90 m agl (the lowest measurement), below-core wind shear cannot be calculated (4 and 19 June). Only 19 June could be a missed detection, however, since 4 June fails the above-core shear criterion.

cMeasurements between 06 and 07 h are unavailable and the average is calculated for the 07 h period.

discerned as LLJs, see section 4. Within each subsection, events are ranked by low-level jet index (LLJi, low to high). For the definition of the LLJi, see section 4.1. Figure 6 summarizes the LLJ detection scheme graphically. For further details on the distinction between LLJs that lead to dust emission and those that do not, see section 7.

A surface temperature inversion criterion was considered but not included for two reasons: (i) Radiosonde soundings were not made at 0600 on 7/28 mornings, and (ii) on 2/7 mornings when cold pool outflows occur together with LLJs, a surface temperature inversion is not present at 0600. However, a temperature inversion criterion alone is not sufficient to detect cold pools which is why we restrict the LLJ detection criteria to wind metrics and use the multiplatform detection approach of Allen et al. [2013] for cold pools (see sections 2.4, 4.2, and 7.2.4).

The thresholds used for LLJ detection were developed from subjective analysis of individual wind speed profiles. Discriminant analysis was subsequently used to demonstrate that the subjectively derived

are likely caused by processes other than frictional decoupling from the surface since they are found several hundred meters above the nocturnal temperature inversion. (Indeed, Fiedler et al. [2013] acknowledge that a 1500 m window is a generous allowance for LLJ heights.) Second, the wind shear between the LLJ core and 500 m above the core must be ≤ −1.8 m s⁻¹. Tests for wind shear over multiple, shallower layers above the core were considered but rejected since several events subjectively identified as LLJs have periods when the above-core wind shear reverses and becomes positive. Third, the wind speed under the core must decrease to the hundred meters above the nocturnal temperature inversion. (Indeed, Fiedler et al. [2013] acknowledge that a
thresholds were objectively reproducible. Discriminant analysis is a statistical technique that objectively classifies categories on the basis of a set of variables. Comparison with the objective classification derived from the linear combination of a set of variables reveals the extent to which an a priori classification scheme which might have been subjectively derived is reproducible [e.g., Diab et al., 1991; Michailidou et al., 2009; Garrity et al., 2010]. Using the below 600 m agl wind speed maximum, above-core wind shear and below-core wind shear as the discriminating variables (the same as those presented in the LLJ detection scheme; Table 2), the technique was used to objectively reclassify the profiles into the two classes. On 19/21 occasions, profiles which were classified a priori as LLJs by the original detection scheme remained in the same class, and on 7/7 occasions, profiles which were classified a priori as not being LLJs remained in the same class. Since 93% of the observations are well classified according to discriminant analysis, the detection scheme is considered to be apposite.

There is a clear distinction between composite lidar wind profiles for LLJ mornings and mornings without LLJs (Figure 4). On LLJ mornings, there is a well-defined LLJ structure, similar to the all-June composite (Figure 1) but the core wind speeds (300 m agl) reach a maximum of 13.5 m s\(^{-1}\) at 04–05 h, 1.5 m s\(^{-1}\) faster than the all-June composite. Core wind speeds stay above 12.5 m s\(^{-1}\) until 08–09 h. At 10 m agl, flux tower wind speeds follow a similar structure to the all-June composite (Table 1), also peaking at 09–10 h but at 7.5 m s\(^{-1}\) (Table 3), 0.5 m s\(^{-1}\) faster than the all-June composite. On non-LLJ mornings, there is a weak and shallow LLJ-like structure from 00 to 03 h (the LLJ criteria are applied at 06–07 h for the reasons given above) but the low-level winds decay rather than develop from 03 to 04 h onward (Figure 4b). This shows that LLJ-like development in the nocturnal hours does not necessarily result in fully fledged LLJs by the morning.

**4.1. An Index of LLJ Strength**

Having classified the LLJs over BBM during June 2011, it is useful to have a measure of their strength. Whilst peak wind speed is one metric, it does not take into account the depth of the atmosphere through which the LLJ exists, or for how many hours high winds persist. Next we develop a more comprehensive index that can be used to compare the strength of different LLJs. The LLJ index (LLJi), which is only applied on mornings

| Time (UTC) | 00–01 | 01–02 | 02–03 | 03–04 | 04–05 | 05–06 | 06–07 | 07–08 | 08–09 | 09–10 | 10–11 | 11–12 | 12–13 |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Composite wind speed (m s\(^{-1}\)) | 5.8   | 5.7   | 6.4   | 6.1   | 5.9   | 5.6   | 5.4   | 6.5   | 7.2   | 7.5   | 7.1   | 6.2   | 5.6   |

\(^{a}\)All available measurements are averaged across the indicated time intervals. Mornings included in the composite (i.e., LLJ mornings) are shown in Table 2.
when LLJs are detected (section 4), is defined as the summation of wind speed exceeding a threshold in lower troposphere over a chosen time period (equation (1)):

$$\text{LLJ}_i = \sum_{h=1}^{n} f_h(z) \, dz$$  \hspace{1cm} (1)

where $n$ is the number of hours in the time period, $z_1$ and $z_2$ are the chosen lower and upper height bounds, and $f_h(z)$ is the wind profile over the chosen threshold wind speed at hour $h$. Units are $\text{m}^2 \, \text{s}^{-1}$. The time period chosen is from 0000 to 0900 in order to capture LLJs that persist after sunrise. We use a threshold wind speed of 8 m s$^{-1}$ and height bounds 90–1100 m. These are chosen to correspond with the LLJ detection scheme (section 4). Below-core wind shear is calculated down to the lowest lidar measurement, 90 m agl, so this is used as the LLJ lower height bound. The detection scheme searches under 600 m agl for wind speed maxima over 8 m s$^{-1}$ and then checks the wind shear between the height of the maximum and 500 m above this, making a logical LLJ upper height bound 1100 m (i.e., 600 m + 500 m). Since the LLJ integrates over any areas within the height bounds where wind speeds are greater than 8 m s$^{-1}$, on mornings when the LLJ is shallow, the LLJ will also capture elevated areas of high wind speed if these are present. However, reducing $z_2$ to 900 m agl or 600 m agl to combat this does not change the LLJ rankings significantly: in all three cases, the strongest five LLJs retain identical rankings and the strongest 14 LLJs remain the strongest 14 LLJs. Reducing $z_2$ also has the undesirable consequence of underestimating the strength of the strongest, deepest LLJs so $z_2$ is kept at 1100 m agl.

The LLJ time series is shown in Figure 5 (numerical values in Table 2). Although LLJ is only applied to mornings when LLJs are detected, there is considerable variability in the strength of the 21 LLJs over the course of the month. The strongest LLJ is on 16 June, followed by 30 and 26 June. A cartoon summarizing the LLJ detection process and LLJ calculation is shown in Figure 6.

### 4.2. LLJs and Cold Pool Outflows

On several mornings when LLJs are present at BBM, cold pool outflows also pass through the supersite. On these mornings, LLJ wind speed profiles are not always easily distinguishable from LLJ wind speed profiles on mornings without cold pools. To ensure that the analysis focuses initially on understanding LLJs rather than LLJ/cold pool combinations, mornings with cold pools ranked within the top 20 events of the month by Allen et al. [2013] are excluded from here onward. This excludes 7/21 mornings (Table 2). The remaining 14 jets will be referred to as “pure” LLJs. This approach also enables direct comparison...
with the Africa LAM, whose representation of cold pool outflows is poor [e.g., Marsham et al., 2011], unsurprising for a model of 12 km resolution and parameterized convection.

5. Africa LAM and ERAI Simulations of the LLJ
5.1. Spatial Position of the LLJ
Analysis of the Africa LAM 925 hPa (roughly 400 m) wind and specific humidity fields on the 14 pure LLJ mornings reveals that six LLJs are embedded in the dry \( q \approx 3 \text{ g kg}^{-1} \) northerly/northeasterly Harmattan flow and five LLJs are embedded in the relatively moist \( q \approx 9 \text{ g kg}^{-1} \) southerly/southwesterly monsoon flow (which is sometimes recirculated to arrive at BBM from another direction, e.g., WNW on 26 June). Jet directions are shown in Figure 7. On the remaining three mornings, the LLJ is simulated as part of an extensive westerly/northwesterly “Atlantic inflow.” The LAM simulates the LLJs not as thin ribbons but rather as wide sheets (≈100–500 km wide). Within each of the three types identified above, there is variability with regard to the maximum LLJ wind speed (from 12–15 to 21–24 m s\(^{-1}\)). The maximum LLJ wind speed is not necessarily found directly over BBM.

5.2. Comparison With Observations at BBM
This section addresses key question 2: How well are LLJs at BBM represented by the Met Office Africa Limited Area Model and ERA-Interim reanalysis?

The lidar instrument makes it possible to compare LLJ wind observations at BBM with the Africa LAM simulations for the BBM grid box. At 0600, simulated 925 hPa wind direction on LLJ mornings is only greater than 22.5° out from observations on two occasions (not shown). On 28 June, an observed southwesterly monsoon LLJ is simulated to arrive from the south. A more major simulation error occurs on 5 June, when an observed southwesterly monsoon LLJ is simulated to reach BBM from the WNW.

The performance of the Africa LAM is significantly different depending on whether the LLJ is embedded in the monsoon or the Harmattan. The simulated 0600 composite wind speed profile for Harmattan LLJs at BBM shows excellent agreement to that measured by the lidar (Figure 8a). A clear LLJ is simulated by the LAM, with the core wind speed only fractionally too slow (12.9 m s\(^{-1}\) compared to 13.1 m s\(^{-1}\)). The core height is also accurately simulated. LAM wind speeds above 300 m are between 0.5 and 2 m s\(^{-1}\) too fast but the surface wind speed is only underestimated by 0.8 m s\(^{-1}\). This is in stark contrast to the ERAI reanalysis, which simulates the Harmattan LLJ structure very poorly, underestimating winds at all levels except the surface and 2 km agl (Figure 8a). Maximum wind speeds are underestimated by 4 m s\(^{-1}\).

At 0900, approximately 3 h after sunrise, wind speeds below 700 m agl are simulated reasonably well by the LAM but wind speeds at the surface are underestimated by 1.8 m s\(^{-1}\) (Figure 8b). Crucially for dust, surface wind speeds in the observed composite are above the BBM emission threshold, estimated at 8 m s\(^{-1}\) [Allen et al., 2013], but the simulated wind speeds are not. There is no 0900 time step in ERAI reanalysis.

The LAM is less successful at simulating monsoon LLJs at BBM. At 0600, a weak LLJ structure is evident but wind speeds are underestimated at all heights below 2 km agl by at least 1.5 m s\(^{-1}\) and underestimated by 8.5 m s\(^{-1}\).
in the jet core (Figure 8c). ERAI performs slightly better (jet core wind speeds underestimated by 6 m s\(^{-1}\)) but the monsoon LLJ profile is still very poorly represented (Figure 8c). At 0900, wind speeds are simulated well by the LAM between 800 m and 1400 m agl but underestimated elsewhere and by 6 m s\(^{-1}\) at the surface (Figure 8d), again taking them below the local dust emission threshold. The underestimation of surface wind speeds by the LAM at 0900 in both Harmattan and monsoon LLJs suggests that the boundary layer processes responsible for momentum mix-down are not adequately represented. However, the Africa LAM simulates Harmattan LLJ profiles much better than monsoon LLJs, which suggests that the moist dynamics present a particular challenge for the model in the boundary layer. A detailed model-observation comparison is beyond the scope of this paper but will be addressed in future work.

6. Conditions for LLJ Development

The following section addresses key question 3: Under what synoptic and local conditions is LLJ development favorable?

6.1. Synoptic Scale

An important control on the development of a LLJ is a sufficient background pressure gradient [Stensrud, 1996; Rácz and Smith, 1999]. This is not present every day over BBM. Unsurprisingly, on mornings when there is no LLJ at BBM, the 925 hPa pressure gradient over BBM is weak compared to mornings when a LLJ is present (Figure 9). On LLJ mornings, the 925 hPa pressure gradient ranged from 1.5 gpm per degree latitude (12 June) to 6 gpm per degree latitude (16 June, the strongest LLJ; Figure 5). (Pressure gradients were calculated in a rectangle centered on BBM from 18°N to 24°N, 0°E to 2°E.) The simulated pressure gradient over BBM is stronger during Harmattan LLJs than monsoon LLJs, resulting in stronger simulated 925 hPa Harmattan winds over BBM (Figures 9e and 9f). It is likely however that the 925 hPa monsoon winds over BBM (Figure 9f) are underestimated, given the comparison with observed LLJ profiles (section 5 and Figure 8).

Figure 8. Composite wind speed-height profiles at BBM (m s\(^{-1}\)) for (a, b) Harmattan LLJs, \(n = 6\), and (c, d) monsoon LLJs, \(n = 5\). Composites on top row are from 0600, and composites on bottom row are from 0900. On each plot, the black curve represents the Africa LAM simulation (computed from the closest grid point to BBM) and the blue curve and cross the observations (lidar and 2 m station measurements). At 0600, ERAI reanalysis is plotted in red; there is no 0900 reanalysis. Lidar measurements are reported at height above instrument (=agl) and LAM at hybrid height. These are comparable since hybrid heights are sigma (i.e., terrain following) coordinates in the lower troposphere. ERAI is plotted on pressure levels. Mornings when both cold pools and LLJs were observed are not included (see section 4.2).
LLJ development over BBM is related to the position and strength of the Saharan Heat Low (SHL). On mornings when LLJs embedded in the monsoon flow are present over BBM, the SHL is centered just to the northwest of the supersite (Figure 9c). The SHL is well defined even at 0600, with a strong colocation of the pressure minimum (<758 gpm) and temperature maximum (>35°C). Winds are cyclonic around the SHL, resulting in southwesterlies at BBM and a strong (19 m s⁻¹) easterly along the northern edge of the SHL where the pressure gradient is strongest (Figures 9c and 9f).

Marsham et al. [2013] identify three main synoptic-scale phases in June 2011 relevant to BBM: two periods when the center of the SHL was close to BBM (prior to 8 June and from 13 June onward) and a period when the center was up to 10° farther east (8–12 June). None of the monsoon LLJs at BBM occurs in the 8–12 June period, affirming the importance of the SHL position for their formation. The SHL is centered just east of the Mali-Niger-Algeria triple point in the Harmattan LLJ composite (Figure 9b); with the SHL this far east, BBM is on the western edge of the cyclonic circulation and LLJs arrive at the supersite from the northeast.

6.2. Local-Scale Conditions for LLJ Development

With a gradient wind in place, strong radiative cooling has been shown to be one effective way to promote LLJ development as it effectively decouples air aloft from the surface [Blackadar 1957] and many studies...
since). The cooling leads to a strong temperature inversion at the top of which the jet core is found [Blackadar, 1957]. Elements which could dampen the cooling include water vapor, cloud, and dust (which absorb and reemit infrared radiation).

In the night of 15–16 June (when the strongest LLJ is observed, highest LLJi, and peak wind speed 23 m s\(^{-1}\); Table 2), favorable conditions for LLJ development are present. The 925 hPa Africa LAM winds show a LLJ over BBM that is part of a wide (~300 km) and strong (>20 m s\(^{-1}\) at 0300 and 0600) northeasterly Harmattan flow originating west of the Hoggar Mountains (not shown). Although the SEVIRI cloud mask flags 65% of the nocturnal (1800–0600) time steps as cloud, water vapor mixing ratio in the bottom 4000 m agl remains uniformly low (~3.5 g kg\(^{-1}\)) through the night and morning (Figure 10a). Nocturnal dust levels are below the IOP background nephelometer scattering value of 2 × 10\(^{-4}\) m\(^{-1}\) identified by Allen et al. [2013], and lidar backscatter is not greater than 10\(^{-5.5}\) m\(^{-1}\) sr\(^{-1}\) in the bottom 3000 m agl (not shown). As a result, a temperature inversion of 8°C develops by 0300 between the surface and 200 m agl, and potential temperature (\(\Theta\)) profiles show that this layer remains more stable than the layer above until at least 0600 (Figure 10), allowing the winds at 200 m to become decoupled from the surface. However, the same LLJ development conditions are not present for every LLJ. Indeed, during monsoon LLJs, the nocturnal surface temperature inversion at 0600 is weak, only 0.6°C/100 m compared to 2.5°C/100 m during Harmattan LLJs (Figure 11). The reduced low-level cooling during the development of the monsoon jets is likely due to longwave absorption by water vapor which, below 600 m agl, is much higher (up to +4.5 g kg\(^{-1}\)) during monsoon LLJs than Harmattan LLJs (Figure 12). (There is no cold pool signal since mornings with cold pools have been excluded; see section 4.2.) The moist monsoon flow approaches overnight and is strongest at 0600 (Figure 12b), when boundary layer turbulence is minimal, as found by Parker et al. [2005]. The relationship between LLJ development and nocturnal dust and cloud cover was also examined but there was no statistically significant association (not shown).

7. Relationship Between LLJs and Dust Emission

The following section addresses key question 4: What are the characteristics of LLJs associated with dust emission?
7.1. Characteristics of Dust-Emitting LLJs

Dust emission does not occur on every morning that a LLJ is present. On most mornings when LLJs dominate the circulation (i.e., those not coincident with cold pools; section 4.2), nephelometer scattering is below $2 \times 10^{-4} \text{ m}^{-1}$ (Table 4), considered a background level of dust at BBM in June 2011 [Allen et al., 2013]. On only three of these 14 LLJ mornings is nephelometer scattering above $2 \times 10^{-4} \text{ m}^{-1}$ (16, 26, and 29 June; Table 4). These mornings are therefore candidates for LLJ-induced dust emission, as are 3 and 5 June, which are before the nephelometer was operational but when lidar backscatter peaked at $10^{-3.5}$ and $10^{-3.0} \text{ sr}^{-1}$, respectively, similar to the peaks on 16, 26, and 29 June (between $10^{-3.25}$ and $10^{-3.0} \text{ sr}^{-1}$; not shown). On 29 June, the LLJ appears to be associated with a monsoon surge, resulting in particularly intense and prolonged dust emission (Table 4; examined in detail in Allen et al. [2013]).

Separately compositing LLJ wind profiles on dusty mornings (i.e., 3, 5, 16, 26, and 29 June) and nondusty mornings reveals that the LLJ is substantially stronger on dusty mornings than on nondusty mornings (Figure 13). Indeed, at midnight on dusty mornings, the LLJ is already stronger than the maximum strength the LLJ reaches on nondusty mornings (11.5 m s$^{-1}$ at 03–04 h). On dusty mornings, the LLJ reaches a maximum wind speed of 18.5 m s$^{-1}$ at 06–07 h, roughly 1 h after sunrise, and in the next hour decreases by less than 0.5 m s$^{-1}$. It is not until 08–09 h that the LLJ structure changes significantly: The core height rises to 500 m agl and wind speeds reduce to 15.5 m s$^{-1}$. Prior to 08–09 h, the core height on dusty and nondusty mornings is the same, 300 m agl, but on dusty mornings, the depth of wind speeds above 8 m s$^{-1}$ is twice as great, 90–1500 m agl compared to 90–700 m agl. This is reflected in the high LLJ values on dusty LLJ mornings (Table 4).

On dusty LLJ mornings, 10 m wind speed begins to increase rapidly at 0700 and peaks at 15 m s$^{-1}$ at 0930, after which it declines. The wind speed curve from 0700 to 1300 resembles a Gaussian shape that matches closely with the lidar backscatter (Figure 14a). As the 10 m wind speeds begin to increase, backscatter also increases through a deeper column of the atmosphere. When the wind speeds slacken, backscatter declines back to pre-sunrise values. The close correspondence between the wind speed and the backscatter is strong evidence for local dust emission, especially as winds are above the local emission threshold of 8 m s$^{-1}$ [Allen et al., 2013] for 6 h. On nondusty LLJ mornings (Figure 14b), wind speeds from 0700 to 1300 follow a lower amplitude Gaussian pattern but never reach 8 m s$^{-1}$ and there is no evidence of corresponding dustiness in the lidar backscatter.

The Gaussian patterns are not a product of the compositing process. On all LLJ mornings when flux tower data are available, a Gaussian pattern can be detected in the mid-late morning wind speed (not shown). When flux tower data are unavailable, local synop station winds are in broad agreement (Figure 14a, pink squares). Likewise, on all dust-emitting LLJ mornings, lidar backscatter data when available follow a Gaussian shape, albeit with differing start times and durations (0700 to 0745 and 6 h to 13.4 h, respectively). The composite can be interpreted with high confidence during the onset and peak of dust emission when
backscatter data on all dust-emitting LLJ mornings are available (Figure 14a, red line). Given the very clear differences between LLJs that lead to dust emission and those which do not (Figures 13 and 14), it therefore appears that on nondusty mornings, the LLJ is simply too weak to provide enough momentum to be mixed down to the surface for emission.

Additionally, on nondusty mornings, the convective boundary layer (as identified by the depth of constant virtual potential temperature) is 100 m shallower at 0900 than on dusty mornings (not shown), extending to only 100 m agl. This suggests that turbulent mixing is also weaker on nondusty mornings.

Three classes of wind profile have so far been identified at BBM: “not LLJ,” LLJ, and now “dust emitting LLJ.” Objective criteria for distinguishing LLJ wind profiles from not LLJ profiles were presented in section 4. In order to distinguish dust-emitting LLJs from nonemitting LLJs, two changes to the original LLJ detection scheme are introduced: (i) Wind speed below the core must not only decrease but decrease with an average shear $\geq 0.6$ m s$^{-1}$/30 m, and (ii) the LLJ wind speed maximum must be $\geq 16$ m s$^{-1}$. These criteria are applied to the 06–07 h wind profiles (see section 4). The below-core wind shear criterion appears to be of particular importance since it allows for the exclusion of 30 June, a morning when the LLJ is very strong (second highest LLJ and peak wind speed of 17.2 m s$^{-1}$) but does not lead to morning dust emission (Table 2). As before, the classification is tested with discriminant analysis, this time for three classes. The technique places 93% observations in the same class as identified a priori.

It is worth noting that application of the Fiedler et al. [2013] LLJ detection criteria to the BBM observations misses 3/5 LLJs that cause dust emission, primarily because the Fiedler et al. [2013] above-core wind shear criterion is too strict for the observed profiles, which do not shear monotonically above the jet core but display “reversal” periods. However, it is also important to be clear that the criteria presented above for distinguishing dust-emitting LLJs are based on only five cases. These were the only dust-emitting LLJs in the IOP; nevertheless, their infrequent occurrence means that the dust-emitting LLJ criteria might be better thought of as a summary of the commonalities between the five cases rather than a detection scheme.

7.2. Momentum Mix-Down

The following section addresses key question 5: Is dust emission consistent with the mix-down of momentum from the jet core?

Central to the theory of LLJ dust emission is that momentum is transferred toward the surface by turbulent mixing after sunrise [e.g., Blackadar, 1957; Knippertz and Todd, 2012]. This momentum is responsible for the high surface wind speeds at midmorning which lead to dust emission. The general decline in 10 to 15 m wind shear at BBM between 0630 and 1040 is consistent with momentum mix-down [Marsham et al., 2013]. However, the BBM data set also provides a rare opportunity to calculate momentum directly for the entire lower troposphere. Two case studies of dust-emitting LLJs are presented next which clearly illustrate the operation of the momentum mix-down process.
Where neither momentum nor lidar wind speed measurements are available and sodar wind speed is used as a proxy.

**7.2.2. 16 June 2011**

Chosen as a starting point is 26 June because it has a strong LLJ (third strongest of June; Figure 5), strong dust emission, and complete surface and boundary layer measurements. The 925 hPa Africa LAM simulations (Figure 15) show that on this morning BBM is under the influence of aged monsoon air (specific humidity 8 \(g \text{ kg}^{-1}\)) which has been recirculated to arrive at the site from the northwest. The sodar measurements show the LLJ clearly, peaking at 0700 around 22 m s\(^{-1}\) at 300 m agl with strong winds then encroaching toward the surface (Figure 16c). As expected, at the time of peak LLJ momentum (06–07 h), 10 m momentum is much lower, 238 kg m s\(^{-1}\) against 619 kg m s\(^{-1}\). By 09–10 h however, the time of maximum dust emission, 10 m momentum has increased from 238 kg m s\(^{-1}\) to 437 kg m s\(^{-1}\), and the jet has shrunk in vertical extent and decayed from 619 kg m s\(^{-1}\) to just over 500 kg m s\(^{-1}\) (Figure 16d). Ten meter wind speeds reflect this increase and show a remarkably similar Gaussian structure to the nephelometer scattering and lidar backscatter (Figure 16, left).

Sunrise on 26 June 2011 is 0516 UTC. From 05 to 06 h, 10 m momentum increases by 20 kg m s\(^{-1}\) (not shown). From 06 to 07 h, the first hour of surface temperature increase, momentum at the LLJ core, 300 m, shows negligible change, whilst momentum below this height increases significantly, with a maximum increase of 150 kg m s\(^{-1}\) at 10 m (Figure 17a). From 07 to 08 h, the near surface is almost the only height gaining momentum, suggesting that the momentum from the LLJ has indeed been transported downward. This is also exactly the period when backscatter begins to increase significantly (Figure 16).

**7.2.2. 16 June 2011**

The strongest LLJ by far at BBM is on 16 June (Figure 5). Its breakdown leads to considerable dust emission (Table 4). From 06 to 07 h, momentum at the jet core (~300 m agl) shows negligible change, momentum in the layers below is decreasing, and momentum in the layers above is mostly increasing (Figure 17b). From 07 to 08 h, there is a dramatic change. Momentum at 300 m decreases by almost 240 kg m s\(^{-1}\) whilst

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**Table 4. Dust Conditions for LLJs of June 2011 at BBM**

| Date   | Morning Dust Conditions (Peak Nephelometer Scattering \(m^{-1} \times 10^{3}\)) [Peak Lidar Backscatter \(m^{-1} \text{s}^{-1}\)] | Momentum Mixed Down (0500–0900)? | LLJi \(m^{2} \text{s}^{-1}\) |
|--------|-------------------------------------------------------------------------------------------------|----------------------------------|-----------------|
| 16     | Considerable LLJ emission (4.5)                                                               | Y                                | 94,550          |
| 26     | Strong LLJ emission (13)                                                                       | Y                                | 53,580          |
| 29     | Very strong LLJ emission (55)                                                                  | Y                                | 44,130          |
| 28     | No emission (1.5)                                                                             | N                                | 29,700          |
| 3      | Considerable LLJ emission from 0800 [10 < \(4.75\)] no data after 1000                        | Y                                | 24,750          |
| 5      | Strong LLJ emission [10 < \(4.25\)]                                                          | N/A                             | 23,120          |
| 9      | No LLJ emission (<1)                                                                          | N                                | 14,350          |
| 14     | No LLJ emission (<2)                                                                          | N                                | 10,860          |
| 15     | No LLJ emission (<2)                                                                          | N/A                             | 7,930           |
| 10     | No LLJ emission (<1)                                                                          | N/A                             | 7,380           |
| 8      | No LLJ emission (<1)                                                                          | N/A                             | 5,060           |
| 20     | No LLJ emission (<2)                                                                          | N/A                             | 4,650           |
| 12     | No LLJ emission (<1)                                                                          | N/A                             | 3,160           |
| 11     | No LLJ emission (<1)                                                                          | N/A                             | 1,410           |

**LLJs Coincident With Cold Pools in the Mornings**

| Date   | Morning Dust Conditions (Peak Nephelometer Scattering \(m^{-1} \times 10^{3}\)) [Peak Lidar Backscatter \(m^{-1} \text{s}^{-1}\)] | Momentum Mixed Down (0500–0900)? | LLJi \(m^{2} \text{s}^{-1}\) |
|--------|-------------------------------------------------------------------------------------------------|----------------------------------|-----------------|
| 30     | Thick dust (19) brought by cold pool until 0300; subsequently weak (2.5)                      | N/A                             | 73,480          |
| 21     | Very thick dust brought by cold pool (27); no evidence of LLJ emission                         | Y                                | 31,240          |
| 25     | Mix of weak cold pool dust (3) and considerable LLJ emission (7)                               | Y                                | 24,180          |
| 13     | Very thick dust (37) advected by cold pool from 0600; no evidence of LLJ emission             | Y/A                             | 14,710          |
| 23     | Considerable (6) dust advected by cold pool between 0200–0300, weak (2.5) until 12 h; no evidence of LLJ emission | N/A                             | 6,170           |
| 22     | Very thick cold pool dust (22) between 0000 and 0300, thick (13) from 0300 to 0900, considerable (9) from 0900 with possible LLJ contribution | Y                                | 3,610           |

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\(^{a}\)Within each category (pure LLJ/LLJ and cold pool), dates are ordered according to LLJi (high to low). Nephelometer scattering used to describe dust conditions. Following Allen et al. (2013), nephelometer scattering \(s_{2} \times 10^{-4}\) is taken as background dust. Scattering (s) is then subdivided as follows: “weak” \(2 < s \leq 4\), “considerable” \(4 < s \leq 10\), thick/strong \(10 < s \leq 20\), and very thick/very strong \(s > 20\). For periods prior to the activation of the nephelometer (i.e., before 6 June), lidar backscatter (in square brackets) is given instead of nephelometer scattering, but these data may not be comparable due to attenuation of the signal in some cases. Criterion used to represent momentum mix-down is a net positive change in momentum between 0500 and 0900 at 90 m agl (lowest lidar measurement) and 10 m agl (from flux tower).

\(^{b}\)Further details of the event can be found in Allen et al. (2013).
momentum at 120 m agl and below increases by over 80 kg m s\(^{-1}\), again suggesting that the momentum is transferred toward the surface during this time interval, 2 h after sunrise.

### 7.2.3. Mix-Down Statistics

Momentum mix-down certainly appears to be the mechanism for dust emission from LLJs in the above cases. Of the five pure LLJ mornings when LLJ-induced dust emission occurs, mix-down of momentum between 0500 and 0900 is observed on four (Table 4). On the remaining morning (5 June), momentum measurements (or a wind speed proxy) are not available. On the nine pure LLJ mornings which do not lead to dust emission, momentum mix-down is not observed between 0500 and 1200 except on 8 June. The reason dust emission does not occur on the morning of 8 June (nephelometer scattering < \(1 \times 10^4\) m\(^{-1}\); Table 4) is likely because the LLJ is simply too weak to begin with (ranked seventeenth in LLJ\(_i\); Figure 5).

On 17/21 LLJ mornings, momentum does not mix down between 0900 and 1200. Of the remaining four mornings, on one there are no data to make an assessment, on two mornings 90 m momentum suggests mix-down but there are no 10 m observations, and on only one LLJ morning (30 June) does momentum mix down between 0900 and 1200 (Table 4). The fact that in most cases momentum does not mix down between 0900 and 1200 is consistent with the decline of 10 m winds after 0900 (e.g., Figures 14 and 16b). (Nine calculations of 0900–1200 momentum use sodar wind speed as a proxy due to missing lidar and/or radiosonde data).

### 7.2.4. Dust From LLJs and Cold Pool Outflows

This section considers LLJ cases which are coincident with cold pool outflows. It is clear that dust loadings are high on many of these mornings (Table 4). A perfect separation of dust produced by cold pools from dust associated with LLJs on these mornings is not possible. However, if nephelometer scattering and surface wind speed follow a coincident Gaussian pattern (as is the case on the pure LLJ dust emission mornings), it is likely that LLJ breakdown is also contributing to the dust loadings. This is particularly clear on 18 June (examined in more detail in section 7.2.2 of Allen et al. [2013]). Of the seven mornings when LLJs are coincident with cold pools, momentum mix-down between 0500 and 0900 occurs on three (including 18 June; Table 4). This suggests that on some occasions, morning LLJ breakdown continues in the presence of a cold pool, whilst on other occasions it does not.

Inspection of Tables 2 and 4 identifies two “anomalous” occasions when limited or no emission occurs, despite high LLJ\(_i\) and no strong cold pools in the late morning. These are examined next.

### 7.2.5. 30 June 2011

Somewhat anomalous is 30 June since it has the second highest LLJ\(_i\) and yet backscatter and scattering are low in the mid-late morning (2.5 \(\times\) \(10^{-4}\) m\(^{-1}\); Table 4). A comparison of momentum profiles with 26 June (which has a lower LLJ\(_i\) but higher emission) shows (i) the LLJ on 30 June decays between 05 h and 07 h whilst on 26 June it strengthens, and (ii) 10 m momentum at 07 h on 30 June is only 295 kg m s\(^{-1}\) compared to 385 kg m s\(^{-1}\) (Figures 18a and 18b). As a result, 10 m wind speed does not show the subsequent characteristic Gaussian LLJ curve and high peak (Figures 18c and 18d), and therefore, although wind speeds are over the 8 m s\(^{-1}\) threshold, there is little dust emission in the mid-late morning.
Between 0500 and 0900 on 30 June, momentum at 90 m agl declines by 65 kg m s\(^{-1}\). Momentum does not appear to mix down from the jet core before sunrise either: lidar profiles (available down to 90 m agl) between 0100 and 0500 do not show wind speeds increasing below the jet core (not shown). The high scattering and backscatter prior to 0300 (Table 4) are very likely related to the very strong cold pool outflow which arrived at BBM at 2100 on 29 June (addressed in more detail in Allen et al. [2013]). The outflow likely contributed to the high winds at 10 m agl from 0000 to 0300 on 30 June. Thunderstorm outflows can display a LLJ wind profile behind the front [e.g., Bowen, 1996; Darby et al., 2002], but the outflow is not the sole cause of the high wind speeds since a LLJ is also simulated by the Africa LAM in the early morning (not shown). (It is possible however that the model produces a LLJ instead of an outflow [Heinold et al., 2013].)

The timing of LLJ development is important for dust emission. On 30 June, wind speeds between 90 and 600 m agl begin to decline after 01–02 h. On 16, 26, and 29 June, which are all dusty, this decline does not begin until 5 to 6 h later (Figure 19). Furthermore, by 09–10 h on 30 June, there are no levels between 90 and 600 m with wind speeds >10 m s\(^{-1}\). After 0200, wind speeds at 10 m agl also begin to decline (Figure 18d). Thus, although the LLJ is very strong in the early morning, its decline in the hours prior to sunrise may explain why there is little, if any, dust emission in the mid-late morning. However, somewhat curiously, 30 June is also the only LLJ morning when momentum mixes down between 0900 and 1200. This may explain why the 10 m wind speeds do not decrease after 0900, as on 26 June (Figure 18) and in the LLJ composite (Figure 14). Inspection of the Africa LAM wind fields shows that BBM is on the very edge of a LLJ on the morning of 30 June (not shown): a small change in the orientation of the LLJ could result in a large increase or decrease in wind speeds over the site.

7.2.6. 28 June 2011

Ranked sixth in the LLJi is 28 June. As on 30 June, during the 0600–1200 period, lidar backscatter and nephelometer scattering are very low (10\(^{-5.5}\) m\(^{-1}\) sr\(^{-1}\) and 1.5 \times 10\(^{-4}\) m\(^{-1}\), respectively; Table 4). Flux tower wind speed is unavailable after 0700 but local observers reported 2 m wind speeds to be unsurprisingly low: 6.2 m s\(^{-1}\) at 0600 and 7.2 m s\(^{-1}\) at 0900. Observations show that this is because momentum from the LLJ was simply not mixed down. Momentum at 90 m (the lowest possible lidar observation) decreases by 95 kg m s\(^{-1}\) between 0500 and 0900, and between 0600 and 0800 momentum is decreasing at almost every height below 2 km (Figure 20).

8. Low-Level Oscillations

The Blackadar [1957] theory of LLJ formation posits that the jet is initiated by an inertial oscillation as defined in section 1. At BBM (21.38°N), this would result in an ~32 h oscillation period. If the decoupled period is
assumed to be 10–12 h, only a third of the inertial oscillation will be achieved at Saharan latitudes [Knippertz and Todd, 2012]. RCM experiments in the Bodélé show that this results in a highly super-geostrophic LLJ [Todd et al., 2008].

Marsham et al. [2013, Figure 12a] show that the diurnal cycle in the June 2011 500 m winds at BBM describes a clockwise rotation as expected. However, hodographs on individual days at BBM also display oscillations of much shorter period (as short as 5 or 6 h, beginning at different times). For the nocturnal to late morning period (1800 to 1200), such oscillations occur on 59/292 (20%) possible occasions during the IOP (selected heights; see Table 5). They are almost all clockwise and are only present on certain days (Table 5). On most days, their presence does not appear to be related to LLJ strength or lidar backscatter.

There are 2 days however when these oscillations are particularly clear and do appear to have an association with the LLJ: 25 and 26 June. The oscillations can

Figure 15. The 26 June 2011, 0600 UTC Africa LAM 925 hPa (a) specific humidity (kg kg\(^{-1}\)) and (b) wind speed (m s\(^{-1}\)) and vectors. Cross marks BBM location. White areas indicate topography above 925 hPa.

Figure 16. BBM, 26 June 2011: (a) nephelometer scattering \(\times 10^4\) (m\(^{-1}\)sr\(^{-1}\)) and \(\log_{10}\) lidar backscatter (m\(^{-1}\)sr\(^{-1}\)) time series; (b) nephelometer scattering, 10 m wind speed, and AOT\(_{500}\) time series; (c) sodar wind speed (m s\(^{-1}\)) time series; and (d) momentum profiles (kg m s\(^{-1}\)) for 06–07 h (black) and 09–10 h (blue). Ten meter momentum is indicated with a cross. White areas in the sodar plot are missing data (dropout). Lidar backscatter data are missing from 0445–0515 and 1900–2030. In Figure 16b, periods without red bars do not indicate zero AOT but either (i) no AOT measurements taken or (ii) AOT measurements removed as part of the AERONET level 1.5 cloud-screening process.
be seen in the jet core, 270 and 300 m agl, from 0100 to 0800 (25 June) and from 0300 to 0800 (26 June; Figure 21). This timing is coincident with the growth-decay phase of the jet. There are no discernible oscillations below 270 m agl except at 10 m and 15 m agl. At 10 m and 15 m agl, oscillations begin at 0600 (Figure 21), coincident with the start of the surface temperature increase (not shown). They last until 1200, spanning the period of the Gaussian-like increase and decrease in 10 m winds caused by the occurrence then cessation of momentum mix-down (Figure 16b).

9. Discussion and Conclusions

This paper presents observations of Saharan low-level jets from the Fennec supersite at Bordj-Badji Mokhtar, Algeria, and addresses their correspondence with current theory on LLJ formation and relationship with dust emission. Five key questions were posed in the introduction: (i) What are the observed characteristics of the LLJ in the central Sahara at BBM in summer? (ii) How well are LLJs at BBM represented by the Africa LAM and ERAI? (iii) Under what synoptic and local conditions is LLJ development favorable? (iv) What are the characteristics of LLJs associated with dust emission? (v) Is dust emission consistent with the mix-down of momentum from the jet core? These will now be addressed in turn.

![Figure 17. BBM momentum change profiles (kg m s\(^{-1}\) per hour) for (a) 26 June 2011 and (b) 16 June 2011. Crosses mark 10 m momentum change calculated from the flux tower (not available on 16 June).](image)

![Figure 18. BBM momentum profiles for (a) 26 June 2011 and (b) 30 June 2011. Crosses mark 10 m flux tower calculations. Ten meter wind speed (m s\(^{-1}\)), nephelometer scattering ×10\(^4\) (m\(^{-1}\)) and AOT\(_{500}\) for (c) 26 June and (d) 30 June. Horizontal blue line marks 13 m s\(^{-1}\) wind speed for ease of comparison. In Figures 18c and 18d, periods without red bars do not indicate zero AOT but either (i) no AOT measurements taken or (ii) AOT measurements removed as part of the AERONET level 1.5 cloud-screening process.](image)
The LLJ is clearly evident in the June 2011 mean diurnal wind cycle (Figure 1), as also shown by Marsham et al. [2013], but it is only present on 21/28 of these mornings. Its core is at 300 m agl (approximately 935 hPa). Peak composite wind speeds in the core are 13.5 m s$^{-1}$ (12 m s$^{-1}$ in the all-June composite) and occur between 0400 and 0500. There is significant variability in 10 m wind speeds and wind speeds within the jet core during the month (Figures 2 and 3). Composite temperatures (2 m height; Figure 3) begin to increase half an hour after sunrise (0513 h on 15 June), and the decay of the jet begins between 0500 and 0600. Ten meter wind speeds lag behind those in the jet core; peak 10 m wind speed, 7.5 m s$^{-1}$ (7 m s$^{-1}$ in the all-June composite), occurs between 0900 and 1000, 5 h after the LLJ peak (Tables 1 and 3). This is similar to the lag in the Bodélé Depression: A near-surface wind speed peak at around 0900 was observed during BoDEx, 4 h after surface temperatures began to increase [Washington et al., 2006a]. In southwest Niger the mix-down of the LLJ was found to be slower: Parker et al. [2005] report observed surface winds not peaking until 1100. At Fennec supersite 2, at Zouerate in Mauritania, LLJ mix-down is slower still: the Atlantic Inflow allows the LLJ to persist until 0900–1200, with a prolonged but moderate peak in surface winds over the course of the afternoon [Todd et al., 2013].

LLJ detection at BBM is based on three criteria: (i) wind speed maximum (below 600 m agl) > 8 m s$^{-1}$, (ii) wind shear between the LLJ core and 500 m above the core ≤ 1.8 m s$^{-1}$, and (iii) wind speed under the core decreases all the way to the lowest lidar measurement (90 m agl). Of the 28 mornings when lidar data were available, LLJs were detected on 21.

A low-level jet index (LLJi) was developed to compare the strength of the LLJs at BBM during the IOP. It is defined as the summation of wind speed exceeding a threshold in the LLJ core over the nocturnal-early morning period (equation (1)). The LLJi time series shows that there is significant variability in LLJ strength over the course of the month (Figure 5). Additionally, the LLJi shows that the strongest winds were produced by a relatively small number of events: 85% of the total LLJi is contained in 10/21 LLJs. The LLJi is based on high-quality, high-resolution data from a prime location for dust emission. However, the data were obtained over one summer month and the definitions used do depend on the conditions present during the limited period of observations.

The Africa LAM (key question 2) simulates Harmattan LLJ profiles accurately at BBM during the IOP, particularly at 0600 (Figure 8). Winds in the core of monsoon LLJs, however, are underestimated by 8.5 m s$^{-1}$. Surface wind speeds during the breakdown period of both monsoon and Harmattan LLJs are underestimated by up to 6 m s$^{-1}$. Critically, these underestimations result in surface wind speeds below the local threshold for dust emission. Further work will examine the causes and implications of these underestimates; it may be that the moist dynamics of monsoon LLJs present a particular challenge for the model in the boundary layer.

ERAI representation of monsoon jets at BBM is better than the LAM. However, it is still poor (core wind speeds...
Statistics Showing the Presence and Nature of Wind Oscillations Identified From Daily Hodographs From the IOPa

| Statistic                                      | Value                        |
|-----------------------------------------------|------------------------------|
| Total occasions available for oscillations    | 292 (100%)                   |
| Total no. of observed oscillations            | 59 (20.2%)                   |
| Total no. of clockwise oscillations           | 53 (18.2%)                   |
| Of the 59 observed oscillations…             | (100%)                       |
| No. of “imperfect” oscillations               | 17 (28.8%)                   |
| No. of incomplete oscillations                | 16 (20.3%)                   |
| Favoured heights for oscillations             | 15 m (18.6%), 10 m (16.9%), 270 m (11.9%) |
| Of the 43 completed oscillations…            | (100%)                       |
| No. which lasted 5 h                          | 9 (20.9%)                    |
| No. which lasted 6 h                          | 7 (16.3%)                    |
| No. which lasted 7–9 h                        | 15 (34.9%)                   |
| No. which lasted 10 h or more                 | 12 (27.9%)                   |
| No. of days with oscillation(s) at any height (see caption for heights) | 17/28 |

*aHodograph time period 1800 to 1200 chosen to include nocturnal LLJ growth, mix-down, and surface wind speed maximum. Heights chosen for data availability reasons and to maximize observations near the jet core: 10 m and 15 m (measurements from the flux tower), and 90 m, 150 m, 180 m, 240 m, 270 m, 300 m, 330 m, 420 m, and 510 m (measurements from the lidar). “Occasion” defined as a given height on a given day where enough data are available to make an assessment. An “imperfect” oscillation is one where not all the measurements fall on the circle.

underestimated by 6 m s−1 at 0600; Figure 8). ERAI representation of Harmattan jets at BBM is also poor (core wind speeds underestimated by 4 m s−1 at 0600). These findings demonstrate that ERAI does indeed underestimate LLJ strength in the morning, as suggested by Fiedler et al. [2013]. There is little LLJ structure in the 0600 ERAI wind profiles compared to the lidar observations during the IOP at BBM. This is also the case for monsoon LLJs simulated by the LAM. Application of reanalysis-based LLJ detection criteria to observations is inappropriate at BBM. Caution should be exercised when using ERAI as a surrogate for observations of LLJs elsewhere in the central Sahara and likewise the LAM for monsoon LLJs. However, the LAM simulates Harmattan LLJs very accurately. Ashpole and Washington [2013] point to the Harmattan LLJ being the dominant LLJ wind direction in the central Sahara for dust emission. Since this form of the LLJ is more important than the monsoon jet as a whole across the central Sahara in the summer, there is a clear case for favoring the LAM data set.

LLJ development at BBM (key question 3) is favorable under conditions of a strong synoptic-scale pressure gradient. When this is not present, when the heat low is weak in the BBM region, there is little or no LLJ formation (Figures 9a and 9d). Under conditions of a strong synoptic-scale pressure gradient, LLJs at BBM during the IOP can be split into two main types, those embedded in the moist monsoon flow (five LLJs) and those embedded in the dry Harmattan flow (six LLJs; mornings when cold pools were observed coincident with LLJs are excluded in both cases). There is a clear association between the SHL position and the classification of the LLJ. When the SHL is east of BBM, the cyclonic circulation promotes northeasterly LLJs over BBM (Figures 9b and 9e). When the SHL is to the northwest of BBM, the cyclonic circulation promotes southwesterly LLJs over BBM (Figures 9c and 9f). This highlights the importance of correct model simulation of the position and strength of the SHL. Southwesterly LLJs accelerating toward the SHL have been shown to be an important feature of the diurnal monsoon circulation [Parker et al., 2005]; the monsoon flow intensifies overnight as boundary layer turbulence dies down.

The local conditions for LLJ development are appreciably different depending on whether the LLJ is embedded in the Harmattan or the monsoon flow. Harmattan LLJs are associated with stronger surface temperature inversions than monsoon LLJs: on average, 2.5°C/100 m at 0600 compared with 0.6°C/100 m (Figure 11). The strongest LLJ, which is embedded in the Harmattan, has a surface temperature inversion of 2.2°C/100 m (Figure 10b). This highly stably stratified nocturnal boundary layer will promote the decoupling of the winds in the LLJ core from the surface. However, many strong LLJs, particularly those embedded in the monsoon, have much weaker surface temperature inversions (Figure 11). Unlike for the LLJs in Mali documented by Bain et al. [2010], stronger temperature inversions did not necessarily result in stronger jets. Kutsher et al. [2012] document LLJs in the Negev Desert which do not depend on strong surface temperature inversions to form, since the LLJs can be advected as part of the sea breeze circulation. The West African Monsoon could to some extent also be thought of as “advecting” the monsoon LLJs to BBM.
Harmattan and monsoon LLJs develop with considerably different lower tropospheric moisture conditions (Figure 12). The reduced near-surface cooling during the nights and early mornings of monsoon LLJs is most likely because the monsoon LLJs bring relatively high levels of water vapor with them below ~600 m agl (Figure 12b). There is no evidence of turbulent mixing below the LLJ core in the BBM nocturnal potential temperature profiles: Kutsher et al. [2012] found such a mechanism and showed that it could counterbalance nocturnal radiative cooling.

Only particularly strong and deep LLJs lead to dust emission (Figure 13; key question 4). Dust-emitting LLJs at BBM all have core wind speeds ≥16 m s⁻¹ and below-core wind shear ≥0.6 m s⁻¹ per 30 m. At midnight on dusty mornings, the LLJ is already stronger than the maximum strength the LLJ reaches on nondusty mornings. The depth of wind speeds above 8 m s⁻¹ is also twice as great, 90–1500 m agl compared to 90–700 m agl. A deeper convective boundary layer promotes momentum mix-down to the surface, where post-sunrise wind speeds display a Gaussian increase and decay, closely matched by the lidar backscatter from 0700 to 1300 (Figure 14a). During this period, 10 m wind speeds are above the local dust emission threshold of 8 m s⁻¹ [Allen et al., 2013]. Higher LLJ wind speeds on dusty mornings have also been found by other studies. In their subdomain including BBM, Fiedler et al. [2013] find that the median LLJ core wind speed for dust-emitting LLJs is 7 m s⁻¹ faster than that for all LLJ periods (16 m s⁻¹ compared to 9 m s⁻¹). During BoDEx, LLJ core wind speeds on dusty mornings were, depending on the hour, up to 10 m s⁻¹ faster than on nondusty mornings [Washington et al., 2006a].

Unlike most previous studies where wind speed is used as a proxy for momentum, the simultaneous availability of radiosondes, lidar, and flux tower instrumentation has allowed momentum profiles to be calculated explicitly for the IOP (key question 5). These show that, on all occasions when LLJ-induced dust emission occurs, momentum does indeed mix down from the LLJ core to the surface between 0500 and 0900, after the onset of surface heating (Table 4). The use of momentum change profiles makes it particularly easy to see the transfer of momentum between 1 h and the next at a selection of levels through the atmosphere. Good examples of this occur in the 0700–0800 time interval: On 26 June (Figure 17a), the near surface is almost the only height gaining momentum coincident with a significant increase in backscatter; on 16 June, momentum at 300 m decreases by almost 240 kg m s⁻¹ whilst momentum at 120 m agl and below increases by over 80 kg m s⁻¹ (Figure 17b).
Momentum is not always mixed down. On the nine pure LLJ mornings which do not lead to dust emission, momentum mix-down between 0500 and 0900 is not observed except on 8 June. On this morning, the weakness of the LLJ (Figure 5) probably explains why no dust emission occurs. On 17/21 LLJ mornings, momentum does not mix down between 0900 and 1200. This is consistent with the general decrease in surface wind speeds after 0900 on LLJ mornings (Figures 14, 16b, and 18c). Without momentum being mixed to the surface, the surface wind speeds decline. This suggests that the period of 0600–1200 chosen by Marsham et al. [2013] to span momentum mix-down is too generous for most cases, although, given uncertainties due to missing data, there are between one and four cases when LLJ momentum does mix down from 0900 to 1200. This compares with eight to nine cases when momentum mixes down from 0500 to 0900 (Table 4).

Some cold pool outflows (e.g., 13 and 21 June) appear to disrupt the mix-down process: momentum does not mix down between 0500 and 0900 on either of these mornings (Table 4). Using Lokal-Modell MultiScale Chemistry Aerosol Transport Model (LM-MUSCAT), Heinold et al. [2008] also found that thermal stratification suppresses turbulent mix-down of momentum in the Sahara, although this stratification was specifically due to the presence of dust, which is not always the cause of the stratification at BBM. During three mornings when LLJs were coincident with cold pool outflows (e.g., 18 June; Table 4), momentum does mix down between 0500 and 0900, however. On these mornings, it is plausible that the LLJ also contributes to the dust loadings, especially if a Gaussian pattern in the surface wind speeds can be identified. Following the results of 4 km resolution explicit convection simulations over the West African domain, Heinold et al. [2013] suggest that aged cold pools that glide above a stable nocturnal boundary layer can trigger LLJ formation. This mechanism is not the main trigger for LLJ formation during the IOP (the LLJs observed at BBM are simulated by the 12 km resolution Africa LAM, which parameterizes convection and has very poor representation of cold pools [see also Marsham et al., 2011]). However, the coincidence of LLJ and cold pool outflow is reasonably frequent: of the 21 mornings when LLJs were detected, cold pools occurred on seven. This is similar to the results of Heinold et al. [2013], who found that for 23% dust emissions in the model domain, both LLJs and cold pools were detected together.

LLJs are common features in desert regions, where they can be an important mechanism for dust emission. The Bodélé LLJ in Chad has been well documented [e.g., Washington et al., 2006a], but the remoteness and difficulty of working in the summertime central Sahara has meant that until the Fennec project, direct observations of these features here have been very limited. This paper has presented the first detailed analysis of central Sahara LLJs from ground-based observations and demonstrated their strong association with the heat low. Whilst LLJs occur on most mornings, their presence cannot be taken as a guarantee of dust emission, even over a highly erodible surface: only the strongest LLJs lead to momentum mix-down and emission. The study is limited to one location and one summer however; further Fennec work will expand the analysis beyond BBM and out to other locations.

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