Dust detection from ground-based observations in the summer global dust maximum: Results from Fennec 2011 and 2012 and implications for modeling and field observations

Christopher J. T. Allen¹, R. Washington¹, and A. Saci²

¹Climate Research Lab, Oxford University Centre for the Environment, Oxford, UK, ²Office National de la Météorologie, Algiers, Algeria

Abstract In boreal summer, the central Sahara is the dustiest place on Earth. Fennec supersite 1 is located within the dust maximum. With two field seasons completed, June 2011 (intensive observation period (IOP) 1) and June 2012 (IOP2), we now have an initial measure of their representativeness. Although the number of dust event hours in IOP2 is up to 169 h (60%) more than in IOP1, the relative importance of the different dust mechanisms is the same. In both years, emission by cold pool outflows from deep convection causes most dust, followed by dust advection, monsoon surges, low-level jet emission and lastly dry convective plumes. Given the dominance of cold pools, it is very important that they be incorporated in dust modeling efforts over the region. Because cold pools frequently occur at night and are associated with cloud cover, instruments that can monitor in these conditions are particularly valuable in this region. Sun photometer aerosol optical depth retrievals, for example, are only available for 23% (41%) of the time cold pool emission occurs at the supersite in IOP1 (IOP2). Deployment of instrumentation in remote regions being difficult and expensive, choosing the optimal instrument payload pays dividends. With this motivation, we evaluate the different dust detection instrumentation deployed at the supersite and develop an approach which can identify and characterize individual dust emission mechanisms with a high degree of success purely from routine meteorological observations and remote sensing. This identification is, however, much more challenging in the case of dust advection.

1. Introduction

It is well established that North Africa is the dustiest place in the world [e.g., Prospero et al., 2002; Washington et al., 2003; Ginoux et al., 2012], but it is only recently that the central Sahara, the prime boreal summer dust source [Ashpole and Washington, 2012], has been subject to a comprehensive campaign of instrumentation: Fennec [Washington et al., 2012]. As part of Fennec, eight automatic weather stations were deployed in the central Sahara [Hobby et al., 2013] and two supersites were established, in Bordj-Badji Mokhtar, Algeria [Marsham et al., 2013], and Zouerat, Mauritania [Todd et al., 2013]. Observations from these supersites have provided new insights into Saharan dust, including among others the links between dust, cloud, and the surface energy balance [Marsham et al., 2013]; the relative importance of dust production mechanisms [Allen et al., 2013; Marsham et al., 2013]; the operation of the low-level jet dust emission mechanism [Allen and Washington, 2014]; and the role of the Atlantic Inflow on the diurnal cycle of the boundary layer [Todd et al., 2013].

Considerable progress on African meteorology and climatology have been derived from short-term, intensive campaigns with African Monsoon Multidisciplinary Analyses (AMMA) [Redelsperger et al., 2006] and Fennec [Washington et al., 2012] serving as prime examples for the West and North African regions, respectively. The extreme remoteness of major source regions of mineral aerosols in the central Sahara has led to short-term campaigns in order to make costs and logistics manageable. As a result, the benchmark statistics relating to the meteorology of dust-producing mechanisms emerging from field experiments such as Bodélé Dust Experiment and Fennec, against which model development is posed, are derived from subseasonal campaigns typically in just one calendar year. In the case of Fennec, Allen et al. [2013] have shown that cold pool outflows, which constitute considerable challenges for numerical simulation, account for 45% of total emissions in the central Sahara. What is not clear is whether June 2011, the period from which
this statistic was derived, can be regarded as representative of the mean summer conditions in the Sahara. There is growing evidence based on remote sensing [e.g., Ashpole and Washington, 2013b; Awad and Mashat, 2014; Ridley et al., 2014] and observations distant from dust source regions [e.g., Prospero and Lamb, 2003; Engelstaedter et al., 2006; Mona et al., 2006] that Saharan dust output displays considerable interannual variability. This variability in dust output has been linked to variability in assorted North African atmospheric phenomena. African Easterly Waves, for example, which show significant interannual variability [Thorncroft and Hodges, 2001], can promote cold pool emission and also transport dust aloft toward the Atlantic [Jones et al., 2003; Knippertz and Todd, 2010; Zuluaga et al., 2012]. Interannual variability in the West African Monsoon [reviewed by Rodríguez-Fonseca et al., 2011] is also linked to variability in dust emission: Ashpole and Washington [2013b] find that the dustiest summers are associated with a ≅3 m s\(^{-1}\) positive southwesterly anomaly in 925 hPa wind speed that extends from northern Mali into central Algeria. A strong moist monsoon inflow can lead to dust emission as an intrusive surge or by promoting cold pool activity [Bou Karam et al., 2008; Marsham et al., 2008; Allen et al., 2013; Marsham et al., 2013]; strong low-level jets (LLJs) are also frequently embedded in the moist monsoon inflow [Parker et al., 2005; Allen and Washington, 2014].

Fennec was fortunate to be funded for an unplanned, albeit scaled-down second season in the Sahara in 2012. As a result of this opportunity, the aims of this paper are (a) ontological: a comparison of June 2011 and June 2012 in order to establish the degree of similarity of dust generating mechanisms operating in the remote Sahara and thereby to provide some constraint on interannual variability and (b) methodological: an analysis of the extent to which limited instrumentation can reproduce diagnostics of dust mechanisms compared with more comprehensive instrument deployment. The value in the latter lies in knowing the optimal level of instrumentation given the expense of importing, transporting, and deploying instrumentation to remote regions—impediments that have long acted as a brake on knowledge of the meteorology of key dust-producing regions.

Section 2 describes the data sets and field instrumentation employed; section 3 describes the dust detection methodology for June 2012; this is then validated in section 4. Sections 5–8 compare the characteristics of the dust events of June 2011 and June 2012, and section 9 assesses the instrumentation. A discussion and conclusions are presented in section 10.

2. Data Sets and Instrumentation

This paper focuses on Fennec supersite 1, the most comprehensively instrumented Fennec ground station, located at the existing synoptic station of Bordj-Badjji Mokhtar (BBM) in southwest Algeria (21.38°N, 0.92°E; altitude 420 m above sea level; World Meteorological Organization ID: 60686). BBM is located very close to the center of the boreal summer global climatological dust maximum [e.g., Ashpole and Washington, 2012] and is proximate to several frequently active dust sources [Ashpole and Washington, 2013a] making it an ideal location to study dust emission processes. Figure 1 shows the location of BBM in North Africa. Fennec instrumentation has been deployed at BBM since June 2011 as part of the Fennec extended observation period, with additional instruments being available during the June 2011 intensive observation period (IOP) and, to a much lesser extent, the June 2012 IOP. The instruments, their precision and deployment lengths are described in Table 1. False color imagery with 15 min temporal resolution 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] is used to identify the presence of cloud and to help classify dust events. A detailed evaluation of the SEVIRI dust detection algorithm is provided by Brindley et al. [2012]. A SEVIRI cloud mask product (available from the European Organisation for the Exploitation of Meteorological Satellites data archive (archive.eumetsat.int/umarf/)) is employed to detect cloud over BBM. In addition, we use an objective...
Table 1. Instruments Available in June 2011 and June 2012\textsuperscript{a}

| Instrument Description | Precision | June 2011 | June 2012 | Notes |
|------------------------|-----------|-----------|-----------|-------|
| "Flux tower" (10 m and 15 m agl sonic anemometers) | 0.1 ms\textsuperscript{-1} (wind speed) | 6th–30th | 1st–30th | |
| Flux tower (2 m agl sensors) | 2\% (RH), 0.3°C (T), 0.5 hPa (P) | 6th–30th | 1st–30th | |
| Cimel Sun photometer (formed part of the Aerosol Robotic Network (AERONET) project) \cite{Holben1998}. Level 1.5 data (cloud screened) as it is common to 2011 and 2012. | 0.01 (440 nm AOD) | 4th–30th | 1st–30th | Measurements not continuous—data gaps discussed in section 9.1 |
| Vaisala RS92 GPS radiosondes (launched at up to 3-hourly intervals) | 0.2 ms\textsuperscript{-1} (wind speed) | 8th–30th | 2nd–25th | Not launched at 0600 on all of these mornings |
| HALO Photonics Streamline 1.55 μm Doppler lidar (measurements taken every 30 m from 90 m agl to 9990 m agl) | 0.1 ms\textsuperscript{-1} (wind speed) | 3rd–30th | NA | Wind speed derived using a modified velocity-azimuth display algorithm \cite{Browning1968, Banta2002} |
| Inverse nephelometer (2 m agl, 670 nm) | 10\textsuperscript{-7} m\textsuperscript{-1} (scattering) | 5th–30th | NA | |
| Scintec medium phased array sodar | 0.3 ms\textsuperscript{-1} (wind speed) | 2nd–30th | NA | |

\textsuperscript{a}RH = relative humidity, T = temperature, P = pressure, and agl = above ground level. Precision is reported for the variables used in this paper. Filters from the vacuum pump aerosol sampler are still being analyzed, and the data are not used in this paper. An automatic weather station was available in June 2012, with instruments as per the flux tower (described by \textit{Hobby et al.} [2013]). It was not used in this analysis. Further details of the instrumentation at BBM can be found in \textit{Marsham et al.} [2013]. NA = not available.

For the June 2012 IOP (IOP2), the more limited instrumentation available makes this more difficult. In particular, the loss of the nephelometer and the lidar makes it impossible to simply apply the dust mechanism identification approach of \textit{Allen et al.} [2013] to IOP2. We therefore use a data-denial approach on the IOP1 data set (i.e., we only use instruments also available in IOP2) to develop identification criteria which can be applied to IOP2. This approach is taken since the classification of IOP1 dust events based on IOP2 instrumentation is verifiable given the spectrum of available instrumentation in IOP1. The criteria are designed to be objective wherever possible. We present the data-denial identification criteria in this section and present a quantitative measure of their skill in section 4.

3. Dust Detection Methodology for June 2012

During the June 2011 IOP (IOP1), the instrumental setup at BBM was conducive to identifying and characterizing dust events and the meteorological mechanisms responsible for them (method and results documented in \textit{Allen et al.} [2013]). For the June 2012 IOP (IOP2), the more limited instrumentation available makes this more difficult. In particular, the loss of the nephelometer and the lidar makes it impossible to simply apply the dust mechanism identification approach of \textit{Allen et al.} [2013] to IOP2. We therefore use a data-denial approach on the IOP1 data set (i.e., we only use instruments also available in IOP2) to develop identification criteria which can be applied to IOP2. This approach is taken since the classification of IOP1 dust events based on IOP2 instrumentation is verifiable given the spectrum of available instrumentation in IOP1. The criteria are designed to be objective wherever possible. We present the data-denial identification criteria in this section and present a quantitative measure of their skill in section 4.

3.1. Detection of Dust Presence

For IOP2, the only data set that can be used to infer dust presence during the day and the night is SDF. A limitation of SDF is that it is relatively poor at flagging dust when the overall loading is low (aerosol optical depth (AOD) < ~1) \cite{Ashpole2012}. As a result, we combine local observers’ observations of the dust conditions with SDF to develop a set of “SDF and observers rules” to determine dust presence. These are summarized in Table 2. The SDF and observers rules are applied to aid dust mechanism identification as explained in the following subsections.
is high, substantial 10 m wind speed during the cold pool emission events of IOP1 (as identi
Williams et al.

current [e.g.,
fl
that every cold pool emission event begins with a jump in wind speed of at least 3 ms
Cold pool out
3.3. Cold Pool Out
decrease is approximately Gaussian (as found by
Allen and Washington

turbulent mixing in the boundary layer actually decreases, because the dust reduces the sunlight reaching
surface [\cite{Miller et al., 2004; Pérez et al., 2006; Emmel et al., 2010; Solomos et al., 2012; Allen et al., 2013; Marsham et al., 2013}]. Inspection of 10 m wind speed during the cold pool emission events of IOP1 (as identified by \cite{Allen et al., 2013}) shows that every cold pool emission event begins with a jump in wind speed of at least 3 ms$^{-1}$ in 15 min. We therefore use a jump in wind speed of at least 3 ms$^{-1}$ in 15 min as a first condition. The second condition is that wind speed must be above an emission threshold, since by definition this is a search for dust-emitting cold pools (see also section 4). One characteristic of cold pools is that as they pass over a point, they frequently cause a measureable change in temperature, water vapor mixing ratio (WVMR) and/or pressure [\cite{Miller et al., 2008; Emmel et al., 2010; Marsham et al., 2013}]. This is often but not always the case for cold pool outflows observed at BBM. During the day, continuous temperature fluctuations are recorded which have a magnitude similar to that associated with the passing of moderate or weak cold pools ($\pm 1 ^\circ$C/15 min), so it is difficult to determine when these

\begin{table}
\centering
\caption{SDF and Observers Rules}
\begin{tabular}{|l|l|}
\hline
SDF and Observers Dust Conditions\textsuperscript{a} & Ruling \\
\hline
SDF = 1 and dust visually observed & Dust \\
SDF = 1 and observations clear & Dust \\
SDF = 0 and dust visually observed & Dust \\
SDF = 0 and observations clear & No dust \\
SDF = 1 and no observations made & Dust \\
SDF = 0 and no observations made & Dust if meteorological criteria satisfied (section 3) \\
\hline
\textsuperscript{a}SDF is a binary measure; 1 = dust flagged and 0 = dust not flagged. Conditions are as reported by the local weather observers.
\end{tabular}
\end{table}

3.2. Low-Level Jet Dust Emission Detection
Low-level jets (LLJs) form primarily at night when winds above the nocturnal temperature inversion become decoupled from surface friction [\cite{Blackadar, 1957}]. Turbulent mixing increases after sunrise, and the momentum from the LLJ can be mixed down to the surface [\cite{Lothon et al., 2008; Allen and Washington, 2014}], leading to dust emission [\cite{Washington et al., 2006; Todd et al., 2008; Marsham et al., 2013; Allen and Washington, 2014}]. LLJ dust emission detection is a two-stage process. First, a LLJ has to be detected above the surface. Second, momentum mix down from the LLJ must result in high surface wind speeds and dust emission.

The LLJ detection scheme developed by \cite{Allen and Washington, 2014} is used to identify LLJs. The scheme searches the 0600 wind profiles for wind speed maxima below 600 m above ground level (agl). (This upper limit avoids detecting elevated wind maxima which are not LLJs; these have been found at BBM [\cite{Allen and Washington, 2014} and in northern Algeria [\cite{Cowie et al., 2014}].) The maxima are classified as LLJs if (i) they are > 8 ms$^{-1}$, (ii) the wind shear between the wind maximum (the LLJ “core”) and 500 m above the core is \(\leq -1.8 \text{ m s}^{-1}\), and (iii) the wind speed under the core decreases downward to the lowest measurement. \cite{Allen and Washington, 2014} apply these criteria to lidar wind profiles, but since the lidar is unavailable for IOP2 we use radiosonde wind profiles. Using radiosonde rather than lidar measurements to detect LLJs during IOP1 results in correct LLJ classification on all but 3 out of the 22 occasions when radiosondes were launched at 0600 in IOP1. Two of these are when LLJs and cold pools occurred simultaneously, when one might expect wind profiles to be changing rapidly.

\cite{Allen and Washington, 2014} show that the presence of a LLJ is not a guarantee of dust emission since momentum does not always mix down to the surface. Indeed, in dusty regions it is possible that daytime turbulent mixing in the boundary layer actually decreases, because the dust reduces the sunlight reaching the surface [\cite{Miller et al., 2004; Pérez et al., 2006}]. A detected LLJ is considered to lead to dust emission if (i) the 10 m wind speed is above an emission threshold (section 4), (ii) the pattern of 10 m wind speed increase and decrease is approximately Gaussian (as found by \cite{Allen and Washington, 2014}), (iii) the wind speed increase does not begin before sunrise, and (iv) the SDF and observers rules are passed (Table 2). On mornings when no 0600 radiosonde wind profile measurements are available (eight mornings in IOP1 and eight mornings in IOP2), the detection rests on fulfilling these four criteria alone.

3.3. Cold Pool Outflow Emission Detection
Cold pool outflows form when downdrafts from deep convection spread away from the parent storm as a density current [\cite{Miller et al., 2008; Roberts and Knippertz, 2014}]. At the leading edge of the outflow, where turbulence is high, substantial “walls” of dust can be raised [\cite{Flamant et al., 2007; Knippertz et al., 2007; Miller et al., 2008; Williams et al., 2009; Emmel et al., 2010; Solomos et al., 2012; Allen et al., 2013; Marsham et al., 2013}]. Inspection of 10 m wind speed during the cold pool emission events of IOP1 (as identified by \cite{Allen et al., 2013}) shows that every cold pool emission event begins with a jump in wind speed of at least 3 ms$^{-1}$ in 15 min. We therefore use a jump in wind speed of at least 3 ms$^{-1}$ in 15 min as a first condition. The second condition is that wind speed must be above an emission threshold, since by definition this is a search for dust-emitting cold pools (see also section 4). One characteristic of cold pools is that as they pass over a point, they frequently cause a measureable change in temperature, water vapor mixing ratio (WVMR) and/or pressure [\cite{Miller et al., 2008; Emmel et al., 2010; Marsham et al., 2013}]. This is often but not always the case for cold pool outflows observed at BBM. During the day, continuous temperature fluctuations are recorded which have a magnitude similar to that associated with the passing of moderate or weak cold pools ($\pm 1 ^\circ$C/15 min), so it is difficult to determine when these...
changes are actually due to cold pools. Furthermore, during IOP1 surface temperature, humidity, and pressure measurements are missing for a total of 245, 245, and 147 h respectively after the instruments were activated. As a result of all these factors, we do not use temperature, pressure, or moisture changes as a criterion for cold pool emission detection, although if these are present, they help confirm the detection. We do, however, use the SEVIRI false color dust detection imagery to check whether identification as a cold pool is appropriate, once the wind speed filters have been passed. Dust from large cold pools is often clearly visible in SEVIRI, and the presence of deep convection is a strong clue for potential cold pool activity [e.g., Solomos et al., 2012; Allen et al., 2013; Marsham et al., 2013; Roberts and Knippertz, 2014].

In brief, the criteria for cold pool emission are (i) event starts with a jump in wind speed of at least 3 ms\(^{-1}\) in 15 min, (ii) wind speeds remain above an emission threshold, (iii) SDF and observers rules are passed (Table 2), and (iv) convective cloud is present over BBM in SEVIRI false color imagery, or the dust can be back tracked to deep convection. There is some risk that a single event may be artificially split into two or more separate events; this is discussed in section 6. However, it will not change the calculations of their total duration or total dustiness during the IOPs.

### 3.4. Dry Convective Plume Emission

Dust can also be raised by dry convection, either in nonrotating plumes (diameter ~100 m) [Ansmann et al., 2009] or rotating vortices known as dust devils (diameter ~7 m) [Balme and Greeley, 2006]. Dry convective events are relatively short lived, on the order of a few minutes for dust devils and an hour or so for dry convective plumes [Ansmann et al., 2009]. Light winds (<7 ms\(^{-1}\)) are required to allow dry convective plumes and dust devils to develop [Oke et al., 2007]. Dry convection is usually associated with a pressure drop at the surface, known as a “pressure well” [Balme and Greeley, 2006; Lorenz, 2012]. In a thermodynamical model for dust devils, Renno et al. [1998] show that the net work done by a dust devil is proportional to the surface pressure drop and that the wind speed around a dust devil solely depends on this value, making the pressure well a particularly important variable to consider.

The criteria for dry convective plume emission detection are (i) event starts with a jump in wind speed of at least 3 ms\(^{-1}\) in 15 min and a pressure decrease (pressure “well”) of at least 0.7 hPa in 15 min, (ii) wind speeds prior to the pressure well must be less than 7 ms\(^{-1}\) (following Oke et al. [2007] and Ansmann et al. [2009]), (iii) wind speeds following the wind speed jump remain above the emission threshold (section 4), but for no longer than 2 h, and (iv) the event must occur in the afternoon (i.e., after midday but before sunset). The final criterion is to help distinguish dry convective plumes from the convective mixing which can bring down momentum from LLJs, typically in the morning. Dry convection thus plays a role in two dust emission processes here but the above criteria focus on the short-lived convective plumes and dust devils, having already identified periods of LLJ emission in section 3.2.

Since dry convective plumes are short lived, they are not required to pass the SDF and observers rules (observers report at most every 3 h and it is unlikely that dust from dry convective plumes would be visible from a geostationary satellite due to limitations on the spatial resolution of imagery). Dust devils are not explicitly distinguished from dry convective plumes in this analysis; they are smaller and shorter lived and difficult to detect with only one mast. Missing pressure measurements make it probable that some events are missed. It is likely that the contribution of dry convection is underestimated in both IOPs.

### 3.5. Dust Advection

Without the lidar or nephelometer, detection of advected dust at BBM is difficult. Two classes of advected dust are distinguished: “advection: unknown cause” and “probably cold pool” advection. For the former, the following criteria are adopted: (i) SDF or visually observed dust present, but not identified so far as an emission mechanism and (ii) wind speed below an emission threshold. For the latter, (i) the event begins with a fluctuation in pressure of at least 0.7 hPa in 15 min and/or an increase in WVMR of 1 g kg\(^{-1}\) in 5 min, (ii) wind speed is below an emission threshold, and (iii) event passes SDF and observers rules (Table 2). In both advection: unknown cause and probably cold pool advection, once an event passes the criteria it continues to be classed as advection until dust is no longer identified by SDF or the observers, as long as wind speed is below the emission threshold. The advection: unknown cause category could contain dust from many origins, including aged cold pools with no pressure or WVMR signatures, or advection related to larger-scale processes such as Saharan cyclones or African Easterly Waves.
3.6. Monsoon Surges

Monsoon surges are large-scale incursions of the summer moist monsoon inflow into the central Sahara [e.g., Couvreux et al., 2010]. They can raise dust directly by acting as density currents or indirectly by promoting deep convection and cold pool outflows [e.g., Bou Karam et al., 2008; Marsham et al., 2008]. In this paper, the term “monsoon surge” will only be applied to surge events that produce dust. Allen et al. [2013] did not explicitly identify any monsoon surges during IOP1. They are not always distinguishable from LLJs and cold pool outflows as they can share similar characteristics [Bou Karam et al., 2008; Marsham et al., 2008; Flamant et al., 2009; Marsham et al., 2013]. During IOP2, however, classification of monsoon surges was easier. On three occasions, SEVIRI imagery showed very wide (500–1000 km) dust fronts approaching BBM during the late night/early morning from the south or southeast; WVMR rose from background values of < 4 g kg$^{-1}$ to up to 14 g kg$^{-1}$ (at a rate of up to 7 g kg$^{-1}$ h$^{-1}$); peak wind speeds in the boundary layer were over 13 ms$^{-1}$ but did not have LLJ profiles (section 3.2); 10 m wind speeds began to increase before sunrise and persisted above 6 ms$^{-1}$ for up to 15 h. Figure 2 summarizes the data-denial dust detection methodology.

4. Validation of Data-Denial Dust Detection Methodology

The data-denial dust detection methodology described in section 3 is validated by comparing it with a refined version of the Allen et al. [2013] dust detection results. The refinement is to allow classification of separate advection and emission periods within individual dust events, rather than classing each event once based on whether it is mostly advecting or emitting dust. This refinement is introduced because some cold pool outflows can contain both periods of dust emission (e.g., at the leading edge) and advection (e.g., behind it) [Miller et al., 2008; Emmel et al., 2010]. The same emission threshold (6 ms$^{-1}$) is used for both years.

The Allen et al. [2013] approach used nephelometer scattering as a sampling base and also made heavy use of the height-resolved lidar backscatter profiles to characterize dust events. Both instruments were unavailable during IOP2 and therefore also to the data-denial approach. The nephelometer was unavailable before 2020 h on 5 June 2011 and missed two dust emission-inducing LLJs on the mornings of 3 and 5 June (described in Allen and Washington [2014]); these LLJs are included in the validation.

Validation of the data-denial identification method (section 3) can result in four outcomes. (i) True positive (data-denial method identifies the same dust mechanism as actually observed). (ii) False positive (data-denial identifies a dust mechanism when no dust mechanism is observed). (iii) False negative (a “miss”: data-denial fails to identify the correct dust mechanism or does not identify one at all). (iv) True negative (data-denial correctly identifies that no dust mechanism is occurring). The bias ratio can also be used to provide a basic evaluation of the data-denial method for each dust mechanism; it is defined as total forecast event hours divided by total observed event hours [Wilks, 2006]. Values < 1 are underpredictions, and values > 1 are overpredictions.

The data-denial method is very successful in detecting cold pool emission, LLJ emission and dry convective plumes. For these the true positive rate is around 0.9, the false positive rate is below 0.015 and the bias ratio is close to 1 for each event class (red symbols, Figure 3). With no nephelometer or lidar, detection of local emission using the data-denial approach is unsurprisingly more successful than detection of advected dust (Figure 3, compare orange symbols with red symbols). Without using SDF or local observers as part of the criteria, the true positive rate for advected dust is very low, below 0.1, and the bias ratio is very poor, 0.15 (orange star, Figure 3). Including SDF or observers’ observations results in a marked improvement in the true positive rate, from below 0.1 to 0.3 (orange crosses, Figure 3), and including both improves it significantly further (orange circle, Figure 3). However, the true positive rate is still only 0.47: a large proportion of the advected dust observed during IOP1 is missed. The false positive rate is low, however, only 0.02. We apply the data-denial dust advection detection to IOP2 but highlight that confidence is appreciably lower than for local dust emission detection.

For all dust mechanisms, the false positive rate is very low (Figure 3). This is probably because BBM is within a dust source area itself, a palaeolake [Ashpole and Washington, 2013a]; therefore, emission is not supply limited (the palaeolake surface is readily erodible). Hence, if an emission mechanism is operating, dust uplift will occur. There is little difference in the success of the dust detection methodology between day and night because the only data source used that is not available at night is the local observers (the Sun photometer is not used for dust detection).
We do not validate the monsoon surge data-denial detection since Allen et al. [2013] did not explicitly identify any monsoon surges during IOP1. They did, however, recognize that there were two occasions when event attribution is particularly difficult, and monsoon surges may have been detected as a LLJ and advected dust in a cold pool (see also section 3.6). In the remainder of the paper we class these two events in IOP1 as monsoon surges. In the supporting information (Text S1 and Figure S1) we show that the relative importance of the dust mechanisms is only altered subtly if they are classed otherwise.

**5. Time Partitioning of Dust Mechanisms**

One area of research which has been called for in recent years is a quantitative assessment of the relative importance of dust production mechanisms in the Sahara [e.g., Bou Karam et al., 2008; Marsham et al., 2008].

---

**Figure 2.** Cartoon summarizing data-denial dust detection methodology. (a) LLJ emission, (b) cold pool emission, (c) dry convective plume emission, and (d) dust advection: “unknown cause” (left) and probably cold pool (right). “wspd” = wind speed. For details see section 3.
Progress has been made on this front with modeling [e.g., Marsham et al., 2011; Heinold et al., 2013], reanalysis [e.g., Fiedler et al., 2013], and also from observations during IOP1 [Allen et al., 2013; Marsham et al., 2013]. As with many remote field campaigns, however, the IOP1 observations are from just one calendar year. The fortune to be granted a second field season means that a valuable first assessment can be made of the representativeness of the dust mechanisms observed in this all-important region. The dust detection methodology described and validated in the sections above makes this possible.

Three different estimations have been given for the IOP2 dust production hours (Figure 4). The time resolution is 15 min (the maximum resolution of SDF). The blue box ("lower limit") gives the value based on dust mechanism identification following the methodology outlined in section 3. The open circle ("estimate") does the same but allows the occasional periods where dust could plausibly be produced by two different mechanisms to be counted twice. This allows for incorporation of classification uncertainty. It leads to no change to the dust production hours in the case of advected dust, and only small or moderate changes in the other cases (Figure 4). The third approach (red diamond, "bias ratio correction") divides the lower limit values in Figure 4 by the appropriate bias ratio (see section 4 and Figure 3). This provides a basic correction for the number of hours that are missed by the dust detection techniques. A bias ratio correction is not applied to monsoon surges since there is uncertainty in their detection in IOP1 (section 4 and Supporting Information).

As expected from the low true positive rate of dust advection detection (Figure 3, orange circle), the bias ratio correction leads to a large increase in the duration of dust advection for IOP2, from 128 h to 218 h (Figure 4). For the other dust mechanisms, the bias ratio correction results in very small changes (no more than 3 h, Figure 4), as expected from their high true positive rates (Figure 3, red symbols). Regardless of the estimation method chosen for the duration of the dust events during IOP2, the ranking remains identical.

In terms of the total amount of time a given dust mechanism is operating, the
Comparison of IOP1 and IOP2 Dust Production Hours

| Dust Mechanism         | IOP1 Hours | IOP2 Hours | Percentage of IOP1 Hours | Percentage of IOP2 Hours | Percentage change in Hours (IOP2-IOP1) |
|------------------------|------------|------------|--------------------------|--------------------------|----------------------------------------|
| Dust advection         | 131        | 128–218    | 19%                      | 18–30%                   | –2 to +66%                             |
| Cold pool emission     | 81         | 102–120    | 12%                      | 14–17%                   | +26 to +48%                            |
| LLJ emission           | 41         | 58–62      | 6%                       | 8–9%                     | +41 to +51%                            |
| Monsoon surges         | 20         | 41–44      | 3%                       | 6%                       | +105 to +120%                          |
| Dry convective plumes  | 8          | 3–6        | 1%                       | 0.4–0.8%                 | –25 to –63%                            |
| Total dust production  | 281        | 332–450    | 42%                      | 46–63%                   | +18 to +60%                            |

Table 3. Comparison of IOP1 and IOP2 Dust Production Hours

*IOP hours are taken from Figure 4 and are rounded to the nearest whole number; the rows are in descending order (i.e., ranked). *Total dust production* hours are the sum of the five rows above. The total number of hours used for percentage calculations in columns 4 and 5 is 28 x 24 in IOP1 (no dust classification was made prior to the lidar activation on 3 June, Table 1) and 30 x 24 in IOP2. The IOP1 percentage hours are slightly different from IOP2 (Figure 4), with the percentage of IOP1 hours being 18–30% and 18–30% in IOP2, respectively. The percentage change in hours (IOP2-IOP1) is calculated as follows: +66% for dust advection, +48% for cold pool emission, +51% for LLJ emission, +120% for monsoon surges, and +60% for dry convective plumes.

The relative importance of the dust mechanisms during IOP2 is very similar to IOP1 and the ranking is identical (Figure 4 and Table 3). During both June months, dust advection occurs for more time than any other mechanism (131 h in IOP1, ≥128 h in IOP2), followed by cold pool emission (81 h in IOP1, ≥102 h in IOP2), then LLJ emission (41 h in IOP1, ≥58 h in IOP2), monsoon surges (20 h in IOP1, ≥41 h in IOP2), and finally dry convective plumes (8 h in IOP1, ≥3 h in IOP2). The times as percentages of the IOP totals can also be found in Table 3.

During IOP2, cold pool emission, LLJ emission and monsoon surges occurred for a longer time than during IOP1 (Figure 4). The difference is an increase of up to 39 h (48%) for cold pool emission, up to 21 h (51%) for LLJ emission, and up to 24 h (120%) for monsoon surges (Table 3). During IOP2, dry convective plumes occurred for a shorter time than during IOP1. The difference is a decrease of up to 5 h (63%) (Table 3). Without bias ratio correction, dust advection during IOP2 occurred for a shorter time than during IOP1. The difference is a decrease of 3 h (2%) (Table 3). With bias ratio correction, however, the amount of time dust advection occurred is much greater during IOP2 than IOP1, an increase of 87 h (66%). Overall, there were up to 169 (60%) more dust production hours in IOP2 than IOP1 (Table 3).

6. Duration of Individual Dust Events

The total duration of time that dust mechanisms occupy (section 5) is only one way to compare their characteristics. The number and duration of individual dust events is also informative given that the residence time of dust in the atmosphere is important to interactions with radiation and cloud, for example. For this purpose, cold pools cannot be split between emitting cold pools and probably cold pool advection (section 3.5): while some cold pools purely emit or advect dust, in others there may be periods where dust emission is occurring (e.g., at the leading edge) and periods in the same outflow when wind speeds are below the emission threshold [Miller et al., 2008; Emmel et al., 2010].

In IOP2, there were more events in each class than in IOP1 (Figure 5, top line). There is no statistically significant difference between IOP1 and IOP2 in the proportion of events in each class, however, (2 sample $\chi^2$ test, 90% confidence level). Apart from monsoon surges, the duration of individual events in IOP2 was shorter. Indeed, the median duration in IOP2 was always shorter than the lower quartile in IOP1 (Figure 5).

In both June months, the longest event was a cold pool outflow: 23 h in IOP1 and 19 h in IOP2 (Figure 5). In IOP2, monsoon surges are the category with the second longest events (lasting from 12.25 to 16 h) but the duration of monsoon surges in IOP1 is more varied (from 5 to 15 h). The maximum duration of LLJ emission events is very similar in both June months (13 h in IOP1 and 12.75 h in IOP2), but there is more difference in the median durations (6.25 h in IOP1 and 4.25 h in IOP2). Dry convective plumes are, by nature and design (section 3.4), the shortest-lived events (maximum durations 2 h in IOP1 and 1.5 h in IOP2).

The most significant difference between the two June months is the cold pool category. In IOP1, there are 21 cold pools with a median duration of 11 h; in IOP2 there are 39 cold pools with a median duration of 4.5 h. It is possible that some of this difference relates to the difficulty of detecting advected dust without the lidar or nephelometer (Figure 3). As stated above, an individual cold pool can have periods of active dust emission and periods when dust is only advected. If some of these advective periods are not detected in IOP2, then...
one cold pool event may be artificially split into two or more shorter events. Indeed, in IOP1, five haboobs that contain a mixture of advected and emitted dust are artificially split into 10 separate events by the data-denial identification criteria.

7. Intensity of Dust Events

So far, the comparisons have only provided information on the duration of dust events, either as totals (section 5) or as individual events (section 6). The dustiness, or intensity, of the events is another important measure, as it is an important control on interactions with radiation [e.g., Redmond et al., 2010; Gu et al., 2012]. Unfortunately, there was no lidar or nephelometer available in IOP2, which is a major drawback for understanding the intensity of the dust events in June 2012. However, the Sun photometer was operational during both June months (albeit only during daytime), providing measurements of AOD.

The intensity of LLJ emission events was similar in both IOPs, with the dustiest LLJ emission event of IOP1 (IOP2) having an AOD of 2.4 (2.6) and the least dusty having an AOD of 0.7 (0.5) (Figure 6). The AODs are skewed toward the lower range of the spectrum in both cases. The intensity of cold pool emission events is harder to compare, since for 15 (22) events in IOP1 (IOP2) Sun photometer AODs are not measured, and only two cold pool emission events have measurements in IOP1. However, the dustiest available cold pool emission event of IOP1 is much more intense than the dustiest available cold pool emission event of IOP2 (AOD 2.8 against 1.3, Figure 6). Although a considerable number of AOD measurements of dust advection events are unavailable, enough measurements exist for a rough comparison. The distribution of dust advection AODs is fairly even in both IOPs, but in IOP1 the AODs are offset toward higher values (IOP1 range 0.7–3.3, IOP2 range 0.2–1.7; Figure 6). The small number of monsoon surges makes comparison difficult, but the monsoon surges in IOP1 were less dusty than the one available monsoon surge in IOP2 (AODs 1.1 and 2.4 in IOP1 against 2.7 in IOP2; Figure 6). From the measurements available, dry convective plumes appear to be more intense in IOP1 (AOD ~1.2) than IOP2 (~0.4), although six dry convective plumes in IOP2 do not have AOD measurements. Wind speeds during dry convective plumes were always stronger in IOP1 (not shown).

Sun photometer AODs cannot be used to calculate total dust loadings over the course of the month since they are unavailable under cloud or at night (see section 9.1.1 for a detailed assessment of this drawback). Nephelometer scattering is used for this purpose in
Allen et al. [2013], but the nephelometer is unavailable in IOP2. However, the time that dust events last is known for both IOPs, at 15 min resolution (section 5). For IOP1, ratios can be defined between the total time of each event class and the total nephelometer scattering of that class (the "scattering ratio"). By multiplying the total time of each event class by its scattering ratio, the total nephelometer scattering of each event class in IOP2 can be estimated to first order (the "predicted scattering"). Clearly, the predicted scattering is an approximation that assumes that the relationship between event duration and dustiness holds between the two June months, and apart from LLJs there is some evidence from the AODs that daytime dustiness is different between the two June months (Figure 6). However, in the absence of instrumentation that can measure dust continuously in IOP2, it allows a rough comparison of dustiness to be made between the two field seasons.

Predicted scattering in IOP2 is higher than scattering in IOP1 for cold pool emission (an increase of between 1.02 and 1.9 m$^{-1}$), LLJ emission (an increase of between 0.32 and 0.39 m$^{-1}$), and monsoon surges (an increase of between 1.06 and 1.21 m$^{-1}$) (Figure 7). It is marginally lower in IOP2 for dry convective plumes. For dust advection, it is marginally lower in IOP2 unless a bias ratio correction is applied (section 4) which results in an increase in IOP2 of 2.25 m$^{-1}$ (Figure 7). Overall, Figure 7 suggests that IOP2 is dustier than IOP1. The total difference between predicted scattering in IOP2 and scattering in IOP1 is up to 9.08 m$^{-1}$ which is an increase of up to 63% from IOP1 to IOP2. As mentioned, predicted scattering is a fairly rudimentary metric, but such an increase in dustiness compares well with the number of times dust is detected by SDF over BBM, which increases by 67% from IOP1 to IOP2. In both years, the ranking of the dust events by scattering is the same, with cold pool emission being the most important and dry convective plumes being the least important (Figure 7).

### 8. Comparison of Low-Level Jets

Of all the different dust event types, LLJs are the one which allows the most faithful comparison between IOP1 and IOP2. This is because (i) the detection method in IOP2 is very accurate (Figure 3), (ii) AODs are available for most LLJ events (Figure 6), and (iii) radiosondes are launched at 0600 on 22 mornings during IOP2 and are timed well with respect to LLJ detection. As mentioned above, the number and duration of LLJ emission events is similar (Figure 5) and the dust emission is of a similar intensity (Figure 6). Note that not all LLJs necessarily lead to dust emission (section 3.2) [see also Allen and Washington, 2014]. In this section we compare all LLJs, not just those which led to dust emission.

The number of LLJs that are detected by the Allen and Washington [2014] scheme (section 3.2) is 21 in IOP1 and 13 in IOP2 (Table 4). In IOP2, an additional five LLJs were inferred from surface wind speeds (section 3.2). In IOP1 (IOP2) there were two (three) mornings when wind profiles were not measured, so it is possible there could have been nondust-emitting LLJs on these occasions (Table 4). Thus, 21–23 LLJs were detected in IOP1 and 18–21 in IOP2.

The mean LLJ core wind speed in both June months was very similar, 13 m$^{-1}$ and 14 m$^{-1}$ in IOP1 and IOP2, respectively. The mean core height was different, however, 270 m and 370 m agl, respectively (Table 4). Unlike in IOP1, more LLJs were embedded in the moist monsoon inflow than in the dry northeasterly Harmattan in IOP2, but this difference is not very large (Table 4). In IOP1 (IOP2), 9 (12) LLJs led to dust emission, with 4 (5) overlapping with cold pool outflows.
In IOP1, LLJ orientation can be split into a roughly northerly component and a southwesterly component (Figure 8). In IOP2, the orientations are more varied, with three from the ESE, a direction no LLJs were oriented in IOP1. There are also none from the southwest. However, this may be because no sondes were launched after 25 June, and the moist monsoon flow has more influence on the Sahara in late June and early July [Sultan and Janicot, 2003]. A detailed examination of the LLJ in June 2012 is beyond the scope of this study.

9. Optimal Instrumentation for Dust Detection From Fieldwork

Since dust sources, particularly in the central Sahara, are frequently remote and difficult to access [Washington et al., 2003; Ginoux et al., 2012; Ashpole and Washington, 2013a], optimal instruments for field campaigns are those which provide high-quality information about dust conditions while themselves being as small, light, and affordable as possible. It was shown in section 4 that even without ground instruments which detect dust, field observations can be used together with remote sensing to identify and characterize individual dust emission mechanisms with a high degree of success (Figure 3). For this purpose, the most important measurements come from the anemometer (near-surface wind speeds for all dust event types), the pressure and humidity sensors (for dry convection and cold pool detection), the radiosondes (for LLJ detection), and SEVIRI (useful for most event types but particularly cold pool identification). Admittedly, radiosondes are not particularly practical for remote campaigns because of the need to transport heavy gas canisters; alternatives include sodar (although dropout was a problem in Fennec) or lidar (addressed in more detail below).

The two major setbacks of not using dedicated dust instrumentation are (i) it is difficult to detect dust advection (although SDF and observers’ reports improve capacity to do this, Figure 3) and (ii) such approaches provide only limited quantitative information on the intensity (dustiness) of dust events. The question then arises, which dust instrument is optimal, given the constraints of remote fieldwork? Below we evaluate the ground-based dust detection instrumentation used at BBM in Fennec.

9.1. Measurement Availability

The nephelometer provided continuous measurements at 4 s resolution (averaged to 1 min) during IOP1, with only two gaps (for 9 h on 15 June and 8 h on 23 June). The lidar took measurements at 1.4 s (averaged to 10 s), but there were several data gaps due to overheating. These data gaps totaled approximately 128 h during IOP1 (18% total IOP duration). Lidar backscatter measurements were also attenuated for a total of approximately 26 h (4% total IOP duration) during the thickest dust events, the attenuation starting from heights ranging from 200 m to 600 m agl. The availability of Sun photometer measurements is addressed below.

9.1.1. Availability of Sun Photometer Measurements

A serious limitation of the Sun photometer at BBM during the IOPs is that measurements are unavailable for a large number of events (Figure 6, top line). The photometer cannot take measurements at night; and cloud-contaminated AOD measurements must be removed. Since a significant proportion, if not the majority of dust emission in the region occurs at night or is associated with cloud [Marsham et al., 2011; Allen et al., 2013].
AOD measurements are therefore not representative of the overall or average atmospheric dust loading. This is addressed further in the discussion.

LLJ emission is the only category where Sun photometer AOD measurements are available in both IOPs for >50% of the total time dust is produced by this mechanism (hereafter the “event time”) (Figure 9). This is unsurprising as LLJ emission usually occurs in the morning in the southern Sahara [Washington et al., 2006; Schepanski et al., 2009; Fiedler et al., 2013; Allen and Washington, 2014], when the Sun photometer can take measurements. LLJs were only associated with a total of 7 h of cloud cover over BBM in IOP1, and 0 h in IOP2 (Figure 9). By contrast, in both IOPs, emitting cold pools had Sun photometer AODs available for <50% event time (just 23% in IOP1 and 41% in IOP2; Figure 9). The main reason for this was the large number of hours emitting cold pools occurred at night (53 h in IOP1 and 55 h in IOP2; Figure 9). The secondary reason was cloud cover (7 h in IOP1 and 20 h in IOP2).

Monsoon surges, dry convective plumes, and advected dust had Sun photometer AODs available for >50% event time in IOP1 and <50% event time in IOP2 (Figure 9). Apart from LLJ dust emission, cloud cover was a bigger problem in IOP2 than in IOP1. This is consistent with the moist monsoon inflow being stronger and penetrating farther north in 2012 than in 2011 [Cornforth, 2013].

9.1.2. Other Instrument Properties

As a result of its relatively small size and low weight, operation at high temperatures and measurement availability at night and under cloud, the nephelometer stands out as the optimal instrument from the ones compared here for dust fieldwork in remote desert locations, especially those where cloud cover is frequent, such as BBM in summer (Table 5). The lidar has the added advantage of providing height-resolved dust measurements and wind profiles; however, this is offset by its large size and weight, the necessity for air conditioning on very hot days, and the fact that in the dustiest conditions, attenuation reduces the data quality (Table 5). The Sun photometer does not suffer from the latter two problems, but it is severely limited in regions where dust production occurs at night or under cloud (section 9.1.1 and Table 5).

There is a strong correlation between the Sun photometer AOD and the nephelometer scattering (Spearman Rank ($r_s$) 0.86, $n = 634$, Figure 10). This is perhaps surprising given that air is drawn into the nephelometer chamber at 2 m agl while the AOD is a total-column measurement. However, the correlation is much weaker in
For example, if only the points with AOD ≥ 0.5 are correlated, $r_s$ is reduced to 0.70. If only the points with nephelometer scattering ≥ $2 \times 10^{-4}$ m$^{-1}$ (the dust event threshold in Allen et al. [2013]) are correlated, $r_s$ is only 0.43. Therefore, both instruments agree well when there is low dust, but when there is high dust at the surface (i.e., high nephelometer scattering), the AOD is not always proportionately high (Figure 10). At low nephelometer scattering, column water values are particularly low (Figure 10), supporting the findings of Marsham et al. [2013] that the driest period of IOP1 was the least dusty. The dustiest points are not associated with the highest column water, but Figure 10 covers less than half of the IOP since nocturnal and cloudy periods cannot be included (section 9.1.1), and it is these periods when cold pool outflows (associated with high moisture levels) are frequent.

10. Discussion and Conclusions

The Fennec field campaign of 2011 was the first to instrument the remote central Sahara [Washington et al., 2012]. However, with only one season of measurements, it is not possible to say whether the dust events of Table 5. Summary of Relative Merits of Dust Detection Instruments During IOP1

| Instrument   | Works at Night? | Can be Used With Cloud? | Does Not Need Air Conditioning? | Not Attenuated by Thick Dust? | Provides Height-Resolved Measurements? | Approx Packing Volume | Approx Packing Mass |
|--------------|-----------------|-------------------------|-------------------------------|-------------------------------|----------------------------------------|-----------------------|-------------------|
| Nephelometer | ✓               | ✓                       | ✓                             | ✓                             | ✓                                      | 0.08 m$^3$             | 20 kg             |
| Lidar        | ✓               | ✓                       | ✓                             |                               | ✓                                      | 1.5 m$^3$              | 100 kg            |
| Sun photometer | ✓               | ✓                       | ✓                             |                               | ✓                                      | 0.47 + 0.37 m$^3$ a   | 70 + 26 kg a      |

aIn the case of the Sun photometer, the second value given for the volume and mass is for the satellite transmission equipment, which is optional.
monsoon inflow, with greater monsoon activity associated with higher dust presence. Cowie et al. [2013] shows that the intertropical discontinuity (averaged between 10°W and 10°E) was over 1° north of its climatological position in late June 2012, bringing deep moist convection closer to BBM.

The total time occupied by dry convective plumes was 5 h (63%) less in IOP2 than IOP1. In IOP2, uncertainty in dust advection detection results in a difference that is either a small decrease (3 h, 2%) or substantial increase (87 h, 66%) (Figure 4 and Table 3). Overall, the number of dust event hours in IOP2 was 51–169 h (18–60%) more than in IOP1. In both June months, dust advection occupied the longest amount of time (IOP1 12%, IOP2 ≥18%), followed by cold pool emission (IOP1 12%, IOP2 ≥14%), LLJ emission (6%, ≥8%), monsoon surges (3%, ≥6%), and then dry convective plumes (1%, ≥0.4%) (Table 3); i.e., the ranking of the mechanisms by time is the same in both IOPs. The importance of dust advection is in agreement with the climatological study of Cowie et al. [2014], who use a longer record of observers’ observations across the Sahara and show that advected dust occurs more frequently than locally emitted dust at BBM.

In IOP2, with the exception of monsoon surges, dust events were more frequent and shorter lasting than in IOP1 (Figure 5). Between the two June months, however, there was no statistically significant difference in the proportion of events of each mechanism type. Using a rudimentary method to predict nephelometer scattering for IOP2, this season is found to be dustier overall than IOP1 (up to 63% dustier), and dustier specifically in the case of cold pool emission, LLJ emission, and monsoon surges (Figure 7). Due to predicted scattering assuming the preservation of relationships between event duration and nephelometer scattering from IOP1 into IOP2, this result should be treated carefully, but it does compare well with the number of times dust is detected by SDF over BBM, which increases by 67% from IOP1 to IOP2.

In both IOPs, the ranking of the events by scattering is the same: cold pool emission produces the most scattering, followed by dust advection, monsoon surges, LLJ emission, and then dry convective plumes (Figure 7). In essence, the results presented here show that while June 2012 was a dustier season than June 2011, the same dust mechanisms dominated in both years. In other words, the BBM observations show a large interannual variability in dust output from the central Sahara, but little variability in the relative contribution of the dust-producing mechanisms. There is thus even more incentive than before to focus research, model development, and observational networks on the key mechanisms. The relatively small contribution of dust emission from LLJs is intriguing, especially as LLJs are thought to be fairly commonplace across the Sahara [Schepanski et al., 2009; Fiedler et al., 2013]. Using an atmospheric general circulation model which incorporated the radiative effects of mineral dust, Miller et al. [2004] and Pérez et al. [2006] found that by reducing incoming
During daylight hours, the AOD of cold pool emission, dust advection, and dry convective plumes is higher in the studies mentioned above. The findings reported here confirm the primacy of cold pools for dust emission in the central Sahara, as found by other observational [Allen et al., 2013; Marsham et al., 2013] and model [Marsham et al., 2011; Heinold et al., 2013] studies. This is problematic for current numerical modeling, as configurations without explicit convection struggle to generate cold pool outflows [Reinfried et al., 2009; Marsham et al., 2011; Cavazos-Guerra and Todd, 2012; Solomos et al., 2012]. As well as the implications for dust emission, missing cold pools contribute significantly to a warm and dry model bias in the region [Garcia-Carreras et al., 2013].

Since cold pools frequently occur at night, round the clock dust monitoring is particularly valuable in the summertime central Sahara. Instruments such as lidars and nephelometers are therefore particularly useful, as is 24 h satellite dust retrieval such as SDF [Ashpole and Washington, 2012]. It also invites consideration of more novel instrumentation, such as the lunar photometer [e.g., Barreto et al., 2013]. While the Sun photometer provides excellent quantitative information on dust conditions and dust properties, it is handicapped in the central Sahara where the prime dust emission mechanism occurs frequently at night or under cloud, when Sun photometer retrievals are not possible. Indeed, Sun photometer AODs are only available for 23% (41%) of the time cold pool emission occurs at BBM in IOP1 (IOP2) (Figure 9). They provide much more information about LLJ emission—Sun photometer AODs available for 76% (100%) time LLJ emission occurs in IOP1 (IOP2)—but LLJs are a less significant dust mechanism at BBM (Figures 4 and 7). The missing periods of Sun photometer data correspond to 43% of the attributed scattering in IOP1 and 57–58% of the predicted scattering in IOP2. The percentage calculation assumes that daytime and cloud-free dust events are as intense as nighttime and cloud-covered dust events, which may not be true (and is not possible to check for IOP2), but the key message is that roughly half of the dust in the field seasons is missed by the Sun photometer.

Sun photometer measurements are frequently used to evaluate (or tune) dust loading in numerical models [e.g., Huneus et al., 2011; Pérez et al., 2011; Haustein et al., 2012; Tegen et al., 2013] and satellite retrieval [e.g., Kahn et al., 2009; Klüser and Schepanski, 2009; Carrer et al., 2010; Amiridis et al., 2013]. However, doing this for the summertime central Sahara this will likely underestimate the actual dust burden as so few cold pool outflows can be captured by the photometer. This is supported by the work of Kocha et al. [2013], who show that AOD simulations by the AROME model in the Adrar region of the Sahara (containing BBM) when only simulated under clear-sky conditions, result in a mean reduction of simulated AOD of 0.2 through the diurnal cycle, compared to continuous simulations. Kocha et al. [2013] found that AODs over the Adrar region peaked at 2200 h, consistent with the dominance of cold pool outflows in IOP1 than IOP2 (Figure 6). IOP-mean Sun photometer AOD decreases from 0.98 in IOP1 to 0.73 in IOP2. This belies the increase in dustiness found by SDF and predicted scattering. The Sun photometer is unavailable for 107 h when dust events are occurring in IOP1 and 181 h when dust events are occurring in IOP2. In percentage terms it is unavailable for 37% time dust events are occurring in IOP1 and 49% time dust events are occurring in IOP2. In IOP2 it is unavailable for most of the time that dust advection, dry convection, cold pool emission, and monsoon surges are occurring (Figure 9). Therefore, there is good reason to be suspicious of the apparent decrease in dustiness suggested by the monthly mean AODs. We therefore advocate strongly against uncritical use of monthly mean AODs in dust studies of this region, or regions dominated by cold pool dust production.

When using Sun photometer measurements to evaluate models or satellite retrievals, at the least the model or satellite values should only be averaged for the daylight period, as done by Tegen et al. [2013]. The Sun photometer of course provides useful information on column aerosol properties (which do not have a simple relationship with the surface), and authors are generally aware of its limitations; we feel, however, that it is important to present a quantification of the information that may be lost as we have done in Figure 9. Using the Sun photometer alone would certainly give the wrong conclusions about which dust mechanisms are most important in this region of the Sahara.
At other times of the year and in other regions of North Africa, the balance of importance between the different dust mechanisms is shifted. For example, it is clear that in the Bodélé Depression the semipermanent LLJ is the main mechanism for dust emission year round and particularly in winter [Washington and Todd, 2005; Washington et al., 2006; Fiedler et al., 2013]. European Centre for Medium-Range Weather Forecasts ERA-40 reanalysis shows that northeasterly Harmattan LLJs are also common (~50% nights) in winter across a wide band (roughly 10°-20°N) of North Africa [Schepanski et al., 2009], with BBM on the northern edge of this zone. In summer, reanalysis and SYNOP observations show that LLJs are particularly frequent over Western Sahara and northern Mauritania, the Sahel and southern Sahara, and also central and western Algeria [Schepanski et al., 2009; Fiedler et al., 2013; Cowie et al., 2014].

Current understanding suggests that cold pools likewise occur over a wide domain in North Africa. They have been shown to be of particular importance in the southern foothills of the Atlas Mountains, especially from April to September [Emmel et al., 2010]; in the Sahel and particularly the western Sahel in summer [Williams, 2008; Cowie et al., 2014]; in central Mali and eastern Mauritania [Heinold et al., 2013]; and even more widely across western Africa in late summer [Marsham et al., 2011], where the authors argue that they may be responsible for around half the dust uplift. Cold pools are thus certainly not a phenomenon restricted to BBM and its environs, although the evidence suggests that they are most frequent in the summer months, as would be expected with the northernmost penetration of the moist West African Monsoon and the associated deep convection.

In both IOPs, dry convective plumes/dust devils are found to be the least important mechanism for dust production (present ≤1% time, Table 3). Because there was only one mast at BBM, it is highly likely that many dust devils or dry convective plumes passed close to the site but were not recorded by the pressure sensor or anemometers. Thus, their importance at BBM is almost certainly underestimated. However, given the predominance of larger-scale dust mechanisms at BBM it is hard to imagine that close to 35% of the dust at could be due to dry convective plumes/dust devils, which is the global estimate calculated by Koch and Renno [2005].

This paper has shown that even without ground instruments which detect dust, field observations can be used together with remote sensing to identify and characterize individual dust emission mechanisms with a high degree of success (Figures 2 and 3 and sections 3 and 4). Given the expense of importing and deploying instrumentation to remote regions, the potential for inferring dust mechanisms from standard meteorological equipment and widely available satellite products is valuable. Unfortunately, such approaches suffer from two major drawbacks: they give limited quantitative information about the actual intensity (dustiness) of the dust events and are poor at detecting dust which is being advected rather than locally emitted (Figure 3), which is a significant hurdle since dust advection occurs for more time than any single other mechanism in IOP1 or IOP2. We note, however, the value of SDF and the observations made by the local observers, without which the detection of advected dust would be significantly more difficult (Figure 3). With some exceptions [e.g., Cowie et al., 2013; Cowie et al., 2014], observers’ reports are no longer regularly used in dust research in the region, despite being a valuable resource.

Nonetheless, deploying a dedicated dust detection instrument alongside regular field equipment is preferable. Given the need for an instrument that is operational continuously, and the incentive to keep payloads light and manageable on remote field campaigns, the nephelometer comes out as the best overall performer of the dust detection instruments deployed at BBM (Table 5). Most conventional field campaigns in North Africa have involved large deployment of instrumentation and needed significant human and financial resources, for example, AMMA [Redelsperger et al., 2006], Saharan Mineral Dust Experiment [Ansmann et al., 2011], and Fennec [Washington et al., 2012]. This makes organizing and delivering such programs very taxing. It appears, however, that with the choice of the right instrumentation, a more limited payload can also deliver very comprehensive results. The Bodélé Dust Experiment [Washington et al., 2006] is a case in point. In the case of the central Sahara, a nephelometer and automatic weather station combination would go a long way toward identifying and quantifying dust events. Of course the instrumentation that is deployed needs to be able to answer the questions that are posed. But the great advantage of inexpensive and lightweight deployments is that they can be replicated in many places, and for a long duration of time. Such approaches should be given serious consideration when planning future field research in remote regions.
Acknowledgments

Fennecc was funded by a NERC consortium grant (NE/G017166/1). The authors wish to thank the following individuals and institutions. For comments which improved the manuscript: Zhanqng Li, Ron Miller and two anonymous reviewers. For establishing and instrumenting the supersite: B. Alderberame, M. Bart, B.J. Brooks, C. Cavaços-Guerra, F. Davies, S. Engelstaedter, L. García-Carreras, M. Gascogne, M. Hobby, A. Lima, M. Limam, J.H. Marsham, V. Martins, J.B. McQuaid, A. O’Leary, B. Ouchene, A. Okalidiche, D.J. Parker, M. Salah-Ferroudj, D. Siddal, M.C. Todd, the AERONET PHOTONS team, ONM Algérie, the University of Leeds, and the University of Sussex. For providing the SEVIRI imagery: I. Ashpole, C.A. is also particularly grateful to I. Ashpole for helpful discussion of all stages of the manuscript. We also thank FQAM (Facility for Ground-based Atmospheric Measurement), UK Met Office, and NCAS (National Centre for Atmospheric Science) for the use of the sodar, lidar, and radiocesium units. Data sets are available through the British Atmospheric Data Centre or upon request from the authors.

References

Allen, C. J. T., and R. Washington (2014), The low-level jet dust emission mechanism in the central Sahara: Observations from Bordj-Badjri Mokhtar during the June 2011 Fennecc Observation Period, J. Geophys. Res. Atmos., 119, 2990–3015, doi:10.1002/jgrd.50239.

Allen, C. J. T., R. Washington, and S. Engelstaedter (2013), Dust emission and transport mechanisms in the central Sahara: Fennecc ground-based observations from Bordj-Badjri Mokhtar, June 2011, J. Geophys. Res. Atmos., 118, 6212–6232, doi:10.1002/jgrd.50534.

Ansmann, A., M. Tesche, P. Knippertz, E. Bierwirth, D. Althausen, D. Müller, and O. Schulz (2009), Vertical profiling of convective dust plumes in southern Morocco during SAMUM, Tellus B, 61(1), 340–353, doi:10.1111/j.1600-0889.2008.00384.x.

Barta, A. M., and A.-W. S. Mashat (2014), Synoptic features associated with dust transition processes from North Africa to Asia, Bull. Am. Meteorol. Soc., 105, D8202, doi:10.1175/BAMS-D-13-00179.1.

Bou Karam, D., C. Flamant, P. Knippertz, O. Reitebuch, J. Pelon, M. Chong, and A. Dabas (2008), Dust emissions over the Sahel associated with dislocations of the West African Monsoon, J. Geophys. Res., 113, D24S13, doi:10.1029/2008JD006250.

Cowie, S. M., P. Knippertz, and J. H. Marsham (2013), Are vegetation-related roughness changes the cause of the recent decrease in dust emissions over northern Africa? J. Geophys. Res. Atmos., 118, 6100–6119, doi:10.1002/jgrd.50273.

Fiedler, S., K. Chipanshi, B. Heinold, P. Knippertz, and I. Tegen (2013), Climatology of nocturnal convective dust plume outflow events, Q. J. R. Meteorol. Soc., 140, 2933–2958, doi:10.1002/qj.2070.

García-Carreras, L., I. H. Marshall, D. J. Parker, C. M. Taylor, P. Cammas, O. Bock, F. Timouk, and J. Pelon (2007), Airborne observations of the impact of a convective system on the planetary boundary layer thermodynamics and aerosol distribution in the inter-tropical discontinuity region of the West African Monsoon, J. R. Meteorol. Soc., 133(7), 1619–1632, doi:10.1002/j Met. 2011JD017454.

Heinold, B., P. Knippertz, J. H. Marsham, S. Fiedler, N. S. DIXON, K. Chipanshi, B. Laurens, and I. Tegen (2013), The role of deep convection and nocturnal low-level jets for dust emission in summertime West Africa: Estimates from convection-permitting simulations, J. Geophys. Res. Atmos., 118, 4358–4400, doi:10.1002/jgrd.50402.
Sultan, B., and S. Janicot (2003), The West African monsoon dynamics. Part II: The “preonset” and “onset” of the summer monsoon, J. Clim., 16(21), 3407–3427.

Tegen, I., K. Schepanski, and B. Heinold (2013), Comparing two years of Saharan dust source activation obtained by regional modelling and satellite observations, Atmos. Chem. Phys., 13(5), 2381–2390, doi:10.5194/acp-13-2381-2013.

Thorncroft, C., and K. Hodges (2001), African easterly wave variability and its relationship to Atlantic tropical cyclone activity, J. Clim., 14(6), 1166–1179, doi:10.1175/1520-0442(2001)014<1166:aeewva>2.0.co;2.

Todd, M. C., R. Washington, S. Raghavan, G. Lizcano, and P. Knippertz (2008), Regional model simulations of the Bodélé low-level jet of Northern Chad during the Bodélé dust experiment (BoDEx 2005), J. Clim., 21(5), 995–1012, doi:10.1175/2007JCLI1766.1.

Todd, M. C., et al. (2013), Meteorological and dust aerosol conditions over the Western Saharan region observed at Fennec supersite-2 during the Intensive Observation Period in June 2011, J. Geophys. Res. Atmos., 118, 8426–8447, doi:10.1002/jgrd.50470.

Walters, D. N., et al. (2011), The Met Office Unified Model Global Atmosphere 3.0/3.1 and JULES Global Land 3.0/3.1 configurations, Geosci. Model Dev., 4(4), 919–941, doi:10.5194/gmd-4-919-2011.

Washington, R., and M. C. Todd (2005), Atmospheric controls on mineral dust emission from the Bodélé Depression, Chad: The role of the low level jet, Geophys. Res. Lett., 32, L17701, doi:10.1029/2005GL023597.

Washington, R., M. C. Todd, N. J. Middleton, and A. S. Goudie (2003), Dust-storm source areas determined by the total ozone monitoring spectrometer and surface observations, Ann. Assoc. Am. Geogr., 93(2), 297–313, doi:10.1111/1467-8306.9302003.

Washington, R., M. C. Todd, S. Engelstaedter, S. Mbainayel, and F. Mitchell (2006), Dust and the low-level circulation over the Bodélé Depression, Chad: Observations from BoDEx 2005, J. Geophys. Res., 111, D03201, doi:10.1029/2005JD006502.

Washington, R., et al. (2012), Fennec—The Saharan Climate System, CLIVAR Exchanges, 17(3), 31–33.

Wilks, D. S. (2006), Statistical Methods in the Atmospheric Sciences, p. 627, Academic Press, London.

Williams, E. (2008), Comment on “Atmospheric controls on the annual cycle of North African dust” by S. Engelstaedter and R. Washington, J. Geophys. Res., 113, D23109, doi:10.1029/2008JD009930.

Williams, E., N. Nathou, E. Hicks, C. Pontikis, B. Russell, M. Miller, and M. J. Bartholomew (2009), The electrification of dust-lofting gust fronts (“haboobs”) in the Sahel, Atmos. Res., 97(2–4), 292–298.

Zuluaga, M. D., P. J. Webster, and C. D. Hoyos (2012), Variability of aerosols in the tropical Atlantic Ocean relative to African Easterly Waves and their relationship with atmospheric and oceanic environments, J. Geophys. Res., 117, D16207, doi:10.1029/2011JD017181.