Dust mobilization due to density currents in the Atlas region: Observations from the Saharan Mineral Dust Experiment 2006 field campaign

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[1] Evaporation of precipitation is a ubiquitous feature of dry and hot desert environments. The resulting cooling often generates density currents with strong turbulent winds along their leading edges, which can mobilize large amounts of dust. Mountains support this process by triggering convection, by downslope acceleration of the cool air, and by fostering the accumulation of fine-grained sediments along their foothills through the action of water. For the Sahara, the world’s largest dust source, this mechanism has been little studied because of the lack of sufficiently high resolution observational data. The present study demonstrates the frequent occurrence of density currents along the Sahara side of the Atlas Mountain chain in southern Morocco using the unique data set collected during the Saharan Mineral Dust Experiment (SAMUM) field campaign in May/June 2006. The density currents are related to convection over the mountains in the afternoon hours and have lifetimes on the order of 10 h. The passage of the sharp leading edge that sometimes reaches several hundred kilometers in length is usually associated with a marked increase in dew point and wind speed, a change in wind direction, and a decrease in temperature and visibility due to suspended dust. It is conceivable that this mechanism is relevant for other mountainous regions in northern Africa during the warm season. This would imply that simulations of the dust cycle with numerical models need a reliable representation of moist convective processes in order to generate realistic dust emissions from the Sahara.


1. Introduction

[2] Airborne mineral dust plays an important role in a wide range of atmospheric, oceanic, and biological processes and has a strong impact on human health [Perry et al., 1997; Prospero et al., 2002, and references therein]. To reliably simulate the emission, transport, and deposition of mineral dust aerosol with the help of numerical models is one of the great challenges of dust research [Tegen and Fung, 1994; Ginoux et al., 2001; Tegen et al., 2002; Stier et al., 2005; Vogel et al., 2006]. Ultimately such work will help to better understand the influence of dust on climate, weather, atmospheric chemistry, cloud microphysics, radiation, and many other processes. The emission term is the most crucial point in dust modeling and depends on two factors: the nature of the soil and the near-surface wind speed [Tegen et al., 2002; Vogel et al., 2006]. Soil-dependent source functions are estimated from surface elevation and/or satellite data, and then varied depending on soil moisture and snow cover [Fécan et al., 1999; Ginoux et al., 2001; Tegen et al., 2002]. The low-level wind speed is entirely model generated. Since dust models usually work with threshold velocities, dust emissions are particularly sensitive to errors in this quantity. A general problem for model validation is the limited number of high-quality observations from the Sahara [Washington et al., 2006], the world’s largest dust source region [Goudie and Middleton, 2001]. The present study uses the unique data set collected between 11 May and 10 June 2006 during the first Saharan Mineral Dust Experiment (SAMUM) field campaign to analyze meteorological processes involved in dust mobilization at the northwestern fringes of the Sahara in southern Morocco. The results, though purely observational, can serve as a basis for addressing specific problems of regional or even global dust models.

[3] In the Sahara, a number of different weather systems generate winds strong enough to mobilize dust [Hastenrath, 1991; Warner, 2004], provided that they occur over areas with suitable soil conditions. These are (1) synoptic-scale surface lows and cold fronts, which are often related to
upper level disturbances from midlatitudes and sometimes to lee cyclogenesis [Thorncroft and Flocas, 1997]; (2) strong harmattan flow during the cool season, which is caused by an enhanced north-south pressure gradient over North Africa, often the result of a sudden intensification of the subtropical anticyclone [Kalu, 1979]; such situations frequently cause dust outbreaks from preferential regions like the Bodélé Depression [Washington and Todd, 2005; Washington et al., 2006], but can become almost continental in scale [Knippertz and Fink, 2006; Slingo et al., 2006]; and (3) small-scale atmospheric convection in the form of short-lived dust devils and convective plumes within the dry desert boundary layer with extensions of up to a hundred meters [Koch and Renno, 2005] or in the form of density currents fed by evaporationally cooled air related to deep moist convection. The latter mechanism can generate strong winds through the formation of density currents fed by evaporationally cooled air. This mechanism can produce quite dramatic, fast moving “dust walls,“ the most prominent example of which are the haboobs of Sudan with lifetimes of several hours and horizontal extensions of 10–80 km [Sutton, 1925; Lawson, 1971; Hastenrath, 1991]. Similar phenomena exist in semiarid parts of the USA [Idso et al., 1972; Chen and Fryrear, 2002] and the Arabian Peninsula [Membrey, 1985]. The present paper will for the first time provide a detailed analysis of convectively generated density currents in southern Morocco, document their surprisingly frequent occurrence, and demonstrate their link to dust mobilization. It will be argued that the mountainous environment supports their generation, and allows an organization to larger spatial and temporal scales than observed for classical haboobs.

4 The remainder of the paper is organized as follows. In section 2 the observational data is described. Section 3 provides information on the study region and the proposed mechanism. Section 4 contains a detailed analysis of the best documented density current during the campaign, while similar analyses for a total of seven other cases are presented in a more concise form in section 5. Section 6 contains a short summary, conclusions, and an outlook on future research.

2. Data

During the SAMUM field campaign in May/June 2006 a ground station was operating at Tinfou (marked “TNF” in Figure 1, see also Table 1). Temperature and humidity were determined with a Humicap HMP 233 sensor (Vaisala, Helsinki, Finland) and wind speed with an ultrasonic anemometer (model 81000, R. M. Young, Traverse City, MI, USA). A standard vacuum gauge was used to record air pressure. All measurements were carried out with a temporal resolution of 30 s at an altitude of 4 m above ground and 1.5 m above the roof of a container box. In addition, visibility was measured with a VPF-710 visibility sensor (Biral, Bristol, UK) with a time resolution of 1 min. The visibility measurement capability derives from its forward scatter meter configuration. The forward scattering is related to the atmospheric extinction coefficient, which is used to determine the meteorological visibility with the Koschmieder formula [Koschmieder, 1924].
The number size distribution of supermicrometer mineral dust particles was measured both with a Forward Scattering Spectrometer Probe (FSSP-300, Particle Measuring Systems Inc., Boulder, CO, USA) and an aerodynamic particles sizer (APS, model 3321, TSI inc., MN, USA). The FSSP was mounted on a wind vane to allow for quasi-isaxial sampling and was constantly aspirated at approximately 25 m s\(^{-1}\) by an attached fan. Particle number concentrations were recorded every 10 s and integrated over 30 min. The APS was placed downstream of a PM10 inlet and measured the aerodynamic particle mobility every 5 min. In order to convert this quantity to a geometric diameter, the particle density and the dynamic shape factor are needed [DeCarlo et al., 2004]. With a shape factor of 1.26 for mineral dust, particle diameters of 0.4–15.2 μm are obtained. The measured size distributions from both instruments were normalized to the average size distribution to account for the unknown inlet aspiration efficiency and particle losses.

For the regional analysis we used temperature, dew point, wind, and pressure data from eleven automatic weather stations (Campbell Scientific Inc., Logan, UT, USA) operated by the German research initiative IMPETUS (An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa). This station network follows a north-south transect from the peaks of the High Atlas (up to 3850 m) down to the margin of the Sahara (445 m). An overview over the network is given in Figure 1 and information on each station is provided in Table 1. Air temperature and humidity are measured with a HMP45C (Vaisala, Helsinki, Finland), consisting of the precision temperature sensor Pt 1000 (Class B) and the Humicap 180 humidity sensor. The anemometer is an A100R (Vector Instruments, Rhyl, UK), which counts the revolutions of the rotor via a rotating magnet within a varying field. Wind direction is measured with the microtorque potentiometer W200P (wire wound type, Vector Instruments). For precipitation measurements R102 tipping bucket rain gauges (Campbell Scientific) with one tip for each 0.2 mm of rain are used. Temporal resolution is 10 min for Iriki (IRK) and 15 min for all other stations. In addition, we employed observations from nine synoptic weather stations in southern Morocco and Algeria that are listed in Table 2. One thing to bear in mind is that wind speed is measured at different heights above ground at the different station types (10 m at the synoptic stations, 3 m at the IMPETUS stations, and on the roof of a container box at Tinfou).

### Table 1. IMPETUS Stations and SAMUM Measuring Site Tinfou

<table>
<thead>
<tr>
<th>Name</th>
<th>Abbreviation</th>
<th>Latitude, °N</th>
<th>Longitude, °E</th>
<th>Elevation, m a.s.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M’Goun</td>
<td>MGN</td>
<td>31.50</td>
<td>−6.45</td>
<td>3850</td>
</tr>
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<td>Tichki</td>
<td>TIC</td>
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<td>Tizi Tounza</td>
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<tr>
<td>Imeskar</td>
<td>IMS</td>
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<td>2245</td>
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<tr>
<td>Taouigalt</td>
<td>TAO</td>
<td>31.39</td>
<td>−6.32</td>
<td>1900</td>
</tr>
<tr>
<td>Trab Labied</td>
<td>TRB</td>
<td>31.17</td>
<td>−6.58</td>
<td>1383</td>
</tr>
<tr>
<td>Bou Skour</td>
<td>BSK</td>
<td>30.95</td>
<td>−6.34</td>
<td>1420</td>
</tr>
<tr>
<td>Argiouen</td>
<td>ARG</td>
<td>30.65</td>
<td>−6.32</td>
<td>1020</td>
</tr>
<tr>
<td>El Mijit</td>
<td>EMY</td>
<td>30.36</td>
<td>−5.63</td>
<td>792</td>
</tr>
<tr>
<td>Jebel Brâhim</td>
<td>JHB</td>
<td>29.94</td>
<td>−5.63</td>
<td>725</td>
</tr>
<tr>
<td>Iriki</td>
<td>IRK</td>
<td>29.80</td>
<td>−6.50</td>
<td>445</td>
</tr>
<tr>
<td>Tinfou</td>
<td>TNF</td>
<td>30.24</td>
<td>−5.61</td>
<td>680</td>
</tr>
</tbody>
</table>

### Table 2. Synoptic Stations Used for the Study (See Figure 4)

<table>
<thead>
<tr>
<th>Name</th>
<th>Abbreviation</th>
<th>WMO Number</th>
<th>Latitude, °N</th>
<th>Longitude, °E</th>
<th>Elevation, m a.s.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Errachidia</td>
<td>E</td>
<td>60210</td>
<td>31.93</td>
<td>−4.40</td>
<td>1042</td>
</tr>
<tr>
<td>Ouarzazate</td>
<td>O</td>
<td>60265</td>
<td>30.93</td>
<td>−6.90</td>
<td>1140</td>
</tr>
<tr>
<td>Ain Sefra</td>
<td>AS</td>
<td>60560</td>
<td>32.77</td>
<td>−0.60</td>
<td>1059</td>
</tr>
<tr>
<td>Bechar</td>
<td>B</td>
<td>60571</td>
<td>31.62</td>
<td>−2.23</td>
<td>816</td>
</tr>
<tr>
<td>El Golea</td>
<td>EG</td>
<td>60590</td>
<td>30.57</td>
<td>+2.87</td>
<td>403</td>
</tr>
<tr>
<td>Beni Abbes</td>
<td>BA</td>
<td>60602</td>
<td>30.13</td>
<td>−2.17</td>
<td>505</td>
</tr>
<tr>
<td>Timimoun</td>
<td>T</td>
<td>60603</td>
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<td>+0.28</td>
<td>317</td>
</tr>
<tr>
<td>Adrar</td>
<td>A</td>
<td>60620</td>
<td>27.88</td>
<td>−0.28</td>
<td>283</td>
</tr>
<tr>
<td>In Salah</td>
<td>IS</td>
<td>60630</td>
<td>27.20</td>
<td>+2.47</td>
<td>269</td>
</tr>
</tbody>
</table>
boundary layer (PBL) forms and dry convective mixing transports momentum from upper levels to the ground, leading to somewhat higher wind speeds than during the night. On the large scale the daytime ascent over the mountains drives a secondary circulation from the Sahara toward the Atlas chain, causing winds to come predominantly from the sector east to south, a process sometimes called Atlas pumping [Flamant et al., 2007]. The inflow of air from the Sahara during the day is a possible explanation for a weak afternoon minimum in \( T_d \) at the lowland stations. At night radiative cooling of the surface creates an inversion at low levels.

### 3.2. Proposed Mechanism

[10] In synoptic situations with northwesterly vertical wind shear, deep cumulonimbus clouds forming over elevated terrain are blown toward the Sahara side of the Atlas chain. This process is depicted schematically in Figure 2. The evaporation of precipitation falling through the dry and hot PBL in the lowland regions leads to the formation of a cold pool that accelerates downslope toward the Sahara, driven by the density and thus pressure differences to the environment. Atmospheric density currents in various form are a well-known phenomenon, and their shape and propagation speed have been extensively compared with results from theoretical and laboratory studies [Simpson, 2000]. Figure 2 is an adaptation of similar schematics such as Droegemeier and Wilhelmson [1987, Figure 1] to the special situation under study here. The leading edge of the density current is characterized by strong turbulent winds (the gust front) that can mobilize dust and quickly mix it through a deep layer. The propagation of the leading edge is substantially slower than the maximum wind speed behind it [Smith and Reeder, 1988].

[11] For typical atmospheric conditions a temperature decrease of 10°C causes a density reduction of almost 4%. Even for relatively large dust concentrations of 40 mg m\(^{-3}\), contributions to the density differences are three orders of magnitude smaller and can be neglected. Radiative cooling at the surface by dust on the other hand could be a positive feedback mechanism [Miller et al., 2004]. Higher moisture content due to evaporating precipitation on the other hand compensates parts of the temperature effect. An increase in mixing ratio by 6 g kg\(^{-1}\) for instance increases the virtual temperature by more than 1°C and reduces density by about 0.4%. A general problem with the detection of atmospheric density currents from station observations in desert regions is the sensible heat flux from the ground that tends to strongly compensate the cooling in the lowest layers, especially during the afternoon and far away from the evaporative source. On the other hand the heating from below decreases the vertical stability in the lowest layers and supports turbulent mixing of the suspended dust. This process slowly erodes the density current and weakens it over time. In satellite imagery one can often see a ring of arc clouds caused by the rising motion of warm air over the density current head (Figure 2), which aids identification and tracking. During daytime, the deep well-mixed PBL in desert regions is characterized by a dry-adiabatic lapse rate and a constant mixing ratio leading to high relative humidity in the upper parts of the PBL. Thus lifting by a density current can in fact result in cloud formation, even in a relatively dry environment at the surface.

[12] In the highly complex terrain of the Atlas Mountains density currents are likely subject to orographic blocking, for example through the Jebel Sagho. Whether or not this is the case can be estimated with the Froude number \( Fr = V/Nh \), where \( N \) is the Brunt-Väisälä frequency, \( V \) is the low-level horizontal velocity, and \( h \) is the mountain height over the surrounding terrain [e.g., Garreau, 2001]. \( Fr \) is the dimensionless ratio of the inertial force to the force of gravity, and indicates blocking for values < 1. For the Jebel Sagho \( h \) is \( \sim 1200 \) m. Density currents lead to a stabilization of the lower troposphere and therefore \( N \) can be assumed to be on the order of 0.01 s\(^{-1}\) (corresponding to a decrease in virtual potential temperature of about 10°C over the lowest 3000 m). Typical winds speeds are about 10 m s\(^{-1}\) (see sections 4 and 5). Under these conditions \( Fr \)
becomes 0.8, indicating that blocking by the Jebel Saghro is in fact likely.

4. A Detailed Case Study

Of the several density currents observed during the SAMUM campaign, the one that occurred on 31 May 2006 was selected for a detailed case study. Several reasons make this case an ideal example to illustrate the mechanism proposed in section 3.2 in all detail: (1) It occurred in isolation with a relatively weak background flow at low levels, (2) it passed directly over the SAMUM measuring site Tinfou during a time when all instruments were operating, and (3) it occurred during the daytime and therefore could be directly observed by the SAMUM team on the ground and in visible-channel Meteosat satellite imagery (0.6 μm; VIS). The following subsections contain analyses of the synoptic situation, of the high-resolution observations from Tinfou, and of the dust front propagation. In section 5 similar, but more concise analyses will be presented for seven other cases.

4.1. Synoptic Situation

The synoptic situation over northwestern Africa at 1200 UTC on 31 May 2006 is characterized by a weak upper trough with an axis reaching from the Moroccan coast northeastward to eastern Spain (Figure 3). The sea-level pressure analysis shows a region of low pressure across Central Algeria that is probably related to lee effects of the High Atlas Mountains in the presence of the northwesterly flow associated with the upper level trough [Egger et al., 1995].

Starting around midday, satellite imagery shows the development of convective clouds over the High Atlas, most likely fostered by low static stability associated with the cold air at upper levels. A short shower of 0.6 mm was observed at TAO (location see Figure 1) around 1200 UTC. During the following hours the clouds spread southeastward with the midlevel flow and more convective cells develop over the Jebel Saghro and the Sahara Atlas in northern Algeria. At 1500 UTC the synoptic station at Errachidia (marked “E” in Figure 4) reports a thunderstorm accompanied by a drop in temperature of about 10°C, an increase in $T_{d}$, rising pressure, decreasing visibility, and strong northerly winds. Around this time light precipitation was observed at the high-mountain stations MGN and TIC, and some participants of the SAMUM campaign observed a thunderstorm in the Todra canyon between Ouarzazate and Errachidia.

The infrared (10.8 μm; IR) Meteosat satellite image at 1630 UTC shows two regions with active convection close to the study area (marked with black arrows in Figure 4a): A weaker cell over the Jebel Saghro and an intense one over the Jebel Ougnat. To the south of the larger cell is a cloud-free region with a low IR signal that indicates cold, dense outflow from the convection. It clearly stands out against the hot desert surface that appears dark in IR

Figure 3. Synoptic situation at 1200 UTC on 31 May 2006. Shading depicts sea-level pressure in hPa, and thick lines denote 500-hPa geopotential height in gpm. The plot is based on European Centre for Medium-Range Weather Forecast (ECMWF) operational analysis data in 1° resolution.

Figure 4. Meteosat satellite images on 31 May 2006. (a) IR channel at 1630 UTC and (b) VIS channel at 1800 UTC. Letters indicate synoptic stations according to Table 2. The IMPETUS and SAMUM stations used for the frontal analysis are marked with filled circles. A dashed purple line indicates the leading edge of the density current in Figure 4a, and a purple ellipse marks the dusty air behind the leading edge in Figure 4b. The two black arrows in Figure 4a point to convective cells mentioned in section 4.1.
imagery. The sharp convex boundary marked with a purple line in Figure 4a has a length of more than 200 km. The small, elongated clouds along its western part are probably arc clouds. Over the next 1.5 h the cool air continues to spread and move down the topographic gradient toward the Sahara as shown by the VIS satellite image at 1800 UTC (Figure 4b). The blurred appearance of this air mass suggests that dust is suspended in accordance with the mechanism described in section 3.2. Compared to the deep convective cells to the east that cast a distinct shadow, the dusty air appears relatively shallow. After sunset VIS images are not available, but the density current is still traceable in IR imagery until about 2300 UTC (Figure 4a). The approach of the density current is already seen in Figure 1.

The arrival of the dust front is clearly evident in observations taken at Tinfou between 1810 and 1840 UTC (Figures 6a and 6b). The most striking signal is the very abrupt increase in $T_d$ from 1 to 8°C at 1825 UTC (Figure 6a). At the same time the temperature drops by a little more than 1°C. This corresponds to an increase in relative humidity from 13% to 23%. Throughout the period shown there are quasi-regular temperature fluctuations with a period of about 2–3 min indicating the turbulent transport of sensible heat from the hot surface into the atmosphere. The evolution of the virtual temperature reveals that the increase in moisture content almost compensates the drop in temperature, resulting in small density changes. As discussed in section 3.2, the relatively long distance to the source of the cooling probably allows for enough sensible heat fluxes to almost eliminate the temperature contrast near the ground. At higher levels cooler air must still be present as indicated by the signal in IR satellite imagery (Figure 4a).

The passage of the front is associated with a marked change in wind direction and speed (Figure 6b). Before the passage winds come from westerly or southwesterly directions at around 3 m s$^{-1}$. At 1827 UTC there is an abrupt change to easterlies with wind speeds ranging from 6–9 m s$^{-1}$. Concomitant with the wind jump there is an increase in pressure, whose exact magnitude cannot be determined because of the low resolution of the pressure measurements (Figure 6c). At nearby EMY the pressure increases by 1 hPa, too, a value that is typical for haboobs [e.g., Chen and Fryrear, 2002]. The short lag of about 2 min between the thermodynamic and the dynamic signal might be related to the inclined front of the density current making shortly after 1800 UTC. Panoramic photographs of the approaching density current show a vertically confined layer of dusty air with shallow clouds aloft (Figure 5). The shape of the leading edge clearly resembles laboratory density currents [Simpson, 2000] or observations of haboobs [Lawson, 1971; Idso et al., 1972]. Some participants of the SAMUM campaign observed the approaching “dust wall” farther west near Zagora (see Figure 1).

The northwesternmost part of the leading edge of the density current reaches Tinfou shortly after 1800 UTC. Panoramic photographs of the approaching density current show a vertically confined layer of dusty air with shallow clouds aloft (Figure 5). The shape of the leading edge clearly resembles laboratory density currents [Simpson, 2000] or observations of haboobs [Lawson, 1971; Idso et al., 1972]. Some participants of the SAMUM campaign observed the approaching “dust wall” farther west near Zagora (see Figure 1).

4.2. Observations at Tinfou

In Figure 4a another smaller outflow boundary is visible near the Moroccan-Algerian border, just to the east of Bechar (marked “B”), where winds change from light southerlies in the early afternoon to strong northerlies of up to 19 m s$^{-1}$ in the evening accompanied by a pronounced drop in temperature, an increase in $T_d$, and a marked rise in pressure. The station observer reports a visibility of only 2 km and dust being raised near the station at 1800 UTC and a thunderstorm at 2100 UTC, the approach of which is already seen in Figure 4b. Storm totals at Errachidia and Bechar on this day are 15 and 19 mm, which correspond to >10% and >20%, respectively, of the long-term annual average [Fink and Knippertz, 2003]. This clearly underlines the unusual character of this event.

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Figure 4b indicates that the northwesternmost part of the leading edge of the density current reaches Tinfou shortly after 1800 UTC. Panoramic photographs of the approaching density current show a vertically confined layer of dusty air with shallow clouds aloft (Figure 5). The shape of the leading edge clearly resembles laboratory density currents [Simpson, 2000] or observations of haboobs [Lawson, 1971; Idso et al., 1972]. Some participants of the SAMUM campaign observed the approaching “dust wall” farther west near Zagora (see Figure 1).

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the cooler air aloft and thus the pressure rise arrive a little later. Synchronous with the thermodynamic changes, visibility drops from 50 to 14 km and by 1840 UTC reaches values below 3.5 km (Figure 6d). According to members of the SAMUM team most of the dust appeared to be advected from upstream, but localized mobilization was observed, too. This points to stronger dust sources and/or higher wind speeds closer to the convection. Aerosol concentration measurements show an abrupt increase at the leading edge of the front, mainly for particles smaller than 10 μm (Figure 6e). Note that the values shown in Figure 6e are relative to averages over the respective times the ASP and FSSP were operating and should not be directly compared to each other. The small increase in the number of large particles supports the notion that local mobilization was not a major factor. Dusty conditions prevail for about 4 h and in the early morning the relatively clean prestorm conditions are reestablished.

4.3. Frontal Analysis

[21] After the analysis of the dust front passage with the high-resolution data from Tinfou we will now examine its propagation characteristics using the 10- or 15-min resolution data from the IMPETUS network together with 10-min averages from Tinfou. Following the results presented in section 4.2 the change in moisture content is used as the clearest sign of the air mass boundary. Somewhat arbitrarily the time of frontal passage is defined as the center of a half-hour period with maximum $T_d$ increase. According to this definition the front passed EMY at 1800 UTC, TNF at 1825 UTC, JHB at 1945 UTC, and IRK at 2325 UTC with $T_d$ increases of 4.9–7.6°C (Figure 7a). During this time of the day radiative cooling of the ground is likely to enhance the temperature fall during the passage of the front, even over a relatively short period of half an hour. Therefore it is better to regard anomalies with respect to the diurnal cycle averaged over the entire period of study. Such anomalies show cooling at EMY, TNF, and JHB of 2.3–3.5°C synchronous to the $T_d$ jumps, while temperature anomalies at IRK are small (Figure 7b).

[22] In order to document the wind changes at the front 1-h averages were calculated for the time before and after the half hour with the maximum $T_d$ increase. The reason for this longer averaging period is the sometimes-gusty nature of the wind with varying directions during the passage. Maximum wind speeds during the entire 2.5-h period were extracted also. At EMY for example the wind changes from light southwesterlies before the front to northeasterlies at 12 m s$^{-1}$ with a maximum of 13 m s$^{-1}$ (Figure 7c). At IRK the wind is slackening and the direction change is less clear. This indicates a petering out of the density current in this region, which is consistent with the marginal temperature change and the weakening signal in satellite imagery (see section 4.1).

[23] Using the passage time and wind data a hand analysis was done on the premise that frontal movement is approximately parallel to the winds behind the front as predicted by density current theory (Figure 7c). The analysis reflects the southwestward propagation seen in satellite imagery (Figure 4) and points to a source region of the cold air over the Jebel Ougnat. The distance between IRK and this region is about 220 km and the time between first indications for a density current in satellite imagery and the arrival at IRK is about 9 h, suggesting an average propagation speed of 6.8 m s$^{-1}$. Between EMY and IRK, however, the front slows down to only 5.5 m s$^{-1}$, probably because of decreasing density contrasts and flatter terrain. With this propagation speed, the 2-min delay between the
temperature and wind jumps in Figure 6 translates to a distance of 660 m. Assuming a typical height of the current of 1.5 km in the region of the wind jump the angle that the bent-back leading edge spans with the ground is $66^\circ$ and thus similar to theoretical results [Simpson, 2000, chap. 11].

[24] Many studies on atmospheric density currents have used temperature and pressure changes at the ground to estimate the depth of the cold layer and to calculate a theoretical propagation speed [Simpson, 2000, chap. 2]. This is impossible in our case because of the insufficient precision of the pressure data and the nonrepresentativeness of the temperature measurements due to sensible heat fluxes from the ground (see section 4.2). Smith and Reeder [1988] argue that the best way to identify density current phenomena from observations are differences in wind and propagation speed [Simpson, 2000, chap. 2]. Haboobs in the Sudan, for example, usually progress with a speed about half of the maximum gust behind the front [Lawson, 1971]. Observed wind speeds at EMY and TNF are consistent with this result, in particular if one considers the weak opposing environmental winds ahead of the density current (Figure 7c). Interestingly strong winds of up to 15 m s$^{-1}$ were recorded at Ouarzazate and ARG during the afternoon, too. Since no moistening or cooling is observed at these stations, it seems likely that the wind increase is caused by downward mixing of northwesterly momentum from the level of the midlevel trough (Figure 3).

5. Other Cases

[25] During the period 7 May to 7 June 2006 seven other density currents affected the study region. Their identification was mainly based on coherent $T_d$ jumps, but other criteria such as precipitation and abrupt temperature, wind, or pressure changes were considered, too. The moist convection and outflow boundaries involved were analyzed with the help of satellite imagery. The case described in section 5.1 is similar to the one in section 4, but occurred farther to the south. In section 5.2 we discuss a period with daily occurrence of rather localized density currents. Sections 5.3 and 5.4 contain descriptions of an event with two concurrent density currents in Morocco and Algeria, and an unusually large scale early morning case.

5.1. A Sahara Case: 25 May 2006

[26] During 24–26 May a cutoff low formed over northwestern Africa and caused 3.8–24.3 mm of precipitation at the stations between ARG and the High Atlas. Winds were strong throughout this period and blowing sand was observed at TNF with visibility near the ground dropping to below 400 m at times. Several concurrent jumps in $T_d$ and wind were observed, but filtering out a coherent signal from the many signs of unsettled weather was only possible on 25 May. In the morning hours of this day convective clouds form over the eastern High Atlas and Jebel Saghro and spread southeastward toward the Sahara (Figure 8a). Errachidia, Beni Abbes, Bechar, and BSK record precipitation of up to 14 mm, about 10% of the annual average at the former two stations. Around 1530 UTC the Tinfou site measured a clear drop in visibility and an increase in $T_d$. Around 1315 UTC first indications of an outflow boundary are evident in IR imagery just to the south of the Moroccan-Algerian border (see auxiliary material). The sharp east-west-oriented convex leading edge quickly spreads and by 1645 UTC has reached an extension of about 400 km (Figure 8a). The VIS image at 1800 UTC shows a large
region with dusty air behind this boundary (Figure 8b). The air ahead of the density current is probably too dry to allow the formation of arc clouds. Again comparison with the deep convective towers indicates the relatively shallow nature of this air mass.

[27] Because of the passage of the density current through a region with no observations the generation of a frontal analysis was impossible. Still, the effects of the moist convection on the meteorological conditions at a lowland desert location are clearly reflected in observations from IRK. Around 1700 UTC the temperature at the station fell by 6°C in 20 min, while $T_d$ increased by almost 6°C (not shown). Yet relative humidity stayed below 45% and no precipitation was observed, which illustrates the enormous potential for evaporation. During the time of the temperature fall, 10-min mean winds accelerated to almost 16 m s$^{-1}$ and backed from easterly to northerly. Only half an hour later they veered again and weakened substantially.

### 5.2. Repeated Occurrence: 2–5 June 2006

[28] The period 2–5 June is characterized by a slowly moving upper level trough over the western Mediterranean that causes weak westerly to northwesterly flow in the free troposphere over the study area (not shown). In the early afternoon of each of these days cellular convection developed over the High Atlas and gets blown downstream toward the Sahara (Figure 9). In particular on 2 and 4 June substantial precipitation was recorded in the High Atlas. Accumulated amounts decreased from more than 32 mm at the high-mountain stations to only 4–5 mm at TRB. On 03 and 04 June slight rainfall was observed also at the synoptic stations Errachidia, Bechar, and Beni Abbes. During the early evening hours outflow boundaries can be detected that spread and move away from the convection toward the south or southwest. The beginning of nighttime cooling of the desert surface makes the identification in IR imagery more difficult than for the daytime systems described in sections 4 and 5.1. Best indication is therefore the ring of arc clouds marked with a purple line in Figure 9. The spatial scale of the outflow boundary on 3 June is much larger than on the other days and reaches from the study region to near Adrar (Figure 9b), where winds of up to 12 m s$^{-1}$ and a visibility of 1.5 km are reported during the early morning hours. Similar conditions are observed at Timimoun a little earlier.

[29] In analogy to Figure 7c frontal analyses were generated for the days 2–5 June. For stations in the Drâa Valley (ARG, EMY, JHB, IRK, and TNF) the frontal passages occur between 1845 and 0145 UTC on the next day, and are marked by a distinct change in $T_d$, temperature, and wind (Figure 10). High-resolution data from TNF show that the strongest changes occur over just a few minutes, similar to the results in section 4. Typical values for the $T_d$ increase are 4–7°C with a maximum of 12.1°C at IRK on 3 June. The temperature anomaly decreases are smaller and range between −0.4 and −4.2°C. An exception is IRK, where values between −0.5 and +2.4°C are observed. Since the density currents reach this station later in the night, a likely reason for the anomalous warming is the breaking of the nocturnal inversion by the induced turbulence. This effect is most likely confined to the lowest levels, while the body of the density current is still colder than the ambient air and supports the forward movement. The frontal passages are associated with strengthening winds and a shift from mostly southerlies to easterlies or northeasterlies. Maximum observed wind speeds are 8–12 m s$^{-1}$. The exception is again IRK, where the signal is often weak, indicating a slackening of the density current in this region. Despite a higher background aerosol concentration, the frontal passages cause marked drops in visibility with minima between 5 and 8 km (not shown). Propagation speeds range from 5 m s$^{-1}$ to 7 m s$^{-1}$, which in all cases is substantially slower than the maximum gusts behind the front.

[30] On all four days there are indications for density currents to the north of the Jebel Saghro, too. On 2 June, observations at TRB suggest cool and moist outflow from convection in the High Atlas flowing through the basin of Ouarzazate (Figure 10a). On 3 June TRB and BSK show a coherent signal with a pronounced change to strong north-easterly winds (Figure 10b). Members of the SAMUM team released a radiosonde from the airport of Ouarzazate at 1925 UTC of this day, shortly after the likely passage of the outflow boundary. The measured wind speed shows a distinct peak at about 260 m above ground that fulfills the definition for a significant maximum by Blackadar [1957] (Figure 11). The profile resembles observations of a haboob by Membery [1985], but with a lower maximum and weaker wind speeds. The time of day appears too early for the development of a nocturnal low-level jet through the decoupling from surface friction [Stensrud, 1996], support-
ing a relation to moist convection. Winds are from easterly to northeasterly directions at low levels and gradually turn to westerlies above 2000 m (Figure 11). On 4 and 5 June signals for density currents are again observed at TRB and BSK (Figures 10c and 10d). On all four days the synoptic station at Ouarzazate reports slight increases in $T_d$ and in wind speed in the evening hours together with a shift to easterly directions. There is a general tendency for the northern density currents to occur earlier than their counterparts to the south of the Jebel Saghro. This is most likely related to the time the convection needs to spread southward during the afternoon. The fact that the density currents do not cross the Jebel Saghro is consistent with the discussion at the end of section 3.2. Over all, the period examined shows that density currents can be a daily feature of the circulation in the Atlas region if suitable synoptic conditions prevail.

5.3. Two Concurrent Events: 7 May 2006

On 7 May two large outflow boundaries are concurrently observed over the Moroccan and Algerian Sahara, again in connection with a weak upper level trough and afternoon convection over the Atlas chain. Precipitation is observed at Errachidia, MGN, Bechar, and Ain Sefra with the latter station recording 27 mm or about 15% of the long-term annual average. Satellite imagery shows two about 400 km long lines of arc clouds moving away from the convection into the Sahara (Figure 12a). The frontal analysis shows that density currents can be a daily feature of the circulation in the Atlas region if suitable synoptic conditions prevail. The density current between 2030 UTC on 7 May and 0055 UTC on 8 May (Figure 12b). The signals in wind and $T_d$ are similar to the systems described in sections 4, 5.1, and 5.2. As in Figures 10b–10d temperature anomalies increase at IRK because of the breaking of the nocturnal inversion. Propagation speed is 7 m s$^{-1}$ and thus only a little slower than the observed maximum winds (Figure 12b). No coherent signal could be analyzed to the north of the Jebel Saghro.

5.4. An Early Morning Case: 13 May 2006

[32] The density current during the night from 12 to 13 May deviates from the other cases in two ways: it is of much larger spatial scale and reaches southern Morocco in the early morning hours. The frontal analysis shows marked increases in $T_d$ and wind with maximum values of up to 15.2 m s$^{-1}$ (Figure 13a). Because of the late occurrence the downward mixing of air from above the nocturnal inversion leads to a very pronounced warming of up to 5°C. The frontal speed is approximately 7.5 m s$^{-1}$. Slack winds at BSK point to a weakening of the front when having to cross the Jebel Saghro. Observations from TRB indicate the passage of another density current to the north of the Jebel Saghro.

[33] The frontal features over the study area appear to be the northernmost parts of a long-lived convective outflow boundary of almost synoptic-scale. Around 0900 UTC on 12 May deep convective cells begin to develop over the Algerian Sahara, particularly over the Great Western Erg

Figure 9. Same as Figure 4a but for (a) 2000 UTC on 2 June 2006, (b) 2130 UTC on 3 June 2006, (c) 2130 UTC on 4 June 2006, and (d) 2200 UTC on 5 June 2006.
near 32°N, 2°E (not shown). In contrast to the other cases, a weak upper trough over northwestern Africa steers clouds northeastward. By 1630 UTC a large area of cold outflow has formed to the west and south of the convective clouds (Figure 13b). At nearby Bechar strong winds and raised dust are observed during this time. At 1800 UTC El Golea reports mean northeasterly winds of 18 m s\(^{-1}\) and a visibility of 1 km. Similar conditions are observed at Timimoun at 2100 UTC. In the evening hours more convection forms over eastern Morocco and the Algerian Sahara Atlas, outflow from which may further strengthen the cold pool that spreads and moves southwestward across Central Algeria. At 2230 UTC the outflow boundary is still visible in IR imagery spanning more than 1000 km from near Errachidia to the northern Ahaggar Mountains (Figure 13c). Shortly before this time the front passes the desert stations Adrar and In Salah followed by visibility as low as 800 m, high dew points, and wind speeds up to 11 m s\(^{-1}\). No convection was active in the High Atlas and Jebel Saghro. A detailed investigation of the dynamics of this case is beyond the scope of this investigation and will be subject of another study.

6. Summary and Conclusions

This study is the first detailed investigation of density currents caused by evaporationally cooled outflow from moist convection in the region of the Saharan foothills of the Moroccan Atlas. The analysis covers both the dynamics involved and the relevance for dust mobilization. The study uses high-temporal-resolution measurements during the SAMUM field campaign in May/June 2006 and the dense climatological station network of the IMPETUS project, which together form a uniquely rich database as compared to other parts of the Sahara. During the month under study, density currents were identified on eight days, suggesting an importance of this phenomenon for the climate of the study region.
The observed density currents are related to upper level troughs over northwestern Africa. The associated reduction in vertical stability favors convection, in particular over elevated heating areas in the High Atlas, the Sahara Atlas, and the Jebel Saghro, where precipitation is occasionally observed. The northwesterly midlevel winds associated with the upper troughs blow the convection toward the Sahara, where a huge potential for evaporational cooling exists. The cold air accelerates downhill and spreads sideways associated with strong turbulent winds that mobilize dust. The resulting sharp outflow boundaries can be detected in both IR and VIS satellite imagery during the day. During the night the IR contrast disappears because of the radiative cooling of the surrounding surfaces, thereby making a tracking of the currents increasingly difficult. Depending on the scale of the convection, the location, and probably the background winds, the leading edge can reach a length of several hundred kilometers, in one case more than 1000 km. The density currents typically form shortly after midday, reach the lowlands in the late afternoon or evening hours, and decay in the second half of the night suggesting a typical lifetime of about 10 h.

The passage of the leading edge of a density current is accompanied by abrupt changes in various meteorological parameters, sometimes occurring within just a few minutes. The most pronounced is a substantial increase in $T_d$, at times as large as 12°C. The concurrent decrease in near-surface temperature is usually much smaller, which is most likely related to sensible heat fluxes from the ground. During the night, the temperature at the surface can even increase with the arrival of a density current due to a downward mixing of air from above the nocturnal inversion as in cold fronts over central Australia [Smith et al., 1995]. Winds usually accelerate strongly behind the leading edge and shift to northeasterlies. Reduced visibility and increased dust concentration can persist for several hours. Maximum mean wind speeds 3 m above ground range from 8 to 15 m s$^{-1}$, suggesting that at least in some of the cases dust is lifted near the stations. Frontal analyses reveal a propagation of the currents in the direction of the wind behind the leading edge, often with a component down the topographic gradient. The propagation speed is usually around 6 m s$^{-1}$ and thus slower than the observed winds. Both observations support the proposed mechanism, which is in principle similar to haboobs observed in other parts of the world [Lawson, 1971; Idso et al., 1972; Membery, 1985].

The results presented have important implications for the dust cycle: Many prior studies have suggested that soils in topographic lows are particularly amenable to dust mobilization [Prospero et al., 2002]. Wind speeds on the other hand usually increase with height making storms most severe in mountainous regions, where deflatable material is
usually scarce. In contrast the strong winds associated with atmospheric density currents follow the topographic gradient into valleys or depressions, where the action of water deposits fine-grained material. It is this match of meteorological and soil conditions that makes the proposed mechanism particularly effective for the mobilization of dust. Mountains play a crucial role for the processes involved in two ways. On the atmospheric side they trigger convective precipitation, and thus evaporation and strong winds. On the hydrological side steep slopes lead to a fast runoff and the accumulation of fine-grained sediments in the foothills. These result point to active dust sources along the fringes of mountains rather than in faraway topographic lows, which is consistent with recent satellite observations (I. Tegen, Leibniz-Institute for Tropospheric Research, Leipzig, Germany, personal communication, 2007). It appears conceivable that the documented mechanism is relevant for other mountainous parts of the Sahara such as the Ahaggar, Aïr, or Tibesti Mountains. In this case moist convection would be a key ingredient in warm-season dust emissions from northern Africa.

[38] Provided the proposed mechanism does in fact contribute significantly to the dust budget of the Sahara, a successful simulation of the dust cycle with numerical models would have to contain a realistic representation of orographically induced moist convection and the associated evaporational processes, presumably quite a challenge for state-of-the-art convection and boundary layer schemes. This aspect is currently being investigated in collaboration with the SAMUM numerical modeling group. Other studies needed for a better understanding of the presented phenomenon are a thorough climatological analysis based on the IMPETUS station data and detailed investigations of cases from other regions.

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