Drivers of Australian dust: a case study of frontal winds and dust dynamics in the lower Lake Eyre Basin

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ABSTRACT

The roles of pre-frontal, frontal and post-frontal winds as the primary wind systems for dust entrainment and transport in Australia are well established. While the relevance of each system has been observed across different wind erosion events in central Australia, the entrainment of dust by all three winds during the passage of an individual front has not been demonstrated until now. Synoptic information, satellite aerosol and imagery, meteorological and dust concentration data are presented for a single case study erosion event in the lower Lake Eyre Basin. This event demonstrates variable dust transport in three different directions from one of the southern Hemisphere's most significant source regions, and the changing nature of the active dust pathways during the passage of a frontal system. While only a single dust event is considered, the findings show the complexity of mineral aerosol emission and transport patterns even within an individual dust outbreak. For the lower Lake Eyre Basin, this appreciation of pathway behaviour is significant for better understanding the role of

aeolian inputs from the dominant Australian source to surrounding marine systems. In a wider context, the findings exhibit the detailed insights into major dust source dynamics that can be obtained from high resolution spatial and particularly temporal data, as used in combination. This work highlights the importance of adequately resolved data for the accurate determination of dust entrainment and transport patterns of major dust sources.

1. INTRODUCTION

Australia is a principal contributor to mineral aerosol in the southern hemisphere, with the major atmospheric driver of dust emission from the continent being the westerly passage of frontal systems across its lower half (McTainsh and Leys, 1993; Leslie and Speer 2006). In particular, the operation of three different ‘wind systems’ in producing dust over Australia is clearly recognised (e.g., Sprigg 1982, Strong et al. 2011). Pre-frontal northerly winds which occur ahead of a front are frequently strong enough to raise dust in advance of the front as it moves across the continent. The arrival of the leading edge of the front itself is typically associated with well-developed westerly winds which have the potential to entrain especially large quantities of dust. These westerlies can raise dust along an extended line aligned roughly north-south, and are characterised by rolling dust storms with snouts often hundreds of kilometres in length (Leslie and Speer 2006). As such, this mechanism tends to produce Australia’s largest dust storms (McTainsh et al., 2005, Leys et al., 2011). Finally, the southerly winds of a post-frontal nature can also entrain dust if they are strong enough to exceed the threshold for suspension of surface sediments.

The geomorphic role of these three wind systems in the entrainment and off-continent transport of dust is well appreciated in Australia (e.g., Bowler, 1976; Sprigg, 1982, McTainsh, 1989) and the three systems are associated with a classic wind-dust pattern associated with fronts (Figure 1). Bowler (1976) was first to propose there were two major dust paths operating in Australia during the Quaternary; the South East Dust Path and the North West Dust Path. He noted that the semi-circular, continental scale pattern of linear dunes in central Australia must also reflect the predominant dust transporting winds. Sprigg (1982) concluded from measurements in the Strzelecki and Simpson dunefields that three wind systems were responsible for entraining and transporting dust within these two dust paths. Subsequent wind erosion mapping (summarised by McTainsh, 1989), studies of individual dust storm events (e.g. Raupach et al., 1994; McTainsh et al., 2005) and air trajectory modelling (McGowan and Clark, 2008) have provided clear evidence that the three wind system model associated with cold fronts is the main mechanism for dust entrainment and transport in Australia.

<< Figure 1 >>

More recently, Strong et al. (2011) investigated the occurrence of these three wind systems in further detail, finding that over half the total dust days in the Lake Eyre Basin (2005-2006) were generated by frontal activity as a whole (i.e. pre-frontal northerly, frontal westerly and post-frontal southerly winds). Subtropical cold fronts are the most significant meteorological feature affecting central Australia (Beringer and Tapper, 2000) and their structure, behaviour and impact on surface energy exchanges were investigated in a series of field experiments (Central Australian Fronts Experiment) in 1991 (CAFE91) (Smith *et al*., 1995) and 1996 (CAFE96) (Reeder et al., 2000; Beringer and Taper, 2000). Fronts were typically found to produce strong pressure gradients across the front lines capable of producing winds of high speeds (Smith *et al.*, 1995). Pre-frontal troughs and heat troughs were also identified as producing wind shifts similar to that of frontal systems, and are therefore also associated with the entrainment of dust. Reeder and Smith (1992) describe the replacement of hot, dry northerly winds with cooler southwesterly winds during spring and summer cold front episodes, and winds shifting anticlockwise with the passage of the front (Reeder et al., 2000).

This paper uses synoptic information, satellite imagery, wind speed/direction and dust concentration data from a single, large scale wind erosion event to demonstrate the operation of the principal wind systems for dust emission and transport in Australia. The case study event is notable as it reveals entrainment of dust by the three front-related wind systems, and that time-dependent shifts in dust transport pathway, can occur through the passage of a single front over the continent.

2. BACKGROUND

The dominant dust source region of Australia and a prominent mineral aerosol source in the southern hemisphere is the arid Lake Eyre Basin (LEB) (Prospero et al., 2002). Like most major dust source regions, different land surface types within the LEB have variable potential to emit dust as controlled by sediment supply and surface erodibility (Bullard et al., 2008; Bullard et al., 2011). Internally draining fluvial systems are important in transporting fine sediments to the lower reaches of major ephemeral rivers such as Cooper Creek and the

Diamantina River, and terminal, occasionally inundated lakes such as Lake Eyre North (LEN). When dry, these river floodplains and lake beds often act as sources of dust (Bullard and McTainsh, 2003; Prospero et al., 2002; Bullard et al., 2008). Flooding of LEN in early 2009, produced a quiescence of dust activity which was prolonged by the existence of moist, stabilised lake surface sediments. By the austral Spring of 2013, however, LEN had dried and become erodible again.

A wind erosion event indicating the reversion of LEN to an active dust source occurred in mid October 2013.This frontally-driven dust outbreak was noteworthy because the occurrence of its three stages coincided with the timing of (cloud free) satellite overpasses, enabling its full development to be captured by moderate resolution imagery. The coincidence of the imagery and the event illustrates the temporal evolution through space of the different wind systems and their associated dust activity.

3. METHODS

To characterise the dust event, mean sea level pressure charts were obtained from the Australian Bureau of Meteorology (ABM). High frequency dust concentration data for the region was available from equipment operated by an Australian dust monitoring network known as DustWatch (http://www.environment.nsw.gov.au/dustwatch/) (Leys et al., 2008). Three (Moolawatana, Birdsville and Tibooburra) of the 42 instrumented DustWatch locations were used in this study (Figure 2).

<<Figure 2>>

Each site consists of an aerosol monitor (DustTrak® model 8520 inside the manufacturer's weatherproof environmental enclosure) that measures the atmospheric aerosol concentration of particulate matter <10 µm diameter (PM_{10}). These instruments sample every 15 minutes, increasing to one minute frequency when PM_{10} concentration exceeds 25 µg/m^3. Factory calibration is undertaken annually by the Australian distributor, adjusted to respirable mass standard ISO 12103-1 A1 Test Dust (Arizona Dust). Calibration for a particular source material is not warranted as the sampling network covers 42 sites across southern Australia with multiple dust source types. Instruments are calibrated on site each month to have a zero (clean air) reading of ±0.003 mg/m3. Inlets are cleaned and water bottles are also emptied. To overcome instrument drift, every 15 minutes a zero reading is taken through the manufacturer's 'zero filter' and stored in the database. This value is then subtracted from all ambient readings until the next zero filter reading is taken. All data are stored and publically accessible via the Community DustWatch information interface (CoDii).

Data are remotely polled by CoDii on a daily basis at 1000 Australian Eastern Daylight Time (EDT), and the calculated hourly averaged aerosol concentrations are quality controlled. Meteorological data from the nearest ABM station is also downloaded and used in conjunction with NASA Moderate Resolution Imaging Spectrometer (MODIS) Rapid Response data to partition the hourly reading into dust, smoke or fog using the following rules. 1) Dust values <0.010 $\mu g/m^3$ are disregarded, 2) data is flagged as fog if humidity is >80% and wind speed is low (< 20km/h) and/or the coupled meteorological observation reported fog at that time, 3) data is flagged as smoke if windspeeds <30 km/h for the 3 hours preceding and subsequent to the value, or windspeeds <10 km/h and fires or smoke were detected within the area (ascertained from global fire mapping by MODIS FIRMS), 4) a malfunction if dust values are <0, are extremely erratic or the DustTrak displays an error message. Only hourly averaged values successfully flagged as dust are used in this study and more information is available from the CoDii manual (http://www.environment.nsw.gov.au/resources/dustwatch/CoDiiManual.pdf).

Hourly wind speed and direction at 10 m height were derived from the ABM station observing closest to each DustWatch site. At Birdsville and Tibooburra, the DustWatch and ABM stations are within 1 km of each other, but at Moolawatana, a remote cattle station operating DustWatch equipment, meteorological data from the ABM station at Marree (170 km to the west) were used for this study (Figure 2).

Data from the MODIS instrument mounted on both the Terra and Aqua platforms were used to observe the dust event. 'True colour' scenes produced by the NASA LANCE Rapid Response system for the 10th October 2013 were obtained, as well as the level 1 MODIS data to produce a simple bi-spectral 'split window' enhancement of the dust in scenes. Based on the contrasting thermal properties of elevated dust and the land surface, the brightness temperature difference (BTD) resulting from subtraction of MODIS bands 31 and 32 is effective in highlighting the appearance of dust (Ackerman, 1997; Baddock et al., 2009). The Deep Blue level 2 MODIS aerosol product (10 km spatial resolution at nadir) was also obtained for the relevant Aqua overpass (0525 UTC, 10th October). The Deep Blue product is derived from an algorithm using multiple MODIS band data to provide an estimation of aerosol optical depth (AOD) designed for better performance over bright desert surfaces (Hsu et al., 2004). It has been used in investigations of dust source dynamics (e.g., Ginoux et al., 2010; Baddock et al., 2009; Ginoux et al., 2012) and its full development and details are described by Hsu et al. (2004). The latest Collection 6 MYD04 data are used here (Hsu et al., 2013).

4. RESULTS AND DISCUSSION

4.1 Synoptic development

On 9th October 2013 at 1100 EDT, a high pressure system was positioned over the east coast of Australia, generating pre-frontal northerly winds over southern and central Queensland, New South Wales and South Australia. A trough system associated with an embedded area of low pressure extended northwesterly from the Great Australian Bight, with a cold front located to the south (Figure 3a). The high pressure cell and trough contracted eastward by 2300 EDT, with the trough and low pressure cell becoming situated over central South Australia. At this time, the trough system linked with the cold front to the south, and formed an extension trough (Figure 3b).

>> Figure 3 <<

By 1700 EDT on 10th October, a strong pressure gradient had developed between the low pressure trough (now over mid New South Wales and northeastern South Australia) and the high pressure cell (Figure 3c). This pressure gradient generated strong post-frontal southerly winds over most of southeastern New South Wales and South Australia. Abrupt changes in wind direction were observed at lower LEB observation stations around 1900-2000 EDT as the front passed through the region at this time (see section 4.3). Winds demonstrated rapid backing in an anticlockwise direction from predominantly NNW, through W, to SSW. The central pressure of the embedded low pressure cell was 999 hPa by now, with another low pressure cell evident at the southern end of the trough line (994 hPa central pressure) (Figure 3c). By 2300 EDT, the trough had continued to the northeast, with the following high pressure cell positioned at the Western Australia-South Australia border, producing post-frontal southerly winds throughout the lower LEB (Figure 3d).

4.2 Dust event imagery

The broad spatial pattern of dust activity is revealed by MODIS imagery from the local morning and afternoon overpasses of the Terra and Aqua satellites respectively (Figure 4).

<< Figure 4 >>

During the morning of 10th October 2013, the 1205 EDT MODIS image showed large dust plumes emanating from the northern part of LEN and moving in a southeasterly direction (Figure 4a). This northern part of LEN and the major ephemeral entry channel into the lake from the north, called the Warburton Groove, represented erodible surfaces covered by fine sediments that had been deposited by the flooding events of 2009 onwards. The presence of these deposits is evident from the contrast of the darker surface of sediment in the north with the white, salt-crusted surface in the southern part of the lake (Figure 4a).

The 1625 EDT afternoon scene reveals LEN was still actively emitting dust some four hours after the morning image, but by 1625 EDT the heading of its dust plumes had shifted to the northeast (Box A, Figure 4b,c). Furthermore, a strongly linear 'wall' of dust can be seen extended diagonally from the southeast to the northwest across the scene, appearing particularly clearly in the BTD enhancement (Box B, Figure 4b,c). This dust wall evidently developed in the time since the 1205 Terra image. Another notable feature is the emission of dust at 1625 EDT from Lake Cadibarrawirracanna, a small dry lake west of LEN. At 1625 EDT dust blew from this source in a NNW direction (Box C, Figure 4b), and is also apparent in the Deep Blue AOD retrieval for that time (Figure 4d). Elevated AOD was identified downwind of LEN, with the Deep Blue retrieval also picking out the densest parts of the wall of dust.

4.3 Wind speeds, direction and measured dust concentration

The timing and spatial development of the dust observed in the imagery can be linked to the recorded wind speeds, directions and dust concentration at the three DustWatch sites plus Marree meteorological station (Figure 2). The dust source areas and plume pathways vary in accordance with changes in the three wind systems. During the course of the event, as the front passed across the lower LEB, the wind shifted from north through west, to south and southwest.

On the morning of 10th October, the pre-frontal synoptic situation produced north to northeasterly winds across central Australia (Figure 3a), which were recorded at all three DustWatch stations (Figure 5). Through the morning at Moolawatana, wind strength intensified from around 3 m/s (0800 EDT) to peak at 11 m/s (1000 EDT) and wind direction shifted from northerly through west-northwest to westerly. Figure 4b indicates light coloured dust transported in a southeast direction under these pre-frontal winds at 1205 EDT, and the dust concentration at Moolawatana (320 km SE of LEN) shows the arrival of the dust on these winds at 1500 EDT, three hours later (Figure 5a).

<<Figure 5>>

While the wind direction at the time of peak dust concentration at Moolawatana had become south-southwesterly, the plume direction evident in Figure 4b, and observations at Marree of northwesterly flow from 0900-1100 EDT indicate that dust entrainment and transport to Moolawatana was the result of pre-frontal winds (Figure 5a). The seeming disparity between the wind direction at the time of dust arrival is due to the enforced use of meteorological data from Marree, located 170 km west of Moolawatana. When the wind direction switched to be consistently from the southwest, Moolawatana was no longer downwind of the LEN source, and this led to the rapid diminishing of dust concentration there by 1700 EDT. The distinctive shift in wind direction, from the west to the southwest, marks the passage of the front. While the speeds of post-frontal southerlies continued to exceed 14 m/s from 1700 EDT onwards, these did not generate significant dust loads at Moolawatana because there was no active dust source to the south (Figure 4a).

At Birdsville, when the pre-frontal northerly winds reached their peak at 1000 EDT, dust concentration showed only a small coincident increase (40 $\mu g/m^3$) (Figure 5b). The limited dust response at this time suggests that only local source surfaces to the north of Birdsville were emitting during these winds. While not evident in the imagery, these sources were most likely to be entrainment from the highly erodible Diamantina floodplain (Channel Country) that Birdsville is sited on (seen to north of Birdsville in Figure 4a) (McTainsh et al., 1999). The largest dust concentration at Birdsville (800 $\mu g/m^3$) was related to westerly winds at the leading edge of the front. Elevated concentrations associated with dust transport were first detected there at 2000 EDT. This rise marked the arrival in Birdsville of the dust wall seen just north of LEN in the 1625 EDT imagery, with the dust having been entrained from LEN and throughout the lower Simpson Desert (Figure 4b), and the Birdsville concentration maximum occurring at 2100 EDT. A third (minor) increase in dust concentration (60 μg/m^3) occurred between 0800-0900 EDT on 11th October. This dust was associated with an increase in post-frontal southerly winds to around 10 m/s (Figure 5b), possibly sourced again from the Diamantina River floodplain, this time to the south of Birdsville.

The peak dust concentration observed at Tibooburra (Figure 5c) was lower than the other two stations. The concentration profile showed little increase during the afternoon of the 10th October despite high pre-frontal northerly wind speeds. The arrival of the front was marked by a change in wind direction as flow came from the west, resulting in the timing of maximum dust concentration at 2000 EDT (40 μg/m^3). This modest peak concentration was one twentieth of that for Birdsville, reflecting the greater distance of Tibooburra from the active LEN source (Figure 2), and the lower local erodibility of Tibooburra compared with the alluvial and dunefield surfaces local to Birdsville. In October 2013, the Tibooburra area retained a relatively low erodibility due to the presence of vegetation cover induced by the wet period responsible for the 2010 LEB flooding. As local surface erodibility was low, the strongest likelihood is that the dust detected at Tibooburra was distantly sourced from the active LEN emission. Following the passage of the front, wind speeds began to decline over time and moved to southerlies without producing any dust response at Tibooburra.

5. SUMMARY

Synoptic analyses of central Australia, the availability of appropriately timed satellite imagery, plus synergistic surface meteorological and dust concentration measurements have provided an opportunity to examine, for the first time in a single event, the dynamics of the three main wind systems responsible for dust entrainment in the lower Lake Eyre Basin. While only a single case study is presented, here we show that during the passage of an individual front, dust entrainment can occur as a result of all three wind systems. This has the potential to produce dust transport in three directions, to the south east (with pre-frontal northerlies), the north east (with frontal south westerlies) and to the north west (with post-frontal southerlies), even in one dust outbreak. This case study illustrates the complex nature of the wind systems that drive dust emission and transport in the Lake Eyre Basin, one of the southern hemisphere's most significant dust sources. While the operation of the different wind systems has important implications for the accurate mapping of dust activity within this region, a larger study encompassing multiple events is required for a truly better developed understanding of the transport pathways. An important impetus for this research comes from efforts to tackle large scale interactions at the heart of Earth Systems Science, as a more accurate appreciation of dust activity can help constrain the timing and location of transported dust in relation to specific marine responses (e.g., possible phytoplankton blooms from aeolian fertilisation).

Furthermore, the findings from this single case study serve to illustrate the type of data required for improved understanding of the erosional and transport role of wind systems in other dust bearing regions. Considerably higher degrees of detail can be added to our understanding of dust processes at a large basin scale with a range of data resolved sufficiently to capture the effects of changeable wind speed and direction, even during the passage of individual dust-producing weather systems.

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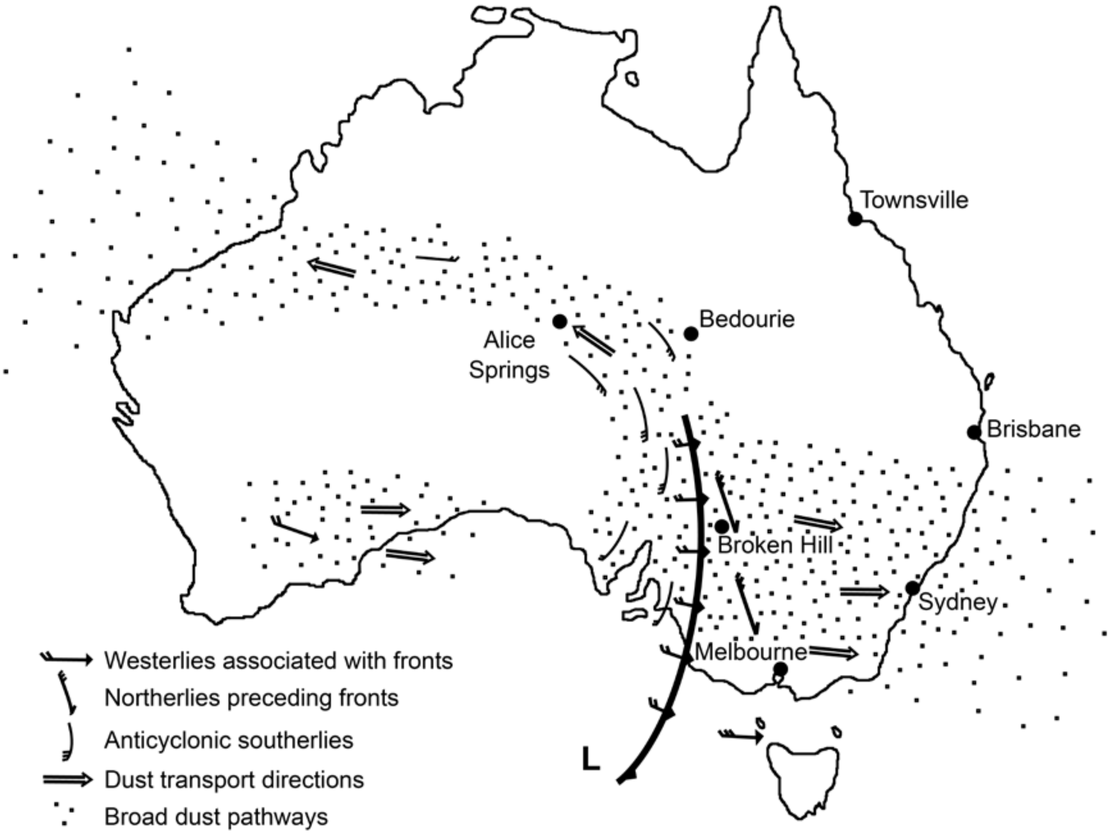

Figure 1: Sprigg's model of dust transporting winds in Australia (after Sprigg, 1982).

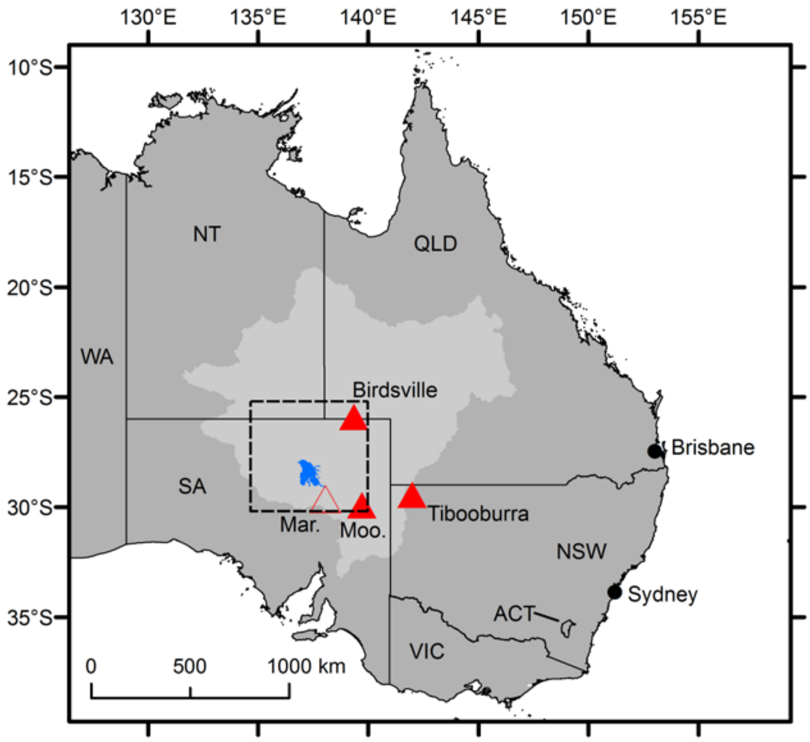

Figure 2: Regional context showing the Lake Eyre Basin (light grey), Lake Eyre North (blue) and locations of both dust and meteorology (solid triangle), and meteorology only (open triangle) observations. Abbreviations: Mar. (Marree), Moo. (Moolawatana). Dashed square is region covered by imagery panels in Figure 4.

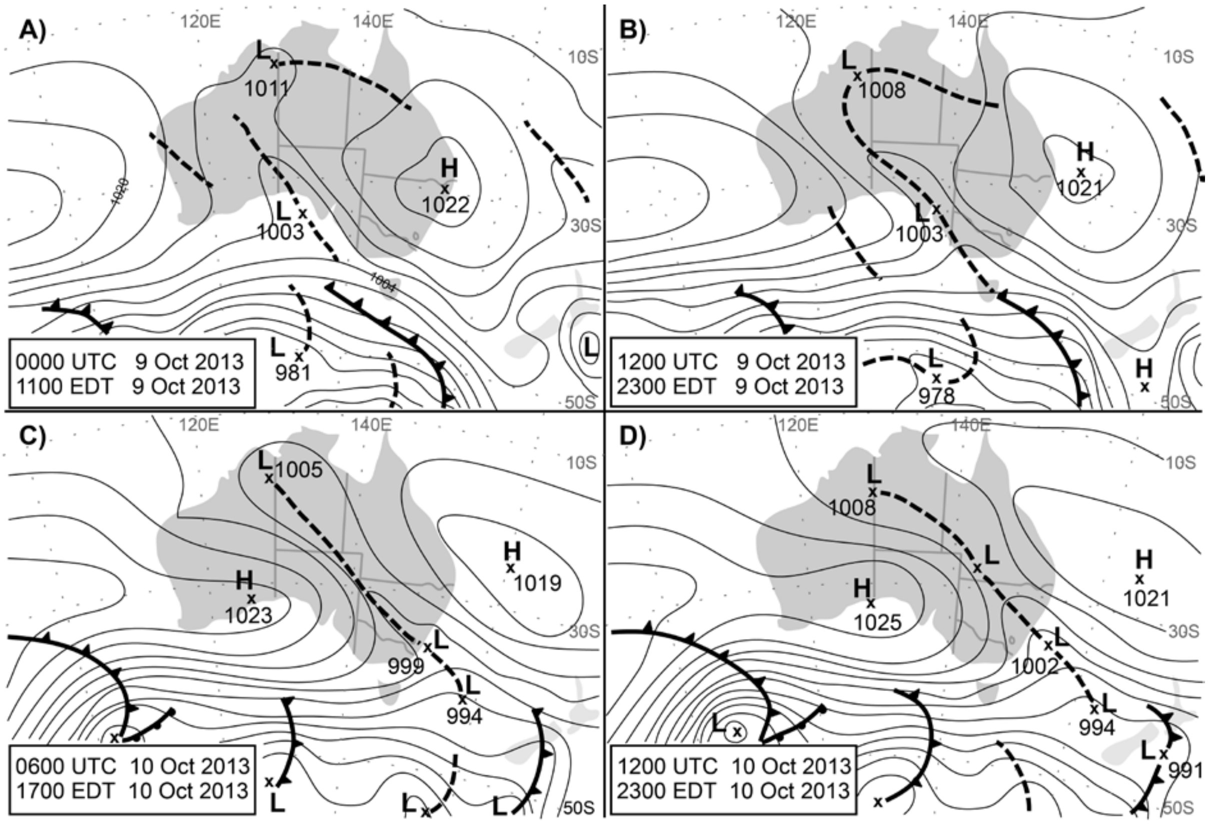

Figure 3: Mean sea level pressure charts for selected times before, during and after the lower Lake Eyre Basin dust event occurring on the 10th October 2013. (Re-drawn from the Australian Bureau of Meteorology.)

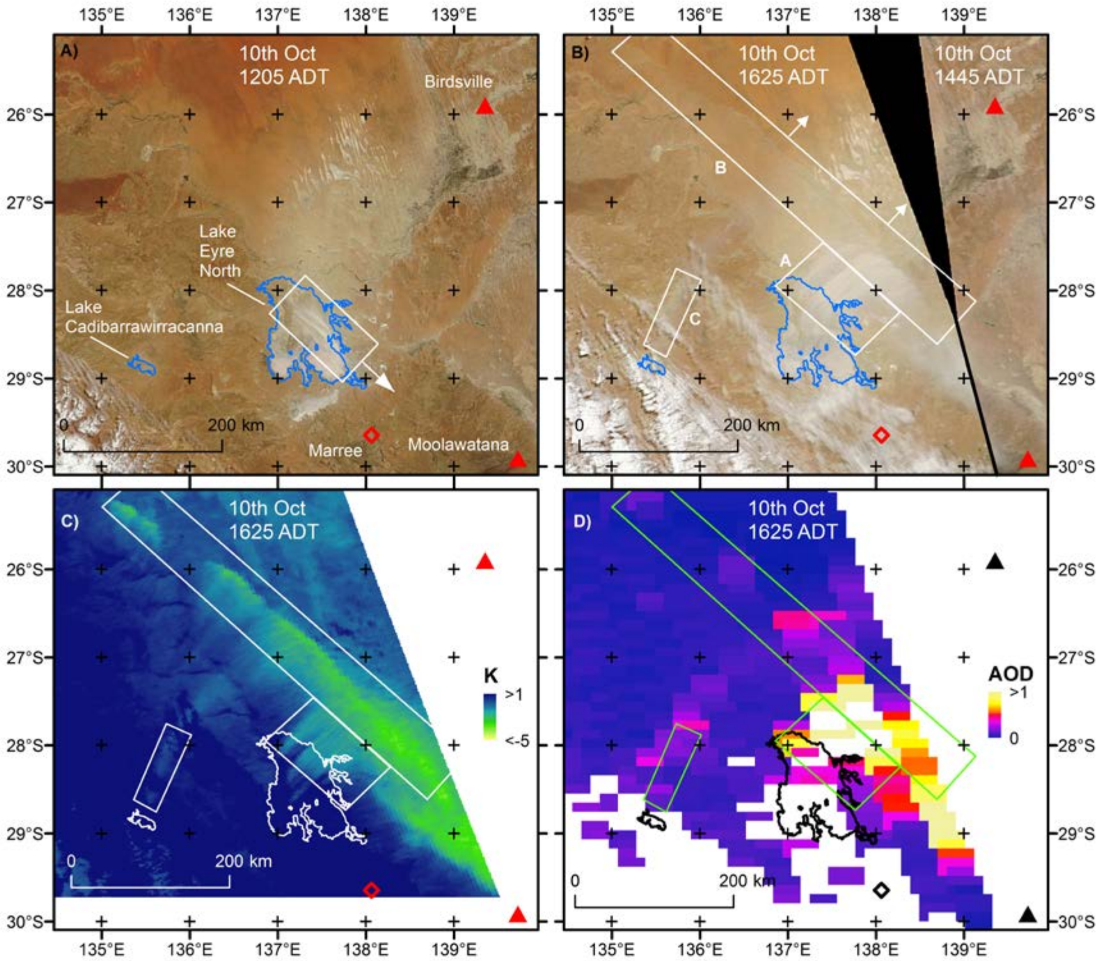

Figure 4: A) Terra MODIS 'true colour' scene for 0105 UTC (1205 EDT) 10th October 2013. B) Aqua MODIS 'true colour' scenes for 0525 UTC (1625 EDT) and 0345 UTC (1445 EDT) 10th October 2013. See time annotations on scenes. C) Brightness temperature difference (bands 31 and 32) (BTD) for the 0525 scene. Data scaled to a range known to represent dust in LEB cases, with dust typically having a negative BTD value (see Baddock et al., 2009). D) MODIS Deep Blue 550 nm aerosol optical depth (AOD) product for 0525 UTC scene only. True colour imagery from NASA LANCE Rapid Response facility.

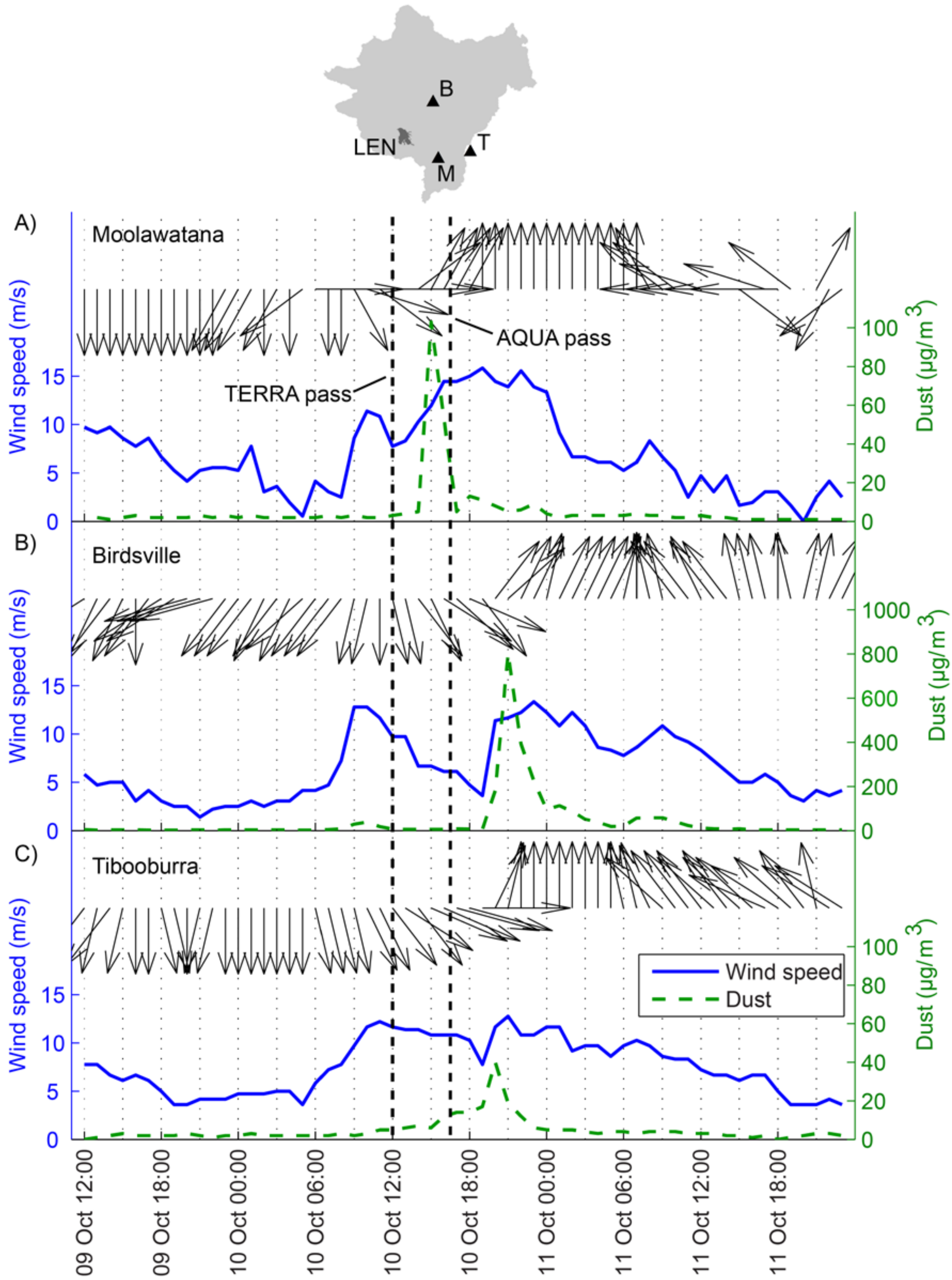

Figure 5: Wind speed, direction and dust concentration ($\mu g/m^3$ of PM_{10}) for the dust event at three DustWatch sites of A) Moolawatana, B) Birdsville and C) Tibooburra. Contextual map shows location of sites in relation to primary dust source, Lake Eyre North. Note the much larger scale for dust concentration at Birdsville, and that meteorological data on the Moolawatana plot is taken from Marree (See text and Figure 2 for locations). Time of the marked Aqua pass is the 1625 EDT scene (Figure 4b).