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Published on: 01 Jun 2008 - Journal of Geophysical Research (American Geophysical Union)

Topics: Haze

A vertical profile of PM10 dust concentrations measured during a regional dust event identified by MODIS Terra, western Queensland, Australia

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Received 29 January 2007; revised 15 June 2007; accepted 10 October 2007; published 8 March 2008.

[1] Accurate determination of the spatiotemporal properties of dust plumes and their dust concentrations is essential for calibration of satellite products and the initialization and validation of numerical models that simulate the physical properties and affects of dust events. In this paper, we present a 500 m vertical profile of PM10 dust concentrations measured during a regional dust event in western Queensland, Australia. PM10 dust concentrations within the haze were found to be >20 times background ambient values and decreased with height following an exponential function. We apply an over-land algorithm to MODIS Terra satellite images of the dust haze to enhance its visual appearance against the bright land surface and define its size. In conjunction with the measured attenuation of dust concentrations with height we calculate the PM10 dust load of the plume to be ~60% of that which would have been calculated assuming a constant dust concentration up to the dust ceiling height. Results extend previous findings from tower-based studies made close to the surface and confirm that atmospheric dust concentrations decrease rapidly with increasing height, thereby enabling more accurate calculation of atmospheric dust loads during synoptic-scale dust outbreaks.

Citation: McGowan, H. A., and A. Clark (2008), A vertical profile of PM10 dust concentrations measured during a regional dust event identified by MODIS Terra, western Queensland, Australia, *J. Geophys. Res.*, *113*, F02S03, doi:10.1029/2007JF000765.

1. Introduction

[2] The wide ranging impacts that mineral aerosols have on the Earth–atmosphere system have received considerable attention over the last decade. They include modification of radiation transfers and atmospheric photochemistry, scavenging of industrial air pollutants, cloud microphysical processes and fertilization of oceans by deposition of dust rich in iron [*Kohfeld and Harrison*, 2001; *Intergovernmental Panel on Climate Change*, 2001; *Tegen*, 2003; *Jickells et al.*, 2005]. However, significant gaps remain in the ability to accurately quantify these effects at high temporal and spatial resolution, and to replicate them in numerical models. Scarcity of observational data from dust "hot spots" currently hinders dust model refinement and evaluation [*Grini et al.*, 2005], a point reiterated by *Darmenova et al.* [2005] who considered that the lack of quantifiable data on the spatial and temporal variability of atmospheric dust loads and their properties in major dust source areas, urgently required investigation at all relevant scales. Accordingly, the need for observational data from dust source areas is undeniable, particularly that which quantifies the physical attributes of dust plumes, their relationship to source area surface characteristics, land use, and synoptic- and local-scale meteorology.

[3] Satellite sensors such as the Total Ozone Mapping Spectrometer (TOMS) which has been used widely to map dust source area activity and plume pathways face several key unresolved challenges. For example, *Herman and Celarier* [1997] argue that TOMS was not able to detect dust below 1.5 km, while *Kubilay et al.* [2005] found that 30% of dust events reported over the northeastern Mediterranean that occurred below 850 hPa (1.5 km) were not detected effectively by TOMS. Such limitations mean that remote sensing of dust plumes should be combined with surface based observations to provide accurate information on plume characteristics. This approach has been used in large-scale research programs such as ACE-Asia [*Huebert et al.*, 2003], TRACE-P [*Carmichael et al.*, 2003], and SHADE [*Highwood et al.*, 2003] that have provided much new information on atmospheric dust, although significant knowledge gaps remain [*Darmenova et al.*, 2005]. This is particularly so for the Southern Hemisphere where large-scale field measurement campaigns have not been conducted, even though atmospheric dust in the Southern Hemisphere may have disproportionately large impacts on weather and climate through, for example, enhancement of marine productivity and subsequent carbon sequestration [*Jickells et al.*, 2005].

[4] In the Southern Hemisphere, the 1.14×10^6 km^2 Lake Eyre Basin in central Australia is the major dust source region [*Prospero et al.*, 2002]. It is characterized by the

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large, internally draining ephemeral rivers of the Channel Country of far western Queensland and in its western sections the linear dunes of the Simpson Desert. The southern sector of the Simpson Desert is the area of greatest dust storm activity in the Basin [*Bullard and McTainsh*, 2003]. This is where the Diamantina and Georgina Rivers supply large quantities of fine grained sediments to their floodplains, which then become susceptible to wind entrainment, often as a consequence of the impact of saltating sand grains that originate from adjacent sand dunes. The large-scale dust storms that result take one of two paths, either traveling to the north and northwest as a result of strong southeasterly winds associated with anticyclonic ridging following the passage of subtropical cold fronts and troughs or to the east-southeast in prefrontal northwest winds and postfrontal westerly winds [*Sprigg*, 1982]. Dust in the east-southeast pathway can affect the large coastal cities of eastern Australia causing reductions in visibility and particulate concentrations to exceed health and amenity guidelines [*Y.-C. Chan et al.*, 2005]. The dust plumes may reach New Zealand, >3000 km from their source, causing red snow, spectacular sunsets, and occasionally dust hazes [*Marx and McGowan*, 2005]. Such events are more frequent during late spring to early summer before the onset of the Australian summer monsoon when rain depressions which form along the monsoon trough over northern Australia travel south to affect the Basin.

[5] The large-scale dust events of central Australia have been documented for >100 years [see *Marx and McGowan*, 2005]. However, few studies have attempted to investigate the physical properties of the dust plumes and their relationship to local meteorological conditions. Those studies that have been conducted, most notably by *McTainsh et al.* [1999], *Nickling et al.* [1999], and *Butler et al.* [2001] in the Channel Country of western Queensland have provided insight to the relative erodibility of different land types in the Lake Eyre Basin, their dust emissions and near surface dust concentrations. *Nickling et al.* [1999] reported that dust concentrations measured within the first 10 m of the surface over a claypan decreased with height following a power function. However, *Butler et al.* [2001] concluded that the decrease in dust concentration with height above the surface reported by *Nickling et al.* [1999] was dependent upon the spatial distribution of nearby sources, thereby limiting the wider application of their results. Recently, *Butler et al.* [2005] documented a series of "kinky" dust concentration profiles measured over the same claypan where *Nickling et al.* [1999] conducted their study. They concluded that the irregular dust concentration profiles (0–10 m agl.) were caused by intense surface heating with resulting convective turbulence lifting dust several meters above the surface.

[6] Near-surface dust concentrations of 172 to 85,861 μg m^{-3} for sites in the Channel Country during dust entrainment events have been reported by *Boon et al.* [1998] and *Butler et al.* [2001], while 600 km east at Charleville, *Boon et al.* [1998] reported background dust concentrations of 10 to 50 μg m^{-3}. The organic content of these dusts was found to range from 2 to 90%, with the lower concentrations associated with conditions when dust was being entrained by the wind. These measurements were made within the lowest 10 m of the atmospheric boundary layer. As a result, they are affected by the limitations discussed by *Butler et al.* [2001] such as the heterogeneity of proximal source area strengths, as well as other factors such as gravitational sorting, surface-generated mechanical turbulence, and the influence of vegetation. Accordingly, there is a need to extend these observations to greater heights to more accurately quantify the physical characteristics of regional scale dust events in the Lake Eyre Basin.

[7] Fundamental to quantifying the properties and likely effects of airborne dust is the ability to also accurately determine the spatial extent of dust plumes. Most of the major global dust source areas including the Lake Eyre Basin are located in remote, sparsely populated subtropical desert environments and accordingly, many events go unreported. An early summary of the spatial extent of Australian dust storms was presented by *Lowe* [1943]. He concluded that between 1938 and 1942 all regions of Australia where affected at some time by either dust storms or dust haze except Cape York Peninsula and other regions north of 17°S, the extreme southwest of Western Australia and Tasmania. Subsequent studies have mapped dust entrainment and transport in Australia's remote arid lands in considerably more detail using meteorological observations [see *Middleton*, 1984]. *McGowan et al.* [2000] and *McTainsh et al.* [2005] used the GIS software MapInfo to interpolate meteorological observations of dust events between sites to identify the spatial extent of dust plumes. However, this approach suffers from a range of limitations, particularly when applied to specific events, as interpolation of observational data between sites can not accurately define the boundary of dust plumes, their shape, or the distal reduction in dust concentrations with increasing distance from source. The approach is, however, effective in developing summaries of dust storm activity but at large scales where detail is not a priority.

[8] In this study we present a 500 m vertical profile of PM10 dust concentration measured during a regional-scale dust event in the Channel Country of the Lake Eyre Basin, western Queensland, Australia. Using MODIS (Moderate Resolution Imaging Spectroradiometer) imagery, we define the spatial extent of the dust plume, the principle source areas, and estimate the PM10 dust loading for the sector of the plume sampled by our kite-mounted sampling system. Local meteorological data was collected by a portable automatic weather station. We combine these data sets to show the benefits of such an approach to quantifying the spatial extent of dust storms in central Australia, their onset and cessation, dust load, and association with local- and synoptic-scale meteorology.

2. Physical Setting

[9] Fieldwork was conducted in Diamantina National Park (DNP) in the Channel Country of the Lake Eyre Basin (Figure 1). This park includes the broad floodplain and numerous channels and waterholes of the ephemeral Diamantina River which are lined by coolibah (*Eucalyptus Coolibah*) and lignum (*Muehlenbeckia florulenta*). A large area of well-vegetated source bordering linear dunes is located west of the river, which is separated by wide, sparsely vegetated swales, claypans, and flood-outs. Mitchell (*Astrebla spp.*) grasslands and gibber stone pavements cover large areas of the park. Mean annual rainfall is

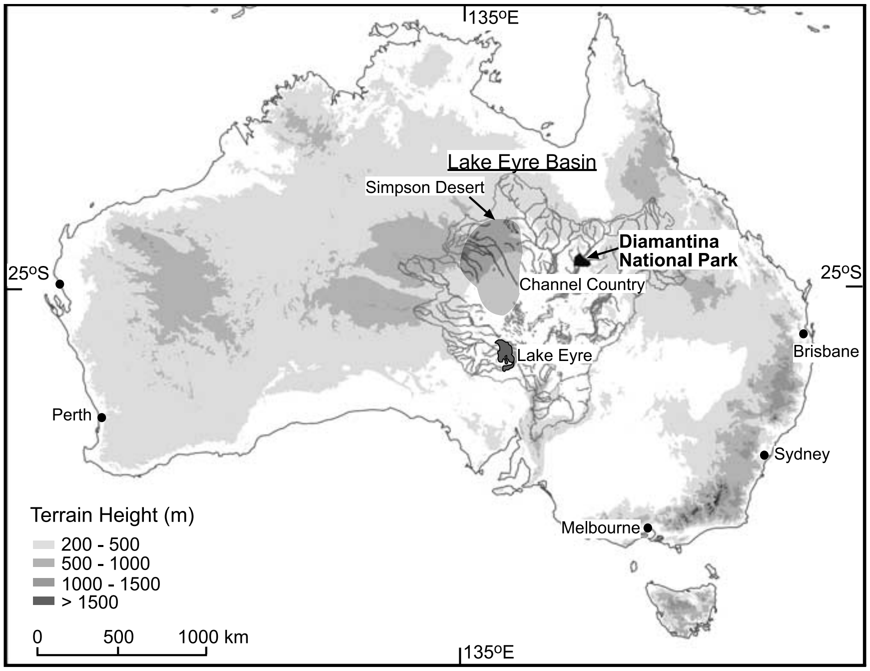

Figure 1. Location map showing the study site Diamantina National Park within the Channel Country of the Lake Eyre Basin, Australia.

<300 mm with the majority of precipitation falling during summer from December to March. Summer temperatures frequently exceed 40°C, while during winter minimum temperatures may approach 0°C.

3. Methodology

[10] Gusty and turbulent dust laden winds associated with the passage of dust storms present a range of challenges to researchers attempting to sample dust concentrations in situ. While towers provide suitable platforms from which to make such measurements, they do not typically exceed 20 m and are commonly fixed in place, therefore requiring a dust storm to pass over the tower before measurements of, for example, dust concentrations can be made. The severe turbulence, high dust concentrations, and need to commence a profile near the surface also exclude using aircraft to monitor conditions within a dust plume. To overcome these problems, we developed a kite-based sampling system with the capability to lift dust sampling devices to heights exceeding several hundred meters above the ground surface that can be flown during the passage of frontal dust storms. The 3 m delta kite is similar to that described by *McGowan and Sturman* [1996] and has been designed to operate in wind speeds up to 25 ms^{-1}. It has the capacity to lift particle samplers that weigh 2 kg at wind speeds >8 ms^{-1}. The kite is flown using a 300 kg breaking strain spectra line tether which is attached to a hand operated winch. While kites have been used previously to sample aerosols from biomass burning [*Mims and Mims*, 2004], sea salts [*Daniels*, 1989], and urban air pollutants [*Brönnimann et al.*, 2001], this is the first time we believe that a kite has been used to sample a dust plume.

[11] During October 2003 and October 2005, vertical profiles of PM10 concentration were measured using the kite sampling system at DNP over a sparsely vegetated plain. The system consisted of a TSI DustTrak^{TM} and Kestrel 4000 weather monitor suspended approximately 1 m below the kite. The DustTrak^{TM} was positioned so that the intake pointed into the wind to minimize any reduction in sampling efficiency that may have resulted from suspending the DustTrak^{TM} below the kite. However, we acknowledge that we cannot quantify the sampling efficiency of the DustTrak^{TM} during the kite flights. The Kestrel 4000 recorded standard meteorological variables, as well as elevation above the surface to an accuracy of ±15 m. The internal clocks of the Kestrel 4000 and DustTrak^{TM} where synchronized before flights. Both instruments were programmed to make measurements every second and to record averages every 20 s. This allowed flights of 40 min duration before the maximum data storage of the Kestrel was exceeded. This was sufficient to allow the kite and attached instrumentation to be flown to a height of approximately 500 m above the surface. Local meteorological conditions were monitored during 2003 by a Campbell Scientific MetData1 portable weather station located 10 km northwest of the Park Headquarters on a well exposed rocky outcrop of the Goyder Range. The site is approximately 15 to 20 m above the surrounding landscape and provided representative measurements of local meteorological conditions. Wind speed and direction was measured by a R.M. Young 05103 Wind Monitor positioned 2.5 m above the surface, while screen air temperature and relative humidity were measured by a CS500 probe at 1.5 m above the surface. Solar radiation was measured with a LI200X-LC pyranometer with a typical accuracy of ±3%. Measurements from all sensors were recorded every second with the 5 min averages logged by a Campbell Scientific CR10X datalogger.

[12] MODIS images of the field area were downloaded from http://modis.gsfc.nasa.gov/. This sensor flown on the Terra and Aqua satellites offers good spatial resolution (250 m to 1 km at nadir) and temporal coverage at twice

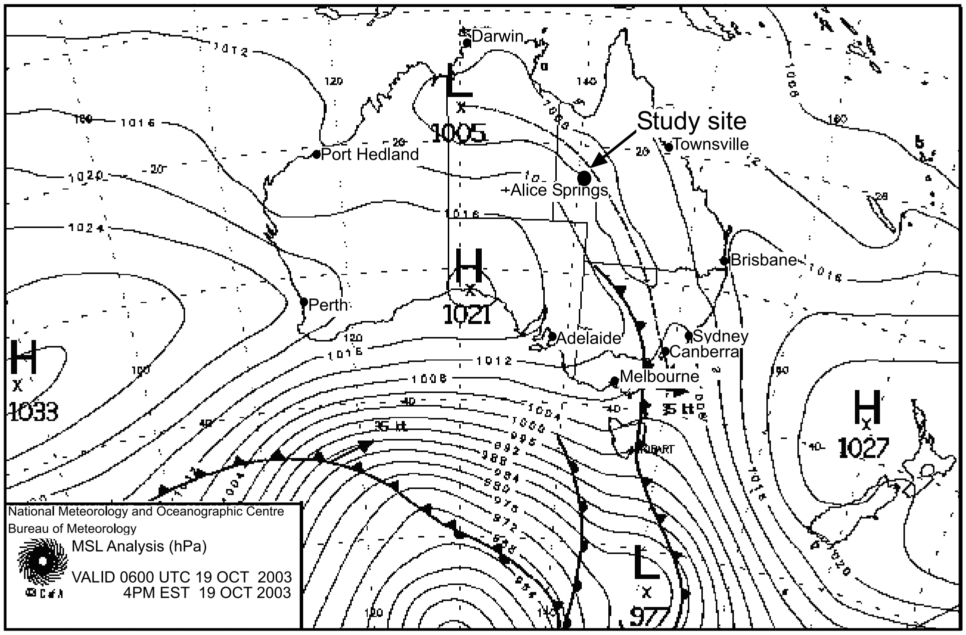

Figure 2. Synoptic surface chart for 1600 EST 19 October 2003 (modified after Bureau of Meteorology).

per day. It has one of the most comprehensive calibration subsystems ever flown and the ability to correct optical data to scaled reflectance with an accuracy of 5% or better in the solar bands, and 1% or better in the thermal bands [*Lillesand et al.*, 2004; *Jensen*, 2005]. MODIS also simultaneously acquires atmospheric sounding data for atmospheric correction. Furthermore, it has good spectral resolution with its 36 channels spanning the visible (0.451 μm) to thermal infrared (14.235 μm) [*El-Askary et al.*, 2003], thereby offering considerable potential for the study of dust storms.

[13] *Miller*'s [2003] over-land algorithm was applied to the radiometrically corrected and geo-referenced images to enhance the appearance of atmospheric dust. This approach is based on the premise that (1) the dust plume will exhibit a lower temperature brightness compared to the hot surface temperature of the land background, (2) the suspended dust layer can be differentiated from water clouds having the same radiometric temperature based on color, and (3) mineral dust often produces a positive 12–11 μm spectral difference (split window approach), where the spectral response of dust in the 12 μm channel will be greater than for cirrus cloud where the 11 μm channel will dominate. However, this approach does have several limitations including the inability to detect dust below clouds, while cold surfaces may be prone to false enhancement. As the event that we report here (19 October 2003) occurred during the daytime under cloud-free conditions in the heat of late spring, these limitations do not affect our analysis.

4. Synoptic Setting and Local Meteorological Conditions, 19 October 2003

4.1. Synoptic Setting

[14] The mean sea level synoptic analyses for 1600 Eastern Standard Time (EST (UTC + 10 h)) (Figure 2) shows a trough line extending southeast from a heat low over the northwest of the continent. The trough lay ahead of a vigorous cold front associated with a depression in the Southern Ocean (Figure 2). At the same time a ridge of high pressure extended north over eastern Australia directing a northwesterly airflow over the field site at DNP ahead of the approaching trough (Figure 2). This synoptic circulation pattern produces ideal meteorological conditions for dust storm genesis in the Lake Eyre Basin. During the austral spring and early summer these synoptic conditions are a common feature of the Australian region [*Smith et al.*, 1995]. Dust may be entrained in the hot and dry northwesterly winds ahead of the trough and/or in the southwesterly winds that follow the passage of the trough. These systems are typically confined to the lowest 1000 to 1500 m of the atmosphere as vertical development is suppressed by an overlying ridge of high pressure at midlevels in the atmosphere [*Smith et al.*, 1995]. As a result, satellite-flown sensors such as the TOMS are often unable to distinguish these dust plumes from the underlying surface, therefore leading to some researchers concluding that central Australia has surprisingly few dust storms [see *Prospero et al.*, 2002].

[15] The trough of the 19 October 2003 passed through the study area early in the afternoon and was not associated with cloud, which is typical [*Sturman and Tapper*, 2006], thereby allowing MODIS imagery to be used by this study to monitor the dust plume.

4.2. Local Meteorological Conditions

[16] Local meteorological conditions monitored by our weather station between 1000 and 2200 EST on the 19 October 2003 are presented in Figures 3a and 3b. The arrival of the dust plume was recorded at 1335 EST, and was associated with a gradual backing in wind direction to the west–southwest with maximum wind speeds of 8 to 12 ms^{-1}. Air temperatures remained constant at approximately 38°C, although the relative humidity increased

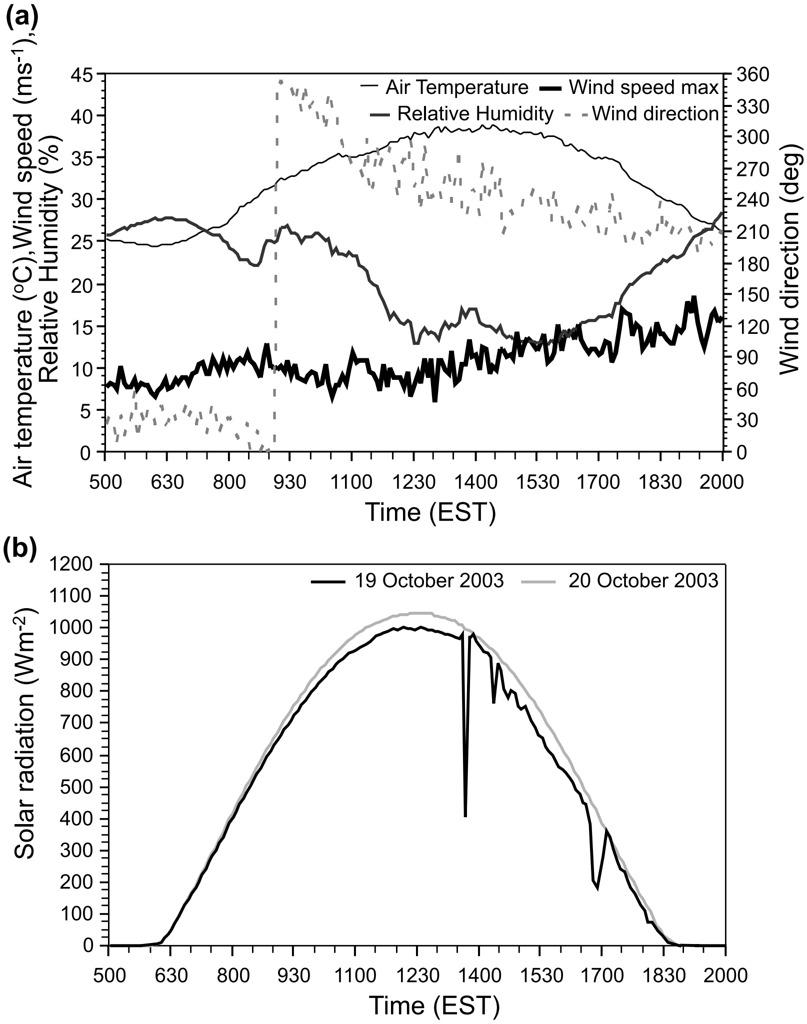

Figure 3. (a) Local meteorological conditions and (b) solar radiation recorded at the field site in Diamantina National Park during 19 and 20 October 2003.

slightly from 14% to 17% with the arrival of the new dust-laden air mass. Dust entrainment within DNP was observed to be confined to small areas on claypans and visibility fell to approximately 8 to 10 km, meaning the event was classified as a dust haze.

[17] The solar radiation trace for the 19 October 2003 is compared to that for the following day in Figure 3b. This shows the arrival of the dust haze at our field site at 1335 EST caused solar radiation at the surface to fall from 984 Wm^{-2} to 409 Wm^{-2} in only 5 min, after which values increased rapidly to 958 Wm^{-2} at 1355 EST. The highest dust concentrations were therefore confined to a narrow band approximately 13.2 km wide at the leading edge of the plume based on local wind speed measurements. Two further pronounced falls in solar radiation were recorded at 1425 EST and 1640 EST (Figure 3b), with neither being associated with a marked change in local meteorological conditions. We believe that the inferred higher dust concentrations at these times represent the arrival of dust from discrete sources within the Channel Country, which became active during the event as local threshold entrainment velocities were exceeded. However, the exact provenance of this dust could not be determined.

[18] The solar radiation traces presented in Figure 3b also indicate that the attenuation of solar radiation by dust on the 19 October 2003 began at approximately 0900 EST during the pretrough northwesterly winds. This is 4.5 h before the arrival of the main plume was observed. At 1200 EST dust was responsible for lowering the receipt of solar radiation at the surface by 40 Wm^{-2} when compared to the dust-free conditions of the following day (Figure 3b). This effect was not obvious to observers in the field and highlights the advantage of monitoring radiation transfers during dust transport events. Cessation of the event occurred at 1820 EST as shown in Figure 3b, with the solar radiation trace indicating a return to clear sky conditions before sunset.

5. Vertical PM10 Dust Profiles

[19] At 1445 EST the kite-mounted sampling system was launched at DNP and flown to a height of 500 ± 15 m agl., which is believed to have been midplume height as the dust haze ceiling height was observed to be approximately 1000 m agl. at DNP. The attenuation of solar radiation by dust at this time was 65 Wm^{-2} when compared to the dust free conditions monitored on the 20 October 2003.

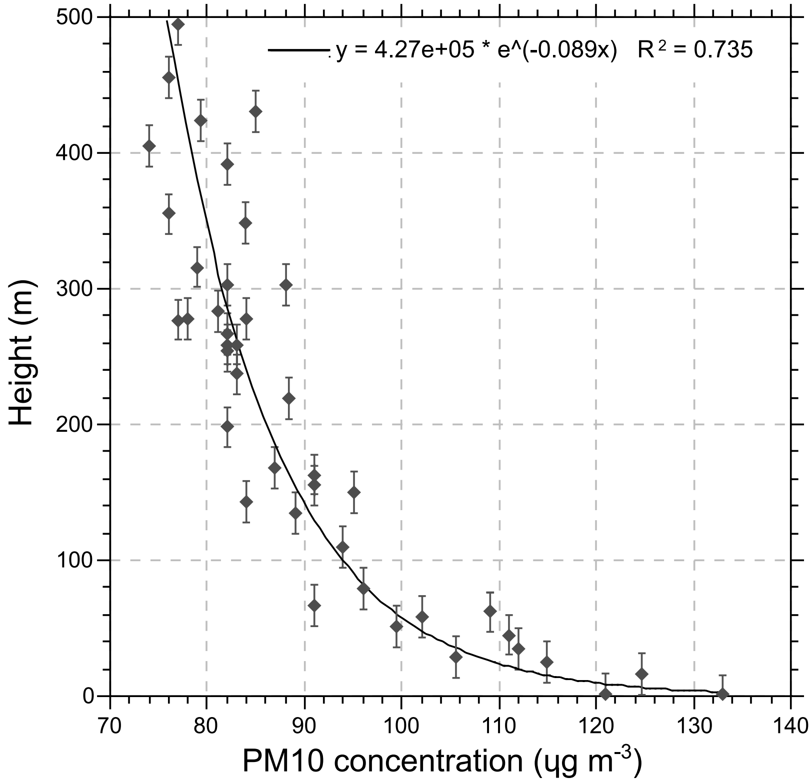

Figure 4. Vertical distribution of PM10 dust concentrations, measured by the kite-mounted DustTrak™ between 1445 EST to 1500 EST on the 19 October 2003. Error bars display the accuracy (±15 m) of the measured height at which PM10 dust concentrations were recorded.

Accordingly, we believe that while the kite-based sampling of the plume was not conducted at the time corresponding to the highest dust concentration in the lower atmosphere, it was representative of conditions that prevailed for the majority of time on the 19 October 2003 between midmorning and late afternoon, as indicated by Figure 3b.

[20] PM10 dust concentrations measured by the kite-mounted DustTrak™ are presented in Figure 4. Also shown is the line of best fit which was achieved by fitting an exponential function to the data, which explained 73% of variance in dust concentration (r^2 0.73) (Figure 4). While only 42 data points are shown in Figure 4, these are 20 s averages of PM10 dust concentration measured every second and represent 840 individual PM10 measurements. Importantly, they show that the vertical PM10 dust concentrations conform to an exponential decrease with increasing height above the surface. Maximum PM10 dust concentrations recorded during the flight were >130 μg m^{-3} near the surface reducing to 82 μg m^{-3} at approximately 300 m agl. These dust concentrations range from 22 to 36 times background PM10 values measured at DNP in the lowest 360 m of the atmosphere during similar synoptic conditions on the 19 October 2005. Dust entrainment did not occur on this occasion due to lower wind speeds.

6. Dust Plume Characteristics Identified by MODIS Terra 19 October 2003

[21] A MODIS Terra image of the event was acquired to define the spatial extent of the dust haze and to assist in identification of source areas. Figure 5 shows the visible image for 1040 EST, 19 October 2003. The pale chalky color of the dust haze is clearly distinguishable from the underlying surface and covers an area of 32,300 km^2 (encircled). We believe that this dust plume originated from the dry ephemeral channels and claypans of the Georgina and Milligan Rivers seen below the haze. As the plume traveled in a north to northeasterly direction toward DNP as indicated by the arrows (Figure 5) dust was entrained from claypans in the Diamantina River system.

[22] *Miller*'s [2003] algorithm was applied to the MODIS image of the 19 October 2003. While this led to some enhancement of the dust haze circled in Figure 5, importantly, it identified a previously unknown area of dust entrainment in the Simpson Desert to the immediate west of the dust haze (Figure 6). This dust can be seen in Figure 6 streaming downwind from fire scars in the northern Simpson Desert. The resulting plume extended over an area of approximately 85,700 km^2. It traveled in a north-northwest direction in gradient south to southeasterly winds associated with anticyclonic ridging following the passage of the trough. This plume did not affect our field site at DNP.

[23] The total dust plume area shown in Figure 6 for the 19 October 2003 event identified by the enhanced MODIS Terra image was calculated to be 118,000 km^2. However, we believe that this figure is conservative as dust may have been obscured by cloud in the southwest corner of the image (bottom left of Figure 6). Areas of dust haze associated with the entrainment of dust from the Simpson Desert may also have gone undetected because of their close

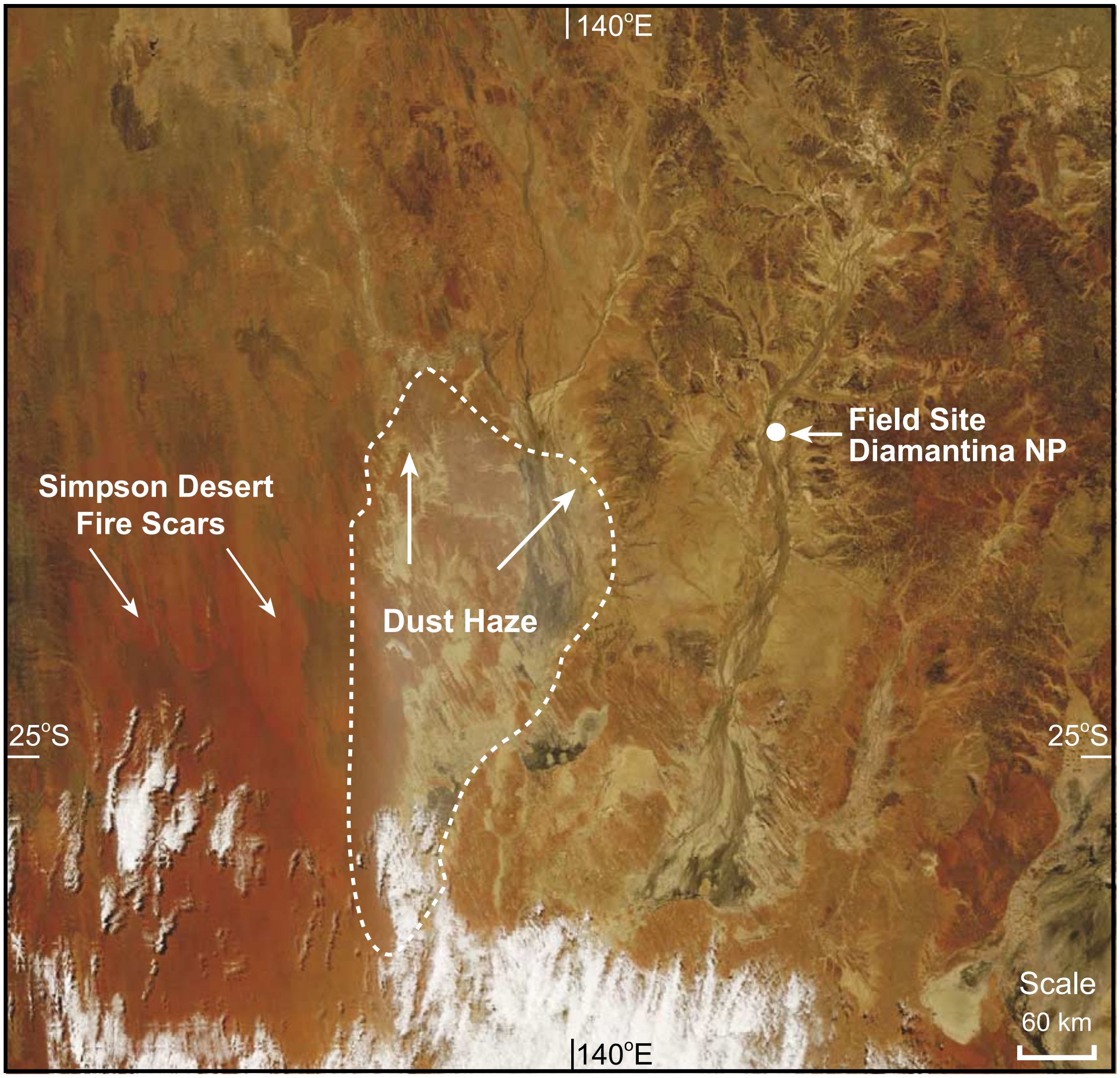

Figure 5. Visible MODIS Terra image acquired at 1040 EST 19 October 2003 (sourced from http://modis.gsfc.nasa.gov/) showing the dust haze east of the Simpson Desert over the channels of the Georgina and Milligan Rivers seen below the haze.

spectral resemblance to the surface and/or low atmospheric concentrations.

[24] Having determined the size of the dust haze (32,300 km^2, Figure 5) that affected DNP and extrapolating the relationship shown in Figure 4 between PM10 dust concentration and height to the observed dust ceiling of 1000 m agl., we estimate the PM10 dust load in the plume shown in Figure 5 to have been 2560 t. In comparison, previous researchers have calculated the mass of dust in similar plumes by assuming the concentration of dust measured at the surface (usually at 2 m agl.) is uniform with height to the top of the plume. *McTainsh et al.* [2005] stated that such an approach may have seemed reasonable given the often turbulent and apparently well mixed nature of dust plumes associated with the passage of cold fronts and troughs. This approach yields a total PM10 dust load of 4199 t using the measured PM10 dust concentration of 130 $\mu g\ m^{-3}$ at approximately 2 m agl. at our field site on the 19 October 2003. This is approximately 1.64 times that calculated using the relationship between PM10 dust concentration and height shown in Figure 4.

7. Summary and Conclusion

[25] Use of the kite-mounted sampling system allowed acquisition of PM10 dust data to c. 500 m above the ground surface. This approach fills a significant gap in dust plume sampling between the use of towers, and aircraft, which are often confined to heights greater than our kite was flown and where dust concentrations are low. While we acknowledge that the sampling efficiency of the TSI DustTrak™ may have been affected by being suspended below the kite in moderately high wind speeds, we believe that any such adverse effects on sampling efficiency were minimal as the measured PM10 dust concentrations display a coherent attenuation with increasing height previously only reported from tower and Lidar studies. However, Lidar studies report optical indices such as the backscattering coefficient that do not directly correspond to dust concentrations as the optical

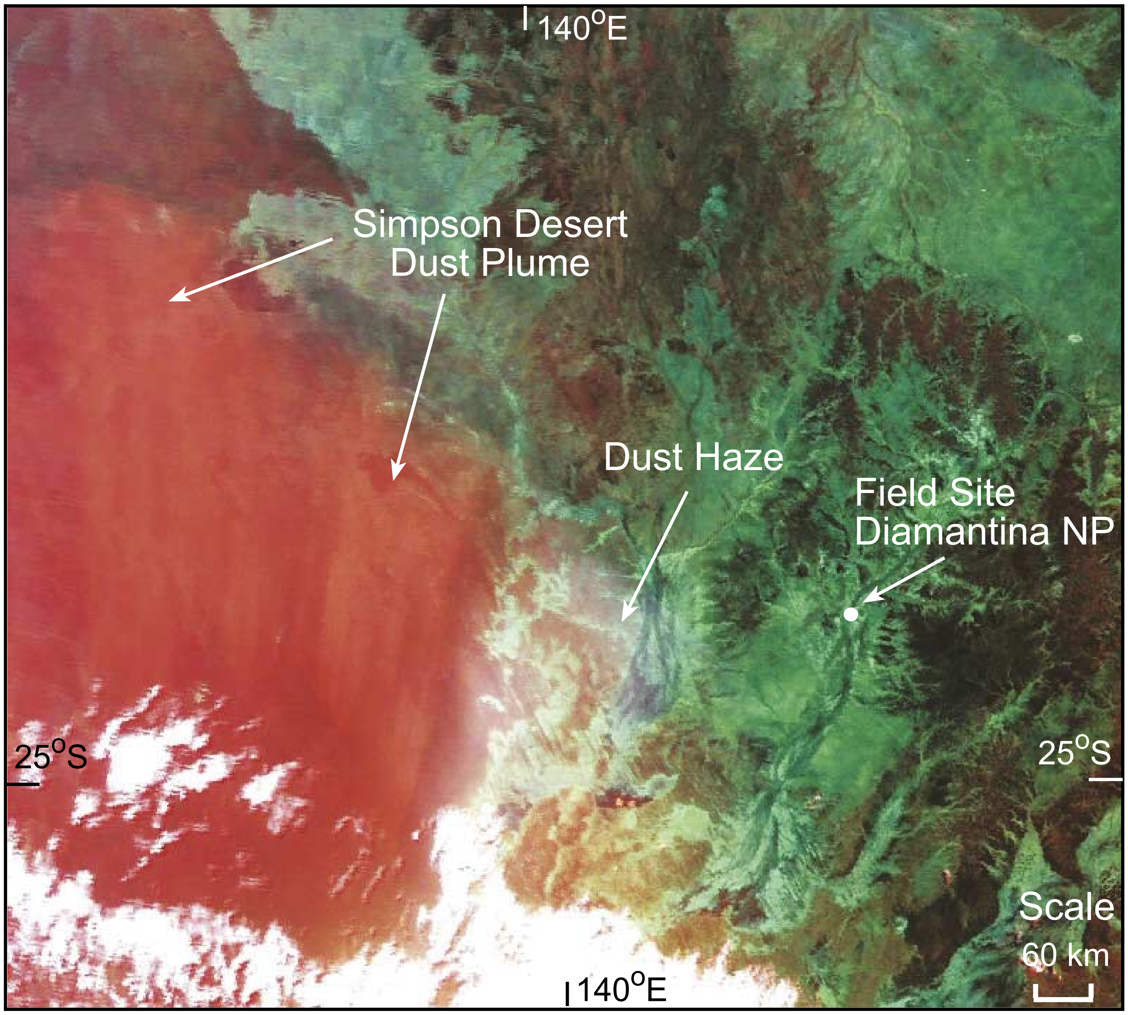

Figure 6. MODIS Terra image acquired at 1040 EST 19 October 2003 (sourced from http://modis.gsfc.nasa.gov/). *Miller*'s [2003] overland algorithm has been applied to enhance atmospheric dust concentrations allowing the dust plumes over the Simpson Desert to be identified as indicated. These were not detectable in the visible image presented in Figure 5.

properties depend on the physical characteristics of the dust such as size, shape, and mineralogy [*Shimizu et al.*, 2004]. To the authors' knowledge, tower-based measurements of dust events in rural settings have not exceeded 21 m agl., while those from, for example, the 325 m high meteorological tower of the Institute of Atmospheric Physics, Chinese Academy of Sciences, located in Beijing city are affected by urban emissions of air pollutants and turbulence generated by adjacent buildings which are 30 to 60 m in height [see *C. Y. Chan et al.*, 2005].

[26] Our results confirm the rapid decrease in dust concentrations with increasing height reported by previous studies [see *Satake et al.*, 2004] and extend the work conducted by *Nickling et al.* [1999] in the Lake Eyre Basin. They support the use of power or exponential functions to describe the relationship between dust concentrations and height during conditions such as those reported here. This is particularly important for accurate quantification of dust plume loads as discussed by *McTainsh et al.* [2005]. In comparison, approaches such as that used by *Raupach et al.* [1994] that assume a uniform dust concentration from the surface to the dust ceiling height will over estimate atmospheric dust loads as shown by this study.

[27] While results presented by this study support previous findings, the concentrations presented only represent PM10 dust load. As a result, there remains a need to conduct similar dust plume sampling studies which measure total suspended particulate (TSP), as well as other dust size ranges to determine the significance of grain size fractionation within plumes under a wide range of meteorological conditions including thunderstorm outflows. For example, the grain size distribution within dust plumes influences calculation of TOMS absorbing aerosol indices [*Yoshioka et al.*, 2005]. Accordingly, observations of grain size distribution and relative dust loading within plumes offers the potential to improve algorithms using archived TOMS data to resolve historical dust plume characteristics and their affect on radiation transfers. Profile measurements should also be conducted to greater heights with the aim of achieving measured dust concentration profiles through the entire height of dust plumes and at sites where widespread dust entrainment is occurring during sampling.

[28] A major challenge to dust plume research is the ability to accurately define the spatial extent of plumes as most major global dust sources are located in remote and sparsely populated deserts. In far western Queensland, observational data on dust plumes is scarce and of varying quality. Previous studies have interpolated observational data, often from sites several hundred kilometers apart, to define the size of plumes. While this approach provides a general indication of the plumes extent, it can not accurately characterize plume size and location. For example, the edge of a dust plume may lie just beyond an observer's line of sight, but the boundary may be interpolated as being at some midpoint to the nearest neighbor, potentially misplacing the boundary of a plume by >100 km. However, this approach does provide the ability to monitor and map the frequency of dust events not identified by remote sensing, while also being a useful tool for the analysis of historical data on the distribution of dust storms.

[29] By comparison with ground-based observational data, satellite-flown sensors such as MODIS allow accurate definition of the spatial characteristics of dust plumes in remote areas such as the Lake Eyre Basin. *Prospero et al.* [2002] used the TOMS to characterize global dust sources including the Channel Country of the Lake Eyre Basin. They found a surprising lack of dust activity which they attributed to the "old and highly weathered" [terrain] and concluded that "fine particles have long since been blown away" [*Prospero et al.*, 2002, pp. 2–20]. This conclusion is in stark contrast to observation-based studies, including this study, which have documented widespread wind erosion and dust storm activity in the Lake Eyre Basin [*Middleton*, 1984]. This reflects the inability of TOMS to accurately identify shallow dust plumes (<1000 to 1500 m agl.) such as that reported by this study which are common in central Australia.

[30] Using MODIS imagery enhanced by the application of *Miller*'s [2003] algorithm, we have shown through a simple visual assessment that this sensor is well suited to identify the shallow dust plumes typically associated with the passage of trough lines through central Australia. This has allowed demarcation of plume borders and quantification of size. Significantly, this approach identified a previously unknown large dust plume during the event we report. This plume originated from fire scars in the Simpson Desert, to the northwest of our field site, and was not evident in TOMS images of the 19 October 2003 event. This result highlights the potential of MODIS to monitor dust emissions from the Simpson Desert, one of the Southern Hemisphere's largest dust source regions.

[31] Neither TOMS nor MODIS sensors were able to detect the low dust concentrations which at DNP reduced receipt of solar radiation throughout late morning on the 19 October 2003, prior to the arrival of the higher dust concentrations in the regional dust haze. These dusts were only detected by the reduction in solar radiation, highlighting the need to use a wide range of approaches to quantify the physical characteristics of dust events, such as their effect on radiation transfers, which may not appear obvious to observers.

[32] **Acknowledgments.** This study was supported by a University of Queensland Early Career research grant to McGowan (122 4052 47) and an Australian Research Council grant to project DP0559577. The authors are most grateful to members of the October 2003 and 2005 field measurement campaigns for their assistance with the operation of the kite sampling system and Queensland Parks and Wildlife Services for access to facilities at Diamantina National Park. David Neil, Thomas Gill, and one anonymous reviewer are thanked for their constructive reviews of this article.

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