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Laser ceilometer measurements of Australian dust storm highlight need for reassessment of atmospheric dust plume loads

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[1] The wide ranging impacts of atmospheric dust have received much attention over the past two decades. This research has been driven by need to better resolve the roles of dusts in atmospheric processes; biogeochemical cycles, particularly in response to changing land use and climate; and impacts on human health. Global dust emissions are estimated to range from 1000 and 2000 Mt yr^{-1}. These estimates have been derived from sediment budgets based on surface monitoring of dust concentrations, analyses of palaeo-dust deposits and satellite monitoring of dust plumes. However, significant discrepancies remain between estimated dust transport rates and dust deposition measured directly, or constructed from sediment records. Here we present the first surface based laser ceilometer measurements of a major dust plume in eastern Australia, the largest dust source of the Southern Hemisphere. Results indicate that previous estimates of dust plume loads may have been overestimated by up to 120%. We conclude that new research is required to accurately quantify dust plume loads to enable the highest confidence of modelled dust emissions and their impacts, particularly on climate at this time of unprecedented uncertainty of future climate. **Citation:** McGowan, H. A., and J. Soderholm (2012), Laser ceilometer measurements of Australian dust storm highlight need for reassessment of atmospheric dust plume loads, *Geophys. Res. Lett.*, *39*, L02804, doi:10.1029/2011GL050319.

1. Introduction

[2] Accurate quantification of dust plume loads has been a major research challenge due to the often remote locations and harsh environmental conditions associated with large dust storms. In-situ sampling of dust plumes has typically been restricted to tower mounted aerosol samplers confined to heights less than 20 m above the ground surface [*Nickling et al.*, 1999; *Dong et al.*, 2011], while kite flown samplers have provided rare insight into dust concentrations at greater heights [*McGowan and Clark*, 2008]. Retrieval of dust plume loads from satellite flown sensors has met with limited success, more often they have been used to monitor the spatial characteristics of dust plumes and their effects [e.g., *Generoso et al.*, 2008; *Tan et al.*, 2011]. Some insight to particle size, sphericity and atmospheric dust concentrations has been achieved using aerosol optical thickness (AOT) measurements from both surface and satellite flown instruments. In general, this has resulted in qualitative assessments of dust plume "thickness" and/or "dust concentrations" only as indicated by change in atmospheric optical properties. Attempts have been made to link AOT to dust column concentrations, and dust transport budgets for Saharan dusts blown across the Atlantic Ocean have been presented. However, these are reliant on assumptions of aerosol speciation and size of dust grains [*Kaufman et al.*, 2005]. This method is suitable only when dust plumes are well above the ground surface and not obscured by cloud to enable clear distinction between the ground and airborne dust, but is fraught with difficulty [*Kalashnikova and Kahn*, 2008]. Quantification of dust plume loads by this method cannot be applied to regions where dust plumes travel close to the Earth's surface, such as Australia [*McGowan and Clark*, 2008].

[3] Australia is the largest dust source in the Southern Hemisphere with dust emissions estimated to be 61 Mt yr^{-1} [*Ginoux et al.*, 2001]. The main dust source regions are the internally draining Lake Eyre Basin (1.2×10^6 km^2) and the Murray-Darling Basin (1.06×10^6 km^2), which display distinct seasonality with dust emissions occurring in winter-spring and spring-summer respectively [*McTainsh et al.*, 1989]. Dust is entrained from these basins primarily during the passage of vigorous cold fronts. It is then transported in a southeast direction in prefrontal north-westerly winds and post-frontal westerly winds; or to the north-west as south-easterly Trade Winds become established over the continent ahead of the next high pressure system as it approaches from the west [*McGowan et al.*, 2000]. Dust from these basins impacts air quality in Australian cities [*Chan et al.*, 2005]; is deposited in the Southern Ocean affecting marine productivity [*Gabric et al.*, 2010] and in New Zealand, where it is believed to be a major factor in alpine soil formation [*Marx et al.*, 2009].

[4] Quantification of dust emissions from Australia has previously been based on the analyses of marine and lake sediment cores [*Hesse and McTainsh*, 2003; *McGowan et al.*, 2008], but coarse temporal resolution of these records mean that considerable uncertainty remains of dust emissions even at centennial time scales. Event based estimates of dust storm loads over the past 30 years have been calculated from surface measurements of dust concentrations, or empirically developed functions that relate change in visibility to dust concentrations. Dust concentrations at the surface have then been assumed to have held constant throughout the vertical extent of dust plumes [*Knight et al.*, 1995], or to have decreased with height following some power function derived from tower based dust concentration measurements [*Nickling et al.*, 1999; *McTainsh et al.*, 2005]. Using these approaches large dust plumes traveling over

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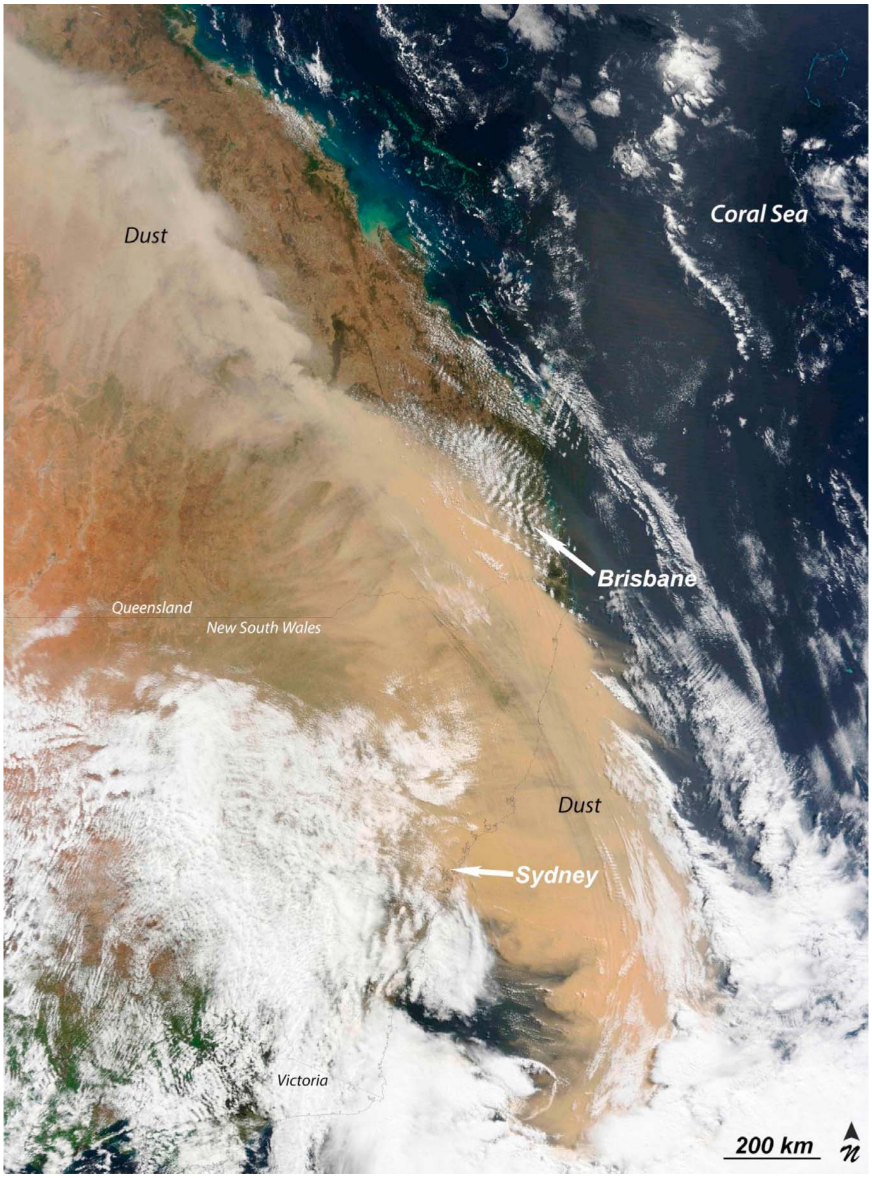

Figure 1. MODIS-Terra base satellite image of the dust storm over eastern Australia 23 September 2009 (Goddard Space Flight Centre).

eastern Australia have been estimated to have had dust loads of 2 to 9 million tons [*Raupach et al.*, 1994; *Knight et al.*, 1995; *McTainsh et al.*, 2005; *Leys et al.*, 2011]. Application of global aerosol models to determine dust loads emitted from Australia have met with limited success. In an intercomparison of 15 global aerosol models within the AeroCom project, the majority of models were found to incorrectly simulate dust transport east from the continent with several models significantly overestimating dust loadings [*Huneeus et al.*, 2011]. As a result, considerable uncertainty remains of dust loads in large east Australian dust storms.

[5] In September 2009 a series of major wind erosion events affected eastern Australia. The largest of these occurred from the 22-24 September when a vigorous cold front entrained dust over a vast area from South Australia to Queensland. The resulting dust plume extended over 3000 km in length from north Queensland to south of Tasmania (Figure 1). This event was believed to have been the largest dust storm to affect Australia for at least 70 years with reports of an estimated dust load of 2.54 to 4 million tons [*Li et al.*, 2010; *Leys et al.*, 2011]. Here we present the first surface based laser ceilometer measurements of this event.

2. Method

[6] The dust plume was monitored on the 23 September 2009 by a Vaisala CL31 laser ceilometer (LiDAR) operated at The University of Queensland, Brisbane, Australia, where dust reduced visibility at the surface to less than 500 m. The CL31 single lens laser ceilometer has been used for aerosol research and found to provide reliable measurements of boundary-layer structure and aerosol plume properties [*Münkel et al.*, 2007; *McKendry et al.*, 2009]. Progressive

attenuation of the CL31 laser beam by aerosols is corrected using the general LiDAR equation. For this event a spatially averaged concentration of particles of <10 μm (PM10) were calculated from measurements provided by four official air quality monitoring sites operating tapered element oscillating microbalance (TEOM) samplers located within 5 km of the CL31. Total Suspended Particulate (TSP) concentrations measurements made by a TEOM sampler were available also from a monitoring station 15 km southeast of the CL31 site. As the dust plume had travelled at least 1000 km to reach these monitoring sites, we believe that the dust plume can be considered to be spatially homogeneous in aerosol concentrations as it travelled over Brisbane.

[7] Pulsed sampling by the CL31 provided 10 m range bins to a height of 7 km every 2 seconds. The laser ceilometer beam was able to penetrate the dust plume during the entire event although unrecoverable attenuation did occur from approximately 12:00 to 15:00 EST coeval with extreme dust loadings (>8000 μg m^{-3}) (Figure 2). In order to calculate total dust loadings for the event, this attenuation period was corrected by modelling the ceilometer reflectivity profile under dust storm conditions. A power function of the laser reflectivity-height relationship was calibrated. using 14 hourly 20-1500 m profiles of ceilometer data after the attenuation period, from 16:00 EST 23 September and 6:00 EST 24 September 2009 when surface TSP ranged between 1962 and 107 μg m^{-3} respectively. The coefficient of determination for this model was 0.93, indicating a statistically significant fit across a range of dust loadings. Modelled CL31 reflectivity with height was calculated using equation (1), where *R(h)* is modelled laser reflectivity at height *h* above the CL31 laser ceilometer; *Rs* is observed surface laser reflectivity and *a* and *b* are the constants 0.426 and 2 respectively. Ceilometer data from 12:00 to 15:00 EST was adjusted to the modelled reflectivity from equation (1) to correct for attenuation.

$$R(h) = R_s e^{-a \ln(h/b)} \qquad (1)$$

[8] A second model was developed based on the relationship between backscatter strength at the lowest retrieval level of the ceilometer of 20 m agl. and average 30 minute PM10 and TSP concentrations measured by monitoring stations from 6:00 to 23 September to 6:00EST 24 September 2009. This data was fitted using a power function with coefficient of determination exceeding 0.99 and 0.98 for average 30 minute PM10 and TSP concentrations respectively. The resulting empirically based relationships between PM10 and TSP concentrations and measured ceilometer backscatter at 20 m agl. were then used to calculate aerosol loads in the dust plume as it passed over the CL31 monitoring site. TSP concentrations with height were calculated using equation (2), where *R(h)* is laser reflectivity at height *h* above the CL31 laser ceilometer and *TSP(h)* is the modelled TSP concentration at height *h* above the CL31 laser ceilometer (μg/m^3). A nominal aerosol cut-off of 37 μg m^{-3} was used to define the dust plume boundary from ambient pre-storm TSP (and PM10) concentrations. This value was found to correspond to the prominent boundary in the CL31 backscatter record between clear air and dust laden air. The quadratic term in equation (2) remains small (<20) for reflectivity values less than 1500 (srad.km.10^5)$^{-1}$, indicating ceilometer reflectivity is approximately linearly proportional to TSP outside of extreme dust loadings.

$$TSP(h) = (2 \times 10^{-5}) R(h)^2 + 0.3008 R(h) + 10 \qquad (2)$$

3. Results

[9] TSP dust plume concentrations calculated using the relationship established between attenuation corrected CL31 backscatter and surface TSP concentrations is shown in Figure 3. Concentrations for PM10 were very similar and therefore not shown. Dust plume load was then calculated up to a nominal dust ceiling height of 1500 m agl. using the CL31 derived TSP values at 30 minute intervals during the passage of the dust plume and a cut-off of 37 μg m^{-3} to define the dust plume boundary. These were compared against vertical dust profile concentrations calculated for the same times using the method of *McTainsh et al.* [2005]. This method uses a power function to calculate the decrease of dust concentrations with height above the ground surface which is assumed to hold true to the ceiling height of the dust plume. It was derived from 10 m tower measurements of dust concentrations made over the surface of a claypan in the Lake Eyre Basin, namely a dust entrainment zone [*Nickling et al.*, 1999]. *McTainsh et al.* [2005] used this method to estimate the dust load of a dust storm that travelled over eastern Australia on 22 October 2002; the most similar event to the 23 September 2009 event reported here to have occurred in the previous 50 years.

[10] Calculated total dust mass for 30 minute intervals from the surface (2 m) to an elevation of 1500 m, a plume width of 20 km and a plume propagation speed of 50 km/h (derived for satellite imagery) are presented in Figure 4 for the CL3l corrected backscatter method. Also shown is the dust load for the same atmospheric volume calculated using analytical integration for the method of *McTainsh et al.* [2005]. The difference in computed TSP dust concentrations with height between the two methods approaches 2.5 fold at the height of the storm and 120% for the entire event. This difference is the result of using an empirically derived function based on dust concentration measurements made in a dust entrainment zone close to the surface to then compute vertical dust concentrations at some distance downwind. Such an approach does not account for the rapid decrease in dust concentrations with increasing height that occur above the surface layer identified by the CL31 measurements (Figure 3). It is also skewed by the very high dust concentrations measured near the surface in the dust entrainment zone where dust concentrations on which this method is based were collected. Therefore, dust plume loads calculated using such empirically based functions derived from dust concentration measurements made near the surface, particularly from in dust entrainment zones, substantially over estimate actual dust plume loads. We believe this may explain uncertainty reported in dust deposition studies compared to measured dust transport rates which may exceed a factor of 10 [*Mahowald et al.*, 2005].

4. Conclusion

[11] Our results highlight the potential of the CL31 laser ceilometer to measure dust loads in major dust storms such as the dust storm of 22 to 24 September 2009 which affected

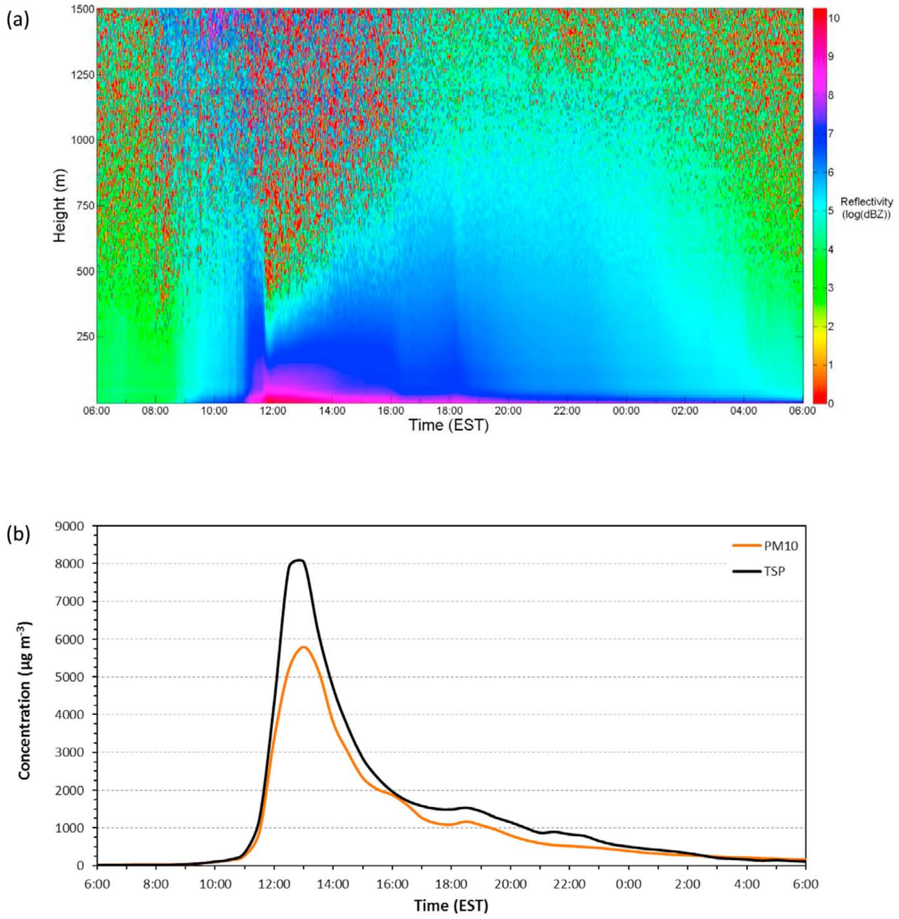

Figure 2. (a) CL31 laser ceilometer backscatter and (b) surface average PM10 and TSP concentrations from 6:00 AM 23 September 2009 to 6:00 AM 24 September 2009.

eastern Australia. Further, they confirm the very significant limitations of using tower mounted dust sampler data collected close to the ground surface to derive empirical functions to calculate dust concentrations throughout the entire height of a dust plume. We have shown that such an approach overestimated the dust load of the 22-24 September 2009 east Australia dust storm by 120% as it passed over the city of Brisbane. Furthermore, this method cannot account for change in the vertical structure of dust plume concentrations caused by elevated dust layers which laser based techniques

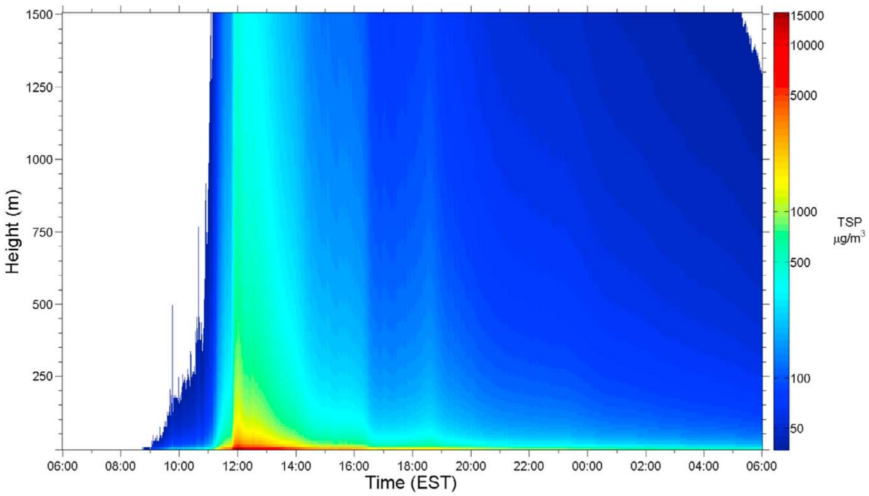

Figure 3. CL31 laser ceilometer derived TSP dust loading from 6:00 AM 23 September 2009 to 6:00 AM 24 September 2009.

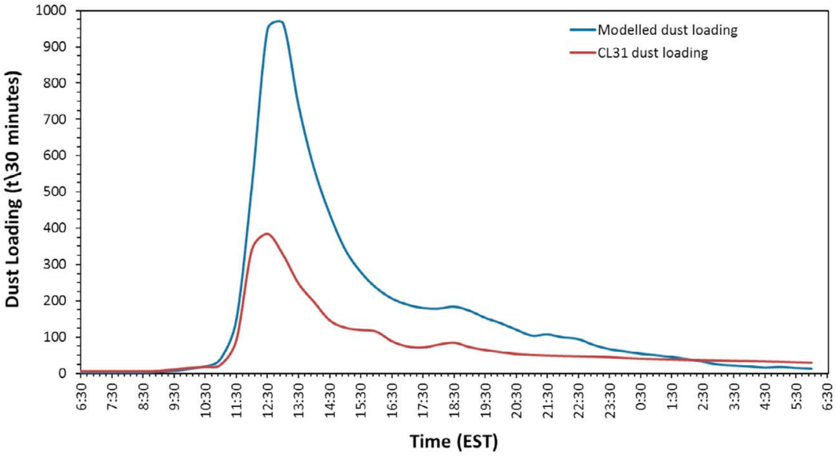

Figure 4. Comparison of CL31 laser ceilometer calculated dust load from 6:30 AM 23 September 2009 to 6:00 AM 24 September 2009 against dust load calculated using the power decay function previously used to estimate dust loads in large east Australia dust storms (see Methods).

as used in this study can [*Zhu et al.*, 2007]. Accordingly there is need to reassess estimates of previous dust plume loads calculated using such empirical functions derived from tower measurements of dust concentrations. For example, *McTainsh et al.* [2005] used such an approach and estimated that the east Australian dust storm of the 22 October 2002 had a dust load of 3.35 to 4.85 Mt. This is similar to *Li et al.*'s [2010] estimated dust load of the 22-24 September 2009 event of 3 to 4 Mt, while *Leys et al.* [2011] who used a time integrated approach to calculate dust flux through a distance perpendicular to the 22-24 September 2009 dust plume, then the method of *McTainsh et al.* [2005] to calculate vertical dust concentration profiles calculated a dust load of 2.54 Mt. Based on the results of this study, these estimates may be at least 120% too large highlighting the need for urgent research to develop robust empirical relationships between surface dust concentrations and measured vertical dust flux profiles, such as presented here using a CL31 laser ceilometer. We believe that this will be fundamental to the improvement of global aerosol models and their ability to model atmospheric dust loads and impacts as reviewed by *Huneeus et al.* [2011].

[12] The implications of this study are significant and far reaching given the wide ranging affects dusts have on climate, biogeochemical cycles, air quality and human health. For example, accurate quantification of atmospheric dust loads are essential for calculating the impacts of dust on climate through modification of radiation transfers, tropospheric temperatures and cloud microphysics [e.g., *Zhu et al.*, 2007; *Li and Min*, 2010; *Rotstayn et al.*, 2011]. They are critical for the development and validation/calibration of robust satellite flown sensor measurements of atmospheric dust loads. These potentially provide the most effective means of obtaining the true spatial and temporal characteristics of dust plumes and their impacts. We plan to undertake further studies of Australian dust plume loads using CL31 laser ceilometers to enable accurate quantification of Australia's contribution to atmospheric dust loads and their downwind impacts.

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