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A visibility and total suspended dust relationship

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HIGHLIGHTS

- An expression relating total suspended dust concentration to meteorology visibility.
- Based on concentration-visibility observations made 10–100 km from eroding sources.
- The new expression is most applicable to data from stations regional to wind erosion.

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ABSTRACT

This study reports findings on observed visibility reductions and associated concentrations of mineral dust from a detailed Australian case study. An understanding of the relationship between visibility and dust concentration is of considerable utility for wind erosion and aeolian dust research because it allows visibility data, which are available from thousands of weather observation stations worldwide, to be converted into dust concentrations. Until now, this application of visibility data for wind erosion/dust studies has been constrained by the scarcity of direct measurements of co-incident dust concentration and visibility measurements. While dust concentrations are available from high volume air samplers, these time-averaged data cannot be directly correlated with instantaneous visibility records from meteorological observations. This study presents a new method for deriving instantaneous values of total suspended dust from time averaged (filter-based) samples, through reference to high resolution PM_{10} data. The development and testing of the model is presented here as well as a discussion of the derived expression in relation to other visibility-dust concentration predictive curves. The current study is significant because the visibility-dust concentration relationship produced is based on visibility observations made 10–100 km from the dust sources. This distance from source makes the derived relationship appropriate for a greater number of visibility recording stations than widely-used previous relationships based on observations made directly at eroding sources. Testing of the new formula performance against observed total suspended dust concentrations demonstrates that the model predicts dust concentration relatively well ($r^2 = 0.6$) from visibility. When considered alongside previous studies, the new relationship fits into the continuum of visibility-dust concentration outcomes existing for increasing distance-from-source. This highlights the important influence that distance to source has on the visibility-dust concentration relationship.

1. Introduction

The visibility distance at the time of observation is a commonly reported atmospheric variable in meteorological data. The presence of smoke, pollution, moisture and suspended mineral dust in the atmosphere can all result in a reduction in visibility. The impact that dust has on visibility is a chief cause of the transport disruptions caused by these aeolian phenomena (Baddock et al., 2013; Tozer and Leys, 2013). For research into aeolian dust, the degree of visibility reduction associated with dust-related weather codes has provided fundamental information on the spatio-temporal characteristics of dust activity. Before the advent of satellite remote sensing, visibility was the dominant variable used in mapping the distribution of wind erosion and dust activity (Orgill and Sehmel, 1976; Middleton et al., 1986; McTainsh and Pitblado, 1987; Goudie and Middleton, 1992).

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Visibility has been widely used in dust studies because these basic data are readily available from thousands of observation stations in the World Meteorological Organisation (WMO) network, and are often available for long time series. Values of the concentration of dust in the atmosphere however represent a more process relevant and precisely quantifiable measure of mineral dust loading than visibility. For instance, dust concentration is the form by which off-site air quality is measured and regulated, such as in maximum concentration for dust particles of all sizes, TSD (Total Suspended Dust), or size-selective e.g., PM_{10} (particles <10 μm) (e.g., Stetler and Saxton, 1996; Neff et al., 2013).

Estimates of dust concentration can be derived from visibility measurements, and several empirical relationships that relate concentration to visibility have previously been put forward (e.g., Chepil and Woodruff, 1957; Patterson and Gillette, 1977; Ben Mohamed and Frangi, 1986; D'Almeida, 1986; Chung et al., 2003; Wang et al., 2008). Such visibility-based estimates of dust concentration have numerous applications in; the mapping of wind erosion (McTainsh et al., 2008; O'Loingsigh et al., 2014), the 'ground truthing' of remote sensing (Wang and Christopher, 2003; Guo et al., 2009), air quality assessments (Ozer et al., 2006; Dagsson-Waldhauserova et al., 2013), the validation of dust activity modelling (Shao et al., 2003, 2007), the estimation of peak loads of large dust storms (Raupach et al., 1994; Chung et al., 2003; McTainsh et al., 2005; Leys et al., 2011) and for better understanding the effects of suspended mineral aerosols on the radiative budget (e.g., Sokolik et al., 2001; Satheesh and Moorthy, 2005).

The various empirical expressions that relate visibility and dust concentration have been found to differ between studies (Patterson and Gillette, 1977; Ben Mohamed and Frangi, 1986; Dayan et al., 2008; Shao et al., 2007; Wang et al., 2008). For such expressions to be useful in dust-atmospheric studies, it is important that this variability be understood. Furthermore, so that accurate estimates of dust concentration can be produced from visibility, it is also important that the most appropriate expression be applied for a given visibility observation location. The need to understand the relationship between visibility and dust concentration as part of wind erosion research has long been recognised (e.g., Ette and Olorode, 1988; Ackerman and Cox, 1989; Shao et al., 2003). In particular, two classic studies in the United States, those of Chepil and Woodruff (1957) and Patterson and Gillette (1977) used empirical fits of observed data to describe the relationship

$$C_m = A/V^{\gamma} \tag{1}$$

with

$$A = C_m V \tag{2}$$

where C_m is total mass concentration, A is a term related to the effects on extinction due to particle size distribution, γ a constant and V is observed visibility. These studies demonstrate the suitability of the power relationship in describing the relationship between visibility and dust concentration. Patterson and Gillette (1977) noted the variety in the values of constant terms put forward to relate concentration and visibility. They attributed the lack of a single applicable term to variations in dust particle size distributions (PSD) between both dust events and study areas. PSDs can be highly variable between wind erosion episodes, and are controlled chiefly by source soil characteristics, wind erosivity and the distance of observation point from the eroding source (El-Fandy, 1953; Chepil and Woodruff, 1957).

It is noteworthy that both the Chepil and Woodruff (1957) and Patterson and Gillette (1977) studies were based on visibility and dust concentration measurements made at, or very close to, eroding sources. This constrains the application of their visibility and dust concentration functions because worldwide, the most readily available source of visibility data is from WMO meteorological stations which are impacted by dust, but are not located directly at the eroding source. An expression describing the visibility and dust concentration relationship at a greater distance from source will therefore be more appropriate for these locations. Following terminology from the transport distance model of Tsoar and Pye (1987), dust within a few kilometres from its source can be termed local, while >10 km dust can be regarded as regional (see also Cattle et al., 2009).

The aim of this study was to produce a relationship between visibility and total suspended dust concentration for dust events observed at a regional scale (10–100 km) from source. A new method is presented here for obtaining instantaneous dust concentrations from time-averaged data, to allow their correlation with instantaneous visibility observations.

2. Methods

2.1. Background to methods

The most reliable source of near-surface dust concentration data is field sampling using active samplers, such as vacuum pump-based devices (e.g., Nickling and Gillies, 1993; Nickling et al., 1999), or from networks of high volume samplers (HVS) (Leys et al., 2008). Such equipment however is costly, labour intensive to operate and largely impractical for widespread spatial monitoring of dust, especially in remote areas. A more widely applicable approach for wind erosion monitoring involves the use of DustTrak® (TSI, St. Paul, MN, USA) samplers (Leys et al., 2008). DustTrak instruments provide real time dust concentrations, but only for particulates with an aerodynamic size of <10 μm (PM_{10}). This size selectivity makes such instruments suitable for monitoring air pollution and the associated effects that fine particles have on human health. While PM_{10} is being successfully used for wind erosion mapping (e.g., Wang et al., 2008), wind erosion events also entrain coarser particles than this size. As a result, PM_{10} does not fully characterise all dust events, or describe the full size range of suspended particles contributing to atmospheric mass loadings (Tsoar and Pye, 1987; Lawrence and Neff, 2009; Neff et al., 2013). It is preferable therefore for measurements of dust concentration for a given dust event to be calculated from the entire range of particle sizes present.

High volume samplers (HVS) collect the total range of particles in the air, but as the resultant dust concentration is time-integrated over the total sampling period for which the HVS was operating (generally 24 h), these time-averaged data have a poor relationship with time-averaged visibility. The focus of the current study is to use the high resolution time series of PM_{10} dust concentration measured with a DustTrak (C_{DT}) to calculate the equivalent total dust concentration measured with a co-located HVS (C_{HVS}) for a point in time (C_{HVSi}), which can then be correlated with the concurrent visibility. The resultant relationship is referred to from here on as the Visibility-Total Suspended Dust (V-TSD) model.

2.2. Site and sampling details

A HVS and a DustTrak instrument, operated by the New South Wales Office of Environment and Heritage (OEH) and Griffith University, provide two forms of dust concentration data at Buronga, New South Wales (34.17°S, 142.20°W). The HVS at this site constitutes the longest rural record of dust concentration in Australia, monitoring dust in the intensively cultivated Mallee region for over 24 years (Leys et al., 2008). For dust events, the HVS collects the full range of suspended particles on glass fibre filter papers (Whatman