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Diurnal patterns of blowing dust on the Llano Estacado

John E. Stout

USDA-Agricultural Research Service, Lubbock, TX, USA

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ABSTRACT

Hourly dust data was collected in Lubbock, Texas, from January 1, 2003, to January 1, 2008. Diurnal patterns of dust concentration were computed by averaging hourly values associated with a given time of day for all days within the 5-yr sampling period. Results suggest that the overall diurnal pattern is characterized by relatively high dust concentrations during the day and relatively low values at night and in the early morning. Diurnal patterns of blowing dust are influenced by daily variations of key climatic factors. Generally, one finds relatively strong winds during the day and lighter winds at night. The morning increase in wind speed is associated with the rising sun, which produces thermal instability and enhances the mixing of high momentum winds from the upper levels of the atmosphere to the surface layer. Solar radiation can also reduce the critical threshold by drying the soil surface. Diurnal patterns of blowing dust were also computed separately for each of the four seasons. The most conspicuous change of the diurnal pattern occurred in the summer where the difference between peak afternoon values and early morning values was considerably less than that of other seasons.

1. Introduction

Gravimetric sampling is an internationally accepted method for measuring dust concentration and forms the basis for regulation of ambient particulate matter concentrations under the U.S. Federal Clean Air Act (USEPA, 1999). The procedure is quite simple: typically, air is pulled through a filter at a controlled rate and the mass of collected dust is determined by comparing the mass of the filter before and after the sample is collected. The total volume of air that passed through the filter is then divided into the mass of collected dust to form the dust concentration. In most cases, dust samples are collected over a period of 24 h and thus represent daily averages.

Daily samples can provide valuable information about long-term changes of ambient dust levels over periods such as years or decades (Stout and Lee, 2003). However, the 24-hr averaging process masks important information about short-term or diurnal variations of dust concentration. For example, a daily sample does not provide information regarding the magnitude of peak dust concentrations during the day, nor does it provide information about the time of occurrence of peak values. Yet these peak values are important, especially with regard to health issues or hazards associated with reduced visibility (Brown et al., 1935; Sidwell, 1938; Hagen and Skidmore, 1977).

Past investigations of blowing dust have shown that there is a tendency for dust storms to occur preferentially during the day. For example, an investigation in India found that "hourly frequencies" of blowing dust tend to be at a minimum in the early morning and the frequency of occurrence increases thereafter to reach a maximum between 16:00 and 18:00 (Sreenivasaiah and Sur, 1937). An analysis of hourly visibility observations recorded at U.S. weather stations showed that higher frequencies of airborne dust occurred in the afternoon from 12:00 to 20:00, during the period of maximum thermal instability (Orgill and Sehmel, 1976). In West Africa, researchers found that the diurnal dust cycle produces a reduction of visibility during daytime hours (N'Tchayi Mbourou et al., 1997). Chaboureau et al. (2007) analyzed satellite observations and found that dust coverage over the Sahara follows a well-defined diurnal cycle, typically reaching a peak at around 15:00.

In a related study of blowing sand, Stout (2010) found a strong tendency for the occurrence of blowing sand during the day compared to night. Measurements of saltation activity taken in West Texas showed that sand transport tends to occur more frequently during daylight hours with a peak in saltation activity occurring in the afternoon between 14:00 and 15:00. Similar results were found using similar methods by Yang et al. (2013) in China and Gillies et al. (2013) in Antarctica. Yang et al. (2013) showed that the diurnal pattern of blowing sand can vary with the seasons and Gillies et al. (2013) demonstrated the importance of latitude and shifting seasonal environmental conditions on daily

E-mail address: john.stout@ars.usda.gov.

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patterns of blowing sand, especially at high latitudes.

None of the aforementioned studies were based on actual measurements of dust concentration; rather they were based on observations of the frequency of blowing events or observations of visibility provided by human weather observers or satellite imagery. These indirect observations of blowing dust likely provide an adequate surrogate for direct measurements of dust concentration but one naturally wonders if the normal daily pattern of dust concentration follows a similar diurnal pattern.

In the present study, attempts were made to investigate diurnal patterns using direct measurements of ambient dust concentration provided by a TEOM (Tapered Element Oscillating Microbalance) sampling system. Instruments such as the TEOM can provide valuable information regarding temporal patterns of blowing dust over periods as short as 10 min to one hour. Since ambient dust concentration can change rapidly, such high-frequency sampling can provide valuable insight into the dynamic nature of dust events.

2. Physical setting

Since the goal of this experiment was to record temporal variations of dust concentration, the specific location of the sampling site was not critical. The choice of a sampling site was made partly out of consideration for the availability of power to run the sampling system and the desire for a sampling location that would provide a representative sample of regional dust conditions on the high plains of the Llano Estacado.

Briefly, the Llano Estacado is an elevated plain located at the southern end of the Great Plains of North America (Cummins, 1892; Holliday, 1990). Called by various names including the Staked Plains or the Southern High Plains, this immense plateau has long been recognized as a physiographic region that is sufficiently distinct from surrounding areas to warrant separate identification (Powell, 1895). The key distinguishing feature is its remarkably level surface that appears to the casual observer to be absolutely flat and featureless (Fenneman, 1931). Prominent escarpments along its outer margins help define the boundaries of this vast region (Fig. 1).

The Llano Estacado has been significantly impacted by production agriculture. The native grass cover that once protected this region from frequent high winds has been replaced, for the most part, by highly erodible cropland (Hall and Valastro, 1995). Today, the skies above the Llano Estacado are occasionally filled with dust, especially during the late winter and early spring (Stout, 2001).

3. Methods

A TEOM (model 1400a) sampling system was mounted on an elevated platform on the roof of the USDA-ARS Plant Stress and Water Conservation (PSWC) Laboratory located in the largest city on the Llano Estacado – Lubbock, Texas (33 35′ 37″ N, 101 53′ 52″ W). Overall, the sampling inlet was 7.0 m above the surrounding ground surface and 2.2 m above the flat roof of the PSWC Laboratory. Dust is primarily generated in the highly erodible cropland outside of the city limits of Lubbock and is transported across the city by winds blowing from various directions. A portion of this dust is blown across the PSWC Lab where dust concentration is measured and recorded.

The TEOM is a commercially available sampling system that measures dust concentration by continuously measuring the mass of dust collected on a small filter. Mass is not measured using a conventional mass balance rather it is measured by detecting the change in natural frequency of a hollow tapered cylinder on which the filter is mounted (Patashnick and Rupprecht, 1991).

The tapered element at the heart of the mass detection system is essentially a hollow cylinder with the wide end of the cylinder fixed while the narrow end is free to oscillate in response to an applied electric field (Patashnick and Hemenway, 1969). An exchangeable Teflon-coated glass fiber filter is mounted at the tip of the free end and the sample stream is drawn through this filter at a constant flow rate of 3 L per minute. As the loading on the filter changes, the vibrational frequency of the tapered element naturally changes providing an inertial measure of the mass of collected dust (Patashnick et al., 2002). The mass of collected dust is measured every two seconds and these readings are then smoothed to reduce noise. Dust concentration is computed by dividing the collected mass by the volume of air that passed through the filter.

Internal temperatures are controlled to minimize the effects of changing ambient conditions. The sample stream is preheated to 50 °C before entering the mass transducer so that the sample filter always collects under conditions of low relative humidity. All measurement, flow, and temperature functions of the instrument are controlled by a dedicated microcontroller, which is mounted within an insulated enclosure that is maintained at a controlled temperature.

Sampling began January 1, 2003 and extended to January 1, 2008, a period of five years. An attempt was made to obtain a continuous record, however, the complexity of the TEOM system and the potential for failure led to occasional gaps in the data record. Steps were taken to minimize data loss by keeping replacement parts on hand so that repairs could be made rapidly. Failure of the main sampling pump was the primary cause of data loss; a total of three pumps were replaced over the course of the 5-yr sampling period. Loss of power at the PSWC Laboratory was responsible for other occasional shutdowns and data loss. Despite these and other minor interruptions, data collection was fairly continuous. Overall, the system collected data for a total period 43,825 h of which data was lost for only 327 h; thus, hourly values were obtained successfully for 99.3% of the time.

In addition to the collection of hourly dust data, hourly meteorological data was collected in an open field immediately to the west of the PSWC Lab. Here a 10-m meteorological tower was equipped with an array of sensors capable of measuring rainfall, relative humidity, air temperature, soil temperature, solar radiation, wind speed and direction. Wind speed was measured at two heights with fast-responding propeller-type anemometers mounted at 2 m and 10 m. Rainfall was measured with a tipping-bucket rain gauge with a resolution of 0.1 mm per tip. Air temperature, relative humidity and solar radiation sensors were mounted at a height of 2 m above the mowed native grass surface that surrounds the tower. All meteorological variables were sampled each second and averaged hourly.

4. Results and discussion

The final raw data set consists of five years of hourly dust concentration values along with a five-year record of hourly meteorological measurements. Combined, these data provide a fairly detailed record of dust concentration and associated climatic conditions from January 1, 2003, to January 1, 2008.

An annual summary of climatic conditions and dust levels is presented in Table 1. For each calendar year, approximately 8760 hourly values were averaged to obtain a single annual average value of dust concentration. Similarly, annual values of climatic factors such as wind speed, relative humidity, and rainfall were computed for each of the five years. These results suggest that 2003 had the overall highest annual dust concentration of 78 $\mu g/m^3$ whereas the second highest annual average of 54 $\mu g/m^3$ was measured in 2006. The lowest annual dust concentration of 41 $\mu g/m^3$ was measured in 2007. Overall annual dust concentration values remained within a range of 41–78 $\mu g/m^3$, which is only slightly higher than the range