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The characterization of haboobs and the deposition of dust in Tempe, AZ from 2005 to 2014

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ABSTRACT

Dust storms known as 'haboobs' occur in Tempe, AZ during the North American monsoon season. This work presents a catalog of haboob occurrence over the time period 2005–2014. A classification method based on meteorological and air quality measurements is described. The major factors that distinguish haboobs events from other dust events and from background conditions are event minimum visibility, maximum wind or gust speed, and maximum PM_{10} (particulate matter with aerodynamic diameters of 10 μm or less) concentration. We identified from 3 to 20 haboob events per year over the period from 2005 to 2014. The calculated annual TSP (total suspended particulate) dry deposition ranged from a low of 259 kg ha^{-1} in 2010 to a high of 2950 kg ha^{-1} in 2011 with a mean of 950 kg ha^{-1} yr^{-1}. The deposition of large particles ($PM_{>10}$) is greater than the deposition of PM_{10}. The TSP dry deposition during haboobs is estimated to contribute 74% of the total particulate mass deposited in Tempe.

1. Introduction

During the North American monsoon season Phoenix, Arizona is reported to experience 2–7 dust storms per year (Raman et al., 2014). Metropolitan Phoenix is a semiarid urban area with a population of 4.2 million (U.S. Census Bureau, 2013); the region has low annual precipitation ranging from 83 to 240 mm yr^{-1}, and high temperatures with an average of 61 days per year exceeding 40 °C (U.S. NOAA, 2015). The monsoon season is now defined by the National Weather Service (NWS) as June 15 to September 30 (similar to the 'hurricane season'; U.S. NWS, 2016); it is characterized by a change in the general upper atmosphere circulation and an average dew point >12.7 °C. The most intense kind of dust storms Phoenix experiences are fostered by monsoon weather through the interaction of atmospheric water and sunlight. In the vicinity of Phoenix, thunderstorm clouds build during the day as moisture-laden air aloft from the Gulf of Mexico and the Pacific Ocean (Sorooshian et al., 2011) is energized by sunlight and rises within the clouds. In the evening, the supply of heated, moist air decreases and there is a net downward movement of moisture as precipitation. Over the semiarid desert, the falling hydrometeors evaporate significantly before reaching the surface; this process cools the surrounding air, causing it to become denser and to displace the dry air below. These powerful downdrafts can produce high winds and turbulent convection over the landscape. These thunderstorm outflows can result in a particular kind of dust storm: an advancing wall of dust hundreds of meters high and tens of kilometers long known as a haboob, from the Arabic *habūb* 'blowing furiously/strong wind' (see Fig. 1 and Fig. 2; Idso, 1976; Idso et al., 1972; Sutton, 1925).

Haboobs occur in only a few parts of the world, including northern Africa (Roberts and Knippertz, 2012; Sutton, 1925), the Arabian Peninsula (Membery, 1985; Miller et al., 2008), and northwest India (there known as *kālī andhī* or *andhī* 'darkening, blinding storm'; Goudie and Middleton, 2000; Joseph, 1982; Joseph et al.,

Abbreviations: AQS, United States Environmental Protection Agency's Air Quality System; ADEQ, Arizona Department of Environmental Quality; BLDU, blowing dust; $c(PM_{10})$, mass concentration of PM_{10}; $c(PM_{2.5})$, mass concentration of $PM_{2.5}$; c(TSP), mass concentration of TSP; DS, dust storm; DU, widespread dust; EPA, United States Environmental Protection Agency; HZ, haze; $J_d(PM_{10})$, PM_{10} dry deposition flux; J_d(TSP), TSP dry deposition flux; KPHX, weather station at Phoenix Sky-Harbor International Airport; MADIS, Meteorological Assimilation Data Ingest System; MCAQ, Maricopa County Air Quality; METAR, Meteorological Terminal Air Report; MFCD, Maricopa County Flood Control District; NAAQS, United States National Ambient Air Quality Standards; NOAA, United States National Oceanic and Atmospheric Administration; NWS, United States National Weather Service; QCLC, Quality Controlled Local Climatological Data; SQ, squall; TS, thunderstorm; *VIS*, visibility; v_{WG}, wind and/or gust speed; WBAN, United States Weather-Bureau-Army-Nav.

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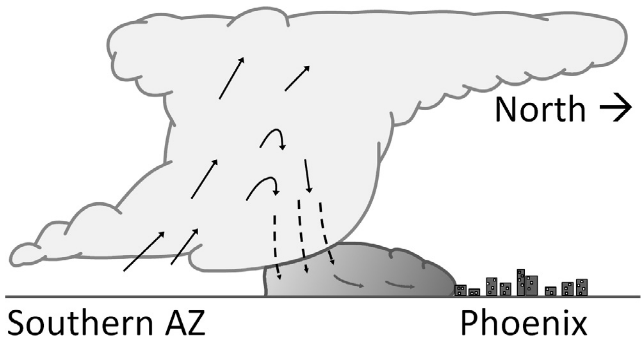

Fig. 1. Conceptual diagram of haboob initiation in Arizona, including a convective thunder storm (anvil cloud) and down drafts (dashed arrows) that push a wall of dust ahead of the storm. Gray shading of the haboob is meant to emphasize the dust font. Note: Not all haboobs originate south of Phoenix and the diagram is not to scale.

1980). In the US, haboobs have been reported in Arizona and Texas (Brazel and Nickling, 1986; Chen and Fryrear, 2002; Idso et al., 1972; Warn and Cox, 1951). In Arizona, haboobs can substantially decrease visibility to less than 1 km (Nickling and Brazel, 1984). Wherever haboobs occur, they are quite intense relative to other types of dust events (Roberts and Knippertz, 2012) and have comparatively short lifetimes of 1–4 h in any single location (Brazel and Nickling, 1986; Sutton, 1925).

1.1. Impact on air quality

Haboobs can have a significant impact on the amount of atmospheric particulate matter (PM) in the metropolitan Phoenix area (Clements et al., 2014, 2016; Lei and Wang, 2014). Particulate matter is classified by size fractions; PM_{10} and $PM_{2.5}$ are particulate matter with aerodynamic diameters of $\leqslant 10\ \mu m$ and $\leqslant 2.5\ \mu m$, respectively. The size of PM determines the extent of penetration into the respiratory tract and therefore the adverse health risk: PM_{10} can penetrate to the bronchi passages while the finer and more hazardous fraction, $PM_{2.5}$, is able to penetrate fully into the alveolar recesses of the lungs (WHO, 2006). Their mass concentrations, $c(PM_{10})$ and $c(PM_{2.5})$ respectively, both increase during haboobs; peak $c(PM_{10})$ can be in the thousands of $\mu g\ m^{-3}$ for several hours and $c(PM_{2.5})$ increases although to a somewhat lesser extent (*e.g.*, tens to hundreds of $\mu g\ m^{-3}$; Clements et al., 2013; Lei and Wang, 2014). The U.S. National Ambient Air Quality Standards (NAAQS) are 12 $\mu g\ m^{-3}$ for $c(PM_{2.5})$ and 150 $\mu g\ m^{-3}$ for $c(PM_{10})$ over a 24-h period (U.S. Environmental Protection Agency (EPA), 2013). High haboob-derived PM concentrations which exceed the EPA standards are typically excluded from regulatory decisions regarding NAAQS compliance since they are high-wind, natural-events that are "not reasonably controllable or preventable" and which overwhelm even stringent dust control measures (ADEQ, 2015; U.S. EPA, 2006, 2007).

Besides the impact on air quality, another impact of haboobs is particle deposition. In the early 1970s, rooftop dust deposition in Tempe was reported to be 540 $kg\ ha^{-1}\ yr^{-1}$, 12% of which was attributed to two haboobs (Péwé et al., 1981). Particle deposition in semiarid regions of southern California and Nevada (which do not experience haboobs) has been reported to be substantially lower, 20–200 $kg\ ha^{-1}\ yr^{-1}$, over the period 1983–2000 (Reheis, 2006).

Identification of haboobs in metropolitan Phoenix from historical data can be challenging since meteorological and radar records often are inadequate in temporal and spatial resolution to capture these short-lived phenomena (Raman et al., 2014). Reliance upon visibility and wind speed data alone can lead to false-positive haboob identifications since these events can occur with several meteorological phenomena. Recent high-resolution modelling efforts have also shown that it is possible to predict the timing and location of haboob events and have presented results simulating a particularly large haboob that occurred in July of 2011 (Vukovic et al., 2014). The METAR (Meteorological Terminal Air Report) weather condition codes provide dust information (*e.g.*, BLDU, blowing dust) but do not distinguish between general dust events and the more intense haboobs. Given the sparse data on dust deposition in the southwestern US, and the difficulty of identifying past haboob events, the magnitude of annual haboob deposition and the impact of that dust on urban ecosystems

Fig. 2. Photograph from an airplane of a haboob advancing northward in Tempe, AZ on August 25, 2015; photo credit: A. Anbar.