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The impact of drought on ozone dry deposition over eastern Texas

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HIGHLIGHTS

- Ozone dry deposition velocities were simulated for years with and without drought.
- Seasonal patterns reflected variations in stomatal and non-stomatal conductances.
- Ozone dry deposition velocities for forests declined substantially under drought.
- Increases in vapor pressure deficit and temperature reduced stomatal conductance.
- Predicted surface ozone concentrations were higher under drought conditions.

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ABSTRACT

Dry deposition represents a critical pathway through which ground-level ozone is removed from the atmosphere. Understanding the effects of drought on ozone dry deposition is essential for air quality modeling and management in regions of the world with recurring droughts. This work applied the widely used Zhang dry deposition algorithm to examine seasonal and interannual changes in estimated ozone dry deposition velocities and component resistances/conductances over eastern Texas during years with drought (2006 and 2011) as well as a year with slightly cooler temperatures and above average rainfall (2007). Simulated area-averaged daytime ozone dry deposition velocities ranged between 0.26 and 0.47 cm/s. Seasonal patterns reflected the combined seasonal variations in non-stomatal and stomatal deposition pathways. Daytime ozone dry deposition velocities during the growing season were consistently larger during 2007 compared to 2006 and 2011. These differences were associated with differences in stomatal conductances and were most pronounced in forested areas. Reductions in stomatal conductances under drought conditions were highly sensitive to increases in vapor pressure deficit and warmer temperatures in Zhang's algorithm. Reductions in daytime ozone deposition velocities and deposition mass during drought years were associated with estimates of higher surface ozone concentrations.

1. Introduction

Dry deposition is broadly defined as the transport of gaseous and particulate species from the atmosphere by turbulent transfer to surfaces in the absence of precipitation (Seinfeld and Pandis, 2012). Dry deposition is estimated to account for 20–25% of total ozone removal from the troposphere globally (Lelieveld and Dentener, 2000; Wild, 2007). On a regional level in Texas, dry deposition represents the most important physical removal mechanism for ozone during the warm spring through early fall seasons (McDonald-Buller et al., 2001); therefore, accurate estimates of ozone dry deposition are required for air quality modeling and management. The magnitude of ozone dry deposition is controlled by the combined effects of all removal pathways, which include stomatal and non-stomatal uptake to vegetation and deposition to soils or any other external surface (Hogg et al., 2007; Fares et al., 2010, 2012). The relative importance of stomatal and non-stomatal removal varies with vegetation types and changes diurnally and seasonally (Lamaud et al., 2009; Rannik et al., 2012; Fares et al., 2012; Neirynck et al., 2012). Stomatal uptake is considered to be the main mechanism through which ozone-associated damage occurs within plants (UNECE, 2004). Exposure to elevated ozone concentrations leads to biochemical and physiological changes including inhibition of carbon assimilation from photosynthesis that can result in reduced agricultural yields (Wittig

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et al., 2009; Mills et al., 2011; Fares et al., 2013). Understanding ozone deposition, especially stomatal uptake, is thus important for risk assessment in order to protect vegetation and ecosystems from ozone damage (Pleijel et al., 2007; Mills et al., 2011). However, despite its importance in various applications, dry deposition remains one of the major uncertainties in modeling ozone in the troposphere (Wild, 2007).

Long-term dry deposition flux measurements over relatively large areas remain difficult (Wesely and Hicks, 2000), and a suitable model parameterization is needed. Dry deposition is often treated as a first-order removal mechanism, where a characteristic dry deposition velocity V_d (ratio of deposition flux to concentration) is used to describe the process. A number of models available to estimate V_d employ a resistance approach analogous to Ohm's law in electrical circuits. For example, the widely used Wesely scheme (Wesely, 1989) and the more recently developed Zhang scheme (Zhang et al., 2003) both treat the canopy as a single layer (or big leaf model). Other models apply a multi-layer approach to account for the vertical distribution of leaf area within the canopy (Finkelstein et al., 2000; Meyers et al., 1998). For example, the Clean Air Status and Trends Network (CASTNET) is a U.S. national air quality monitoring work that uses a multi-layer model (MLM) to simulate dry deposition velocities (Clarke et al., 1997). Validation of dry deposition models against observations, as well as intercomparisons between models, have been conducted in numerous studies (Zhang et al., 2002; Michou et al., 2005; Schwede et al., 2011; Park et al., 2014; Val Martin et al., 2014; Wu et al., 2011), yet significant uncertainties remain (Pleim and Ran, 2011).

Drought is a recurring phenomenon in many regions of the world (Sheffield and Wood, 2012; Melillo et al., 2014). Within the United States, Texas is among the regions that have faced tremendous challenges from recent droughts, for example, in 2011 with record agricultural losses and wildfires (Fannin, 2011). Drought associated high temperatures and soil moisture deficits have the potential to suppress stomatal conductances, and thus lead to reductions in dry deposition and higher surface ozone concentrations (Pio et al., 2000; Solberg et al., 2008). Concurrent effects of ozone and drought on vegetation can be synergistic or antagonistic, depending on the sequence of events and various environmental and phenotypical factors (Bohler et al., 2015). It is critical to understand the effects of drought on ozone dry deposition in Texas and other regions where drought is a frequent occurrence and where requirements exist to achieve and maintain attainment with National Ambient Air Quality Standards (NAAQS).

The purpose of this study was to investigate the impacts of drought on ozone dry deposition during the daytime by exploring interannual variations in predicted dry deposition velocities and associated component resistances in eastern Texas. The Comprehensive Air Quality Model with Extensions (CAMx; ENVIRON, 2014) is a photochemical dispersion model that is currently being used by the state of Texas for NAAQS attainment demonstrations. The dry deposition sub-module within CAMx that is based on the algorithm of Zhang et al. (2003) was applied to simulate ozone dry deposition velocities during years with moderate to exceptional drought (2006 and 2011) as well as a year with slightly cooler temperatures and above average rainfall (2007).

2. Methodology

2.1. Zhang's dry deposition algorithm

Zhang's dry deposition algorithm (Zhang et al., 2003) adopts the resistance method to simulate dry deposition velocity, V_d, which is determined as the reciprocal of the sum for aerodynamic resistance (R_a), quasi-laminar resistance (R_b), and overall canopy resistance (R_c) as follows:

$$V_d = (R_a + R_b + R_c)^{-1} \tag{1}$$

The parameterizations of R_a and R_b are generally similar among different models (Wesely and Hicks, 1977; Zhang et al., 2003; Wu et al., 2011). Daytime ozone deposition over vegetated regions is mainly limited by the overall canopy resistance R_c in Zhang's algorithm (Zhang et al., 2002), which is parameterized as:

$$\frac{1}{R_c} = \underbrace{\frac{1-W_{st}}{R_{st}+R_m}}_{G_{st}} + \underbrace{\frac{1}{R_{cut}} + \frac{1}{R_{ac}+R_g}}_{G_{ns}} \tag{2}$$

The first term of the right side of Eq. (2) represents the stomatal deposition pathway; G_{st} is defined as the stomatal conductance. It should be noted that G_{st} as defined here is not the reciprocal of the stomatal resistance (R_{st}); instead, it accounts for the mesophyll resistance (R_m) and the stomatal blocking (W_{st}) under wet conditions. For ozone, R_m is negligible and R_{st} controls the stomatal pathway. R_{st} is affected by various environmental factors including temperature, solar radiation, relative humidity and is simulated as:

$$R_{st} = 1/[G_s(PAR)f(T)f(VPD)f(\psi)D_i/D_v] \tag{3}$$

The functions $G_s(PAR)$, $f(T)$, $f(VPD)$, $f(\psi)$ represent the stomatal response to photosynthetically active radiation (PAR), air temperature T, leaf-air vapor pressure deficit VPD, and water stress ψ (correlated with solar radiation). D_i/D_v refers to the ratio of the diffusivities of the gas-phase species (i.e. ozone) to water vapor.

The last two terms of the right side of Eq. (2) together represent the non-stomatal deposition pathways; G_{ns} represents the non-stomatal conductance. Zhang's algorithm utilizes the leaf area index (LAI) in the calculation of the in-canopy aerodynamic resistance R_{ac} and cuticular resistance R_{cut} as follows:

$$R_{ac} = R_{ac0} LAI^{0.25} \Big/ u_*^2 \tag{4}$$

$$R_{cutd} = R_{cutd0} \Big/ \left(e^{0.03RH} LAI^{0.25} u_*\right) \quad \text{(dry condition)} \tag{5}$$

$$R_{cutw} = R_{cutw0} \Big/ \left(LAI^{0.5} u_*\right) \quad \text{(dry condition)} \tag{6}$$

where the resistances with zero in the subscript are reference values as described by Zhang et al. (2003). Higher LAI values would increase the in-canopy transport resistance but provide greater leaf area for cuticle deposition. Friction velocity (u_*) is negatively correlated with both R_{ac} and R_{cut}. R_g represents the ground resistance for ozone. The value of R_g for ozone is assumed to be constant at 200 s/m for all vegetated surfaces.

2.2. WRF configuration

Meteorological inputs are essential for estimating dry deposition. In this study, the Weather Research and Forecasting (WRF) Model (version 3.4.1) was used to simulate meteorological conditions over eastern Texas during the growing seasons (April–October) for 2006, 2007 and 2011. These years exhibited moderate to exceptional drought conditions (e.g. 2006, 2011) as well as periods with above average precipitation (e.g. 2007; Huang et al., 2014). Temperature, precipitation, and wind speed patterns during the three years are described in the Supplemental Information. During 2006, on average, Texas had slightly above normal temperatures and below normal rainfall. Within eastern Texas, drought conditions commonly ranged between moderate and severe with