Comparison of Different Algorithms for Stomatal Ozone Flux Determination from Micrometeorological Measurements

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Abstract The determination of stomatal ozone fluxes is essential to assess the potential damage to plants due to ozone uptake. This parameter is not accessible directly with measurements, but can be deduced through algorithms using observational data. Total ozone fluxes and water vapour fluxes are generally used. Water vapour fluxes give an indication on stomatal aperture, which is the controlling factor of ozone uptake by vegetation. In this work, a series of observations made during the growing season over an onion field are used to show the equivalence of two algorithms found in the literature to derive ozone stomatal fluxes and both based on the similarity between ozone stomatal fluxes and water vapour stomatal fluxes. One of these algorithms uses the Penman-Monteith approach, where the water vapour pressure deficit is calculated using air temperatures; the second calculates, with another formulation, the water vapour deficit from the leaf temperature. The two approaches lead to the same results if applied properly, as shown in this work, both theoretically and numerically.

Keywords ozone deposition · stomatal resistance

1 Introduction

Stomata are essential organs for plants. These microscopical pores located at the surface of the leaves are responsible for all gaseous exchange processes occurring between air and vegetation. Oxygen and CO₂ are both absorbed and released for respiration and photosynthesis; water vapour is released to regulate the leaf temperature and the water flow through the plant; several volatile organic compounds like isoprene, terpenes and carbonyl compounds produced by the plants are released to air through the stomata (Guenther, Zimmerman, & Harley, 1993). Also air pollutants penetrate into the plant tissues through the stomata. Special attention is given to ozone, which causes harmful effects and crop yield losses (see e.g., De Temmerman, Vandermeiren, & Guns, 1992; Fuhrer & Ackerman, 1999; Fumagalli, Ambrogi, & Mignanego, 2001); in some cases, visible damage is observed, especially in onion (Engle, Gabelman, & Romanowski, 1965; Rist & Lorbeer, 1983).

Stomatal uptake is the only pathway through which ozone molecules penetrate the tissues of the leaves (Kerstiens & Lendzian, 1989; Monteith & Unsworth, 1990); the cuticula is likely to play a negligible role as it is covered by protective waxes. A reliable stomatal ozone fluxes determination method is thus essential to estimate the potential risk for vegetation exposed to ozone pollution. Stomatal fluxes generally differ from total ozone surface fluxes since only a part of the ozone ‘deposited’ (i.e., removed from the atmo-
sphere) enters the leaf tissues through the stomata. So stomatal ozone fluxes are smaller than total ozone fluxes, and the ratio of these two quantities has formed the subject of a great deal of work (Galbally & Roy, 1980; Gerosa, Cieslik, & Ballarin-Denti, 2003; Hargreaves, Fowler, Storeton-West, & Duyzer, 1992; Labatut & Cieslik, 1997; Massman, 1993; Pio, Feliciano, Vermeulen, & Sousa, 2000; Wesely, Eastman, Stedman, & Yalvac, 1982). Stomata are physiologically active, as they show an opening/closing daily cycle which acts as a regulation process for evapotranspiration. When stomata open out, they release more water vapour; evaporation results in lowering leaf temperature, and this effect is a physiological thermal regulation process, generally during daytime. But this opening allows more ozone to penetrate into the stomata. The opposite situation is observed during the night, when stomata are closed. Then no evaporation occurs and ozone uptake is at its minimum. This suggests that stomatal water vapour fluxes and stomatal ozone fluxes are related in some way, since they both depend on stomatal aperture.

Ozone downward fluxes can also occur through non-stomatal pathways, as ozone reacts with a variety of solid surfaces (bare soil, dead organic matter). This part of the ozone flux is called non-stomatal flux.

There is no means to measure stomatal ozone fluxes directly by micrometeorological methods. They have been determined directly by the enclosure technique only by Grulke, Paoletti, and Heath (2006). However, total ozone fluxes as well as water vapour (evaporation) fluxes can readily be measured by the eddy-correlation technique (Hicks & Matt, 1988). The stomatal ozone flux is usually determined indirectly from eddy-correlation records through an algorithm which makes use of both total ozone flux and water vapour flux, the latter giving an indication about stomatal aperture, which in turn favours ozone uptake. This algorithm has been proposed in various forms, however. One of the goals of this work is to compare these procedures with each other in a critical way by using the same dataset, and to discuss their relative performances and shortcomings.

To meet this goal, results obtained during a measuring campaign over an onion field were used. Onion was chosen because that species is particularly sensitive to ozone (McCool, Musselman, & Teso, 1987), and allegedly important yield losses have been reported by farmers. Measurements have been carried out near Voghera, in the Po river plain Northern Italy, from May to July 2003.

2 Theoretical Background

2.1 The stomatal resistance

The basic assumption of the algorithms permitting the calculation of stomatal ozone fluxes is the molecular nature of the gas diffusion process inside the stomata. It is assumed that, in the stomatal cavity, air motion is laminar and thus any migration of molecules of a minor atmospheric gases through air is governed by molecular diffusion, strictly obeying the Fick’s law. This hypothesis is justified by the small dimensions of the stomata, where turbulent motion is quite unlikely to occur.

The algorithms make use of the resistance analogy, where the resistance against the diffusion of a gas through air is defined as

\[ r = \int \frac{dz}{K} \]  

where \( z \) is a spatial coordinate of the system where the diffusion process occurs and \( K \) is a diffusion coefficient, which can be molecular or turbulent. If we admit that diffusion through the stomatal cavity is purely molecular, then \( K \) is independent from any space coordinate but depends on the nature of the diffusing substance. So, integrating Equation (1) over the spatial coordinate, assuming a spherical shape of the stomatal cavity, we obtain the resistances against molecular diffusion for ozone and water vapour through the stomatal cavity:

\[ r_{O_3} = \frac{z_2 - z_1}{D_{O_3}} \]
\[ r_{H_2O} = \frac{z_2 - z_1}{D_{H_2O}} \]  

where the constants noted \( D \) are the molecular diffusion coefficients for water vapour and ozone. Combining these two expressions leads to

\[ \frac{r_{O_3}}{r_{H_2O}} = \frac{D_{H_2O}}{D_{O_3}} \]  

Thus, to calculate stomatal resistances for ozone uptake fluxes, we need to know stomatal resistances for water vapour fluxes. The latter resistances are