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The open-top chamber impact on vapour pressure deficit and its consequences for stomatal ozone uptake

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ABSTRACT

The vapour pressure deficit (VPD) in open-top chambers (OTCs) was analysed in relation to time of day and ambient meteorology. Effects of observed VPD differences (ΔVPD) between OTCs and the ambient air (AA) on stomatal conductance (g_s) were simulated using 10 model functions from the literature. The dataset originated from 17 OTC crop experiments performed in Belgium, Germany and Sweden. ΔVPD is the resulting difference between the OTC effect on $e_s(T)$, which is the temperature-dependent saturation pressure of water vapour and the OTC effect on e_a, which is the prevailing partial pressure of water vapour in the air ($\Delta \mathrm{VPD} = \Delta e_s(T) - \Delta e_a$). Both $\Delta e_s(T)$ and Δe_a were positive during daylight hours. ΔVPD was small in comparison and sensitive to changes in $\Delta e_s(T)$ or Δe_a. ΔVPD was negative between 07:30 and 10:30 and positive thereafter with a maximum at 20:30 (local time). The positive afternoon ΔVPD was due to an early decrease in Δe_a, probably caused by ceased transpiration, while the positive $\Delta e_s(T)$ persisted throughout the evening, most likely because of restrained cooling in the OTCs. Both the negative morning ΔVPD and the positive evening ΔVPD were more pronounced during clear, warm and dry weather. Circumstances when VPD had a stronger limiting effect on g_s inside the OTCs compared to in the ambient air coincided with high ambient ozone concentrations ($[O_3]$). Calculated wheat O_3 uptake over an $[O_3]$ threshold of 40 nmol mol^{-1} was reduced by 8.7% in OTCs, assuming that VPD was the only factor limiting g_s and that g_s was the only resistance for O_3 uptake. VPD is one factor of considerable importance for g_s and the OTC impact on VPD may contribute to an underestimation of O_3 effects expressed in relation to the external O_3 exposure.

1. Introduction

Risk assessment of ozone (O_3) induced yield loss of crops is today largely based on knowledge achieved by open-top chamber (OTC) experiments. A considerable number of OTC studies have been performed, primarily in Europe and in North America, during the last three decades. There are, however, numerous findings that plant growth performances differ between OTCs and ambient field (e.g. Fuhrer, 1994; Hacour et al., 2002; Sanders et al., 1991). In a recently published study by Morgan et al. (2006), it was clearly indicated that O_3 effects on plants observed in OTCs may be underestimated as compared to effects of the same external O_3 exposure under field conditions. Pleijel et al. (2007) suggested that such an underestimation to a considerable extent may be due to the OTC impacts on O_3 uptake mediated by the enclosure effects on plant microclimate.

One consistent effect of the OTCs on plant microclimate is increased temperature (T) by 1–3 °C (Fuhrer, 1994; Jetten, 1992; Olszyk et al., 1980; Weinstock et al., 1982). However, van Oijen et al. (1999) found that there

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were differences in growth and yield characteristics between wheat (*Triticum aestivum* L.) grown in ambient air (AA) and OTCs even when the chamber effect on T was eliminated by cooling. Thus, it cannot be only the T increase by the OTCs that is of appreciable importance for the performance of the crops and possibly also for the uptake of and sensitivity to O_3 and other pollutants. Another factor that can strongly limit stomatal conductance (g_s), and thus O_3 uptake, is the vapour pressure deficit (VPD; e.g. Emberson et al., 2000).

Seasonal average daytime VPD is often, but not always, increased by OTC enclosure. Among 30 experiments within the EU programmes, *Changing climate and potential impact on potato yield and quality* (CHIP) and *The European Stress Physiology and Climate Experiment. Project 1: Wheat* (ESPACE), the OTC impact on the seasonal average daytime VPD ranged between −15% and +58%, with an average of +21% or 0.1 kPa (calculated from De Temmerman et al. (2002a) and Hertstein et al. (1999)). For the uptake of O_3, *it is most important under what circumstances* (time of day, weather situation) a possible OTC-induced increase in the VPD limits the stomatal uptake of O_3 and, in the open-field situation, high VPD coincides with high $[O_3]$ (Grünhage and Jäger, 1994).

The main objective of the present study was to make a sensitivity analysis of the VPD impact on O_3 uptake in OTCs. The VPD-limitation of g_s was modelled for ambient and OTC conditions by 10 VPD functions from (semi-) multiplicative g_s-models in the scientific literature. The hypotheses were as follows:

- ○ The OTC walls exert a greenhouse effect, which increases $e_s(T)$ and in turn affects the VPD inside the chamber.
- ○ Modelled g_s will be lower in OTCs compared to that in the ambient field because of the higher VPD inside the chambers, assumed that there are no other g_s-limiting factors except for VPD.
- ○ Modelled O_3 uptake will be lower in the OTCs because the VPD effect on g_s is larger under conditions with high $[O_3]$, assumed that there are no other uptake-limiting factors except for the stomatal resistance.

2. Materials and methods

2.1. Theory and definitions

VPD was calculated according to Eq. (1) (e.g. Campbell and Norman, 1998).

$$\mathrm{VPD} = e_s(T) - e_a \tag{1}$$

In the present study, the OTC impact on VPD was defined as ΔVPD (Eq. (2)):

$$\Delta\mathrm{VPD} = \mathrm{VPD}_{\mathrm{OTC}} - \mathrm{VPD}_{\mathrm{AA}} \tag{2}$$

The OTC impacts on the T, the temperature-dependent saturation pressure of water vapour ($e_s(T)$) and the partial pressure of water vapour in the air (e_a) were analogously defined as in Eqs. (3)–(5):

$$\Delta T = T_{\mathrm{OTC}} - T_{\mathrm{AA}} \tag{3}$$

$$\Delta e_s(T) = e_s(T)_{\mathrm{OTC}} - e_s(T)_{\mathrm{AA}} \tag{4}$$

$$\Delta e_a = e_{a\mathrm{OTC}} - e_{a\mathrm{AA}} \tag{5}$$

The OTC effect on VPD can then be written as

$$\Delta\mathrm{VPD} = \Delta e_s(T) - \Delta e_a \tag{6}$$

The air supplying the OTCs was taken from the ambient field at canopy height at a few meters distance from the OTC and e_a in that air was considered to be well represented by $e_{a\mathrm{AA}}$. Since the elevation in $e_{a\mathrm{AA}}$ was relatively constant throughout the day (Fig. 1a), the daytime Δe_a was ascribed to evapotranspiration within the OTC. The meaning of Eq. (6) is that the OTC impact on VPD is the resulting balance between the OTC effect on $e_s(T)$, which is governed by ΔT, and the OTC effect on e_a, which is governed by evapotranspiration.

2.2. Dataset

Meteorological data (T, photosynthetically active photon flux density (PPFD) and relative humidity (RH)) from measurements inside and outside the OTCs were compiled from 17 experiments covering eight different years and three different sites situated in Sweden, Belgium and Germany. The e_a and the $e_s(T)$ values were calculated based on T and RH measurements (e.g. Campbell and Norman, 1998). Wheat (*T. aestivum* L.), ryewheat (×*Triticosecale*), rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.) and potato (*Solanum tuberosum* L.) were grown in the OTCs. Only data from the time period with an actively transpiring crop was used: from 10 days before to 20 days after anthesis for cereals and from tuber initiation until 20 days after maximum leaf area for potato. The resulting dataset included >12 000 hourly mean values of VPD. Four different types of OTCs were used: (i) small with roofs (five experiments), (ii) small without roofs (three experiments), (iii) large with roofs (two experiments) and (iv) large without roofs (seven experiments). All OTCs had a frustum to reduce the influx of surrounding air through the open top. References to more elaborate descriptions of the experiments are presented in Table 1.

2.3. Data analyses

Because meteorological variables such as radiation, temperature and humidity often correlate, it was not attempted to evaluate the individual impacts of different meteorological variables on ΔVPD. Instead, it was investigated how ΔVPD differed between weather situations characterized by such variables. The diurnal air T fluctuation is more strongly marked on clear than on cloudy days (Geiger et al., 2003). Therefore, high hourly T decrease (cooling rate, CR) was assumed to be typical for clear weather and chosen as a tool to identify different weather situations. CR has previously been used by e.g. Lindkvist and Lindqvist (1997) and Sundberg et al. (2006). The diurnal maximum