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An aerodynamic correction for the European ozone risk assessment methodology

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In Europe the risk of ozone damage to vegetation is assessed using two different metrics, the concentration-based AOT40 index and the flux-based $AF_{st}Y$ index. An important part of the definition of both these indices is that ozone concentrations must be known at the top of the vegetation canopy. An estimate of canopy-top concentrations entails an estimate of the above-canopy concentration gradient, which is affected by the roughness sublayer (RSL) present above an aerodynamically rough surface. A calculation method is derived to correct the aerodynamic resistance for the effect of RSL. This correction results in systematically higher canopy-top concentrations as compared to standard Monin–Obukhov similarity theory. The effect of the modified concentration profile is quantified based on data from the chemical transport model of the European Monitoring and Evaluation Programme, with calculations for crops and forests at six different locations in Europe. Although the average change in ozone concentrations is not very large, the resulting changes in AOT40 and $AF_{st}Y$ metrics can be significant. The RSL leads to increases in AOT40 of 6–13% for forests across the example sites, and 11–24% for crops. $AF_{st}1.6$ only increases by 3–4% for forests, but for crops $AF_{st}6$ increases by 16–54%.

1. Introduction

Ozone is considered one of the most harmful air pollutants affecting human health and vegetation. In Europe, the development of emission control strategies is founded on the effects-based approach, with the ozone-induced plant injury being one of the effects considered (Sliggers and Kakebeeke, 2004). Within this framework, the risk of ozone damage to vegetation is related to numerical exposure and dose metrics (Ashmore et al., 2004; Mills, 2004). These metrics aim at biological meaningfulness, allowing accurate local-scale risk assessment, but are also by design sufficiently uncomplicated to provide 'plausible' regional-scale risk maps based upon a limited amount of data, rather than unjustifiably complex formulations (Hayes et al., 2007; Paoletti and Manning, 2007; Simpson et al., 2007).

The exposure- and dose-type metrics differ in that the former can be evaluated from data on ambient ozone concentrations only, while the latter involves the stomatal uptake of ozone by vegetation and thus, additionally, requires the stomatal conductance of plants to be measured or modelled. Both types of risk indicator are used within the air pollution assessment methodology adopted within the Convention of Long-range Transboundary Air Pollution of the United Nations Economic Commission for Europe (UNECE). This methodology is detailed in a technical guideline document, the so-called Mapping Manual (MM), a major part of which is dedicated to ozone (Mills, 2004). More specifically, the AOTX (Accumulated exposure Over a Threshold of X) exposure index and the $AF_{st}Y$ (Accumulated stomatal flux F_{st} above a threshold of Y) dose index

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are defined for ozone in the MM (Mills, 2004). In both cases, the accumulation is to be carried out over the growing season representative of the vegetation in question.

The MM methods have been built into the chemical transport model (CTM) of the European Monitoring and Evaluation Programme (EMEP) (Emberson et al., 2000; Simpson et al., 2003a, 2007). The EMEP model is widely employed within the European air pollution abatement strategy and legislation work (Sliggers and Kakebeeke, 2004; CEC, 2005).

A specific feature common to both the AOT*X* and A$F_{st}Y$ indices, as adopted within the MM, is that they are explicitly defined in terms of the concentration at the top of the vegetation canopy (Mills, 2004). In any application of these indices, whether based on measurements above the canopy or modelling, it is thus necessary to apply a profile correction, because typically there is a positive, deposition-sink generated vertical concentration gradient above an active vegetation surface. A failure to correct for this gradient will potentially overestimate the risk of ozone-induced damage. The same in principle applies to other exposure indices as well, such as those considered in the United States (Paoletti and Manning, 2007). When AOT*X*, A$F_{st}Y$ or other similar indices with a concentration or flux threshold are used to assess the risk, even small uncertainties in estimated concentrations can have a larger, nonlinear effect on the risk metrics (Tuovinen, 2000; Sofiev and Tuovinen, 2001; Tuovinen et al., 2007).

Along with an even simpler methodology, consisting of tabulated scaling factors, the MM details equations for calculating the vertical concentration profile from physical principles (Mills, 2004). These are applicable to the atmospheric surface layer in neutral stability conditions, but this approach can be easily enhanced by applying the well-established Monin–Obukhov similarity theory (MOST), if sufficient meteorological data are available. MOST describes the relationship between the vertical flux and mean gradient also in the non-neutral case, that is, when modifying buoyancy forces are present (e.g. Garratt, 1992; Foken, 2006).

An additional complication for the estimation of vertical gradients of scalar quantities, such as trace gas concentrations, arises from the existence of the so-called roughness sublayer (RSL). The RSL is located in the lower part of the surface layer and represents the region immediately above an aerodynamically rough surface, such as a vegetation canopy, in which the traditional flux–gradient relationships of MOST tend to break down (e.g. Garratt, 1992). This has been observed for various vegetation types including pine forests (Thom et al., 1975; Raupach, 1979; Högström et al., 1989; Rannik, 1998), a mixed pine–spruce forest (Mölder et al., 1999), mixed coniferous–deciduous forests (Bosveld, 1997; Neirynck et al., 2005), a mixed pine–oak forest (Schween et al., 1997), savannah forests (Garratt, 1980), an aspen forest (Nakamura and Mahrt, 2001), a mixed aspen–maple forest (Simpson et al., 1998), beech forests (Dellwik and Jensen, 2005; Mammarella et al., 2008), bushland (Chen Fazu and Schwerdtfeger, 1989), a sugar cane field (Cellier, 1986) and a maize field (Cellier and Brunet, 1992). Observations suggest that the RSL extends from the vegetation canopy height (h) to approximately $2h$.

The studies listed above do not explicitly consider trace gas concentration profiles but provide quite a consistent picture of the deviations of RSL from the traditional MOST that is applicable to any scalar. In simple terms, while the time-averaged vertical turbulent fluxes of energy and mass remain approximately constant with height in the surface layer, in the RSL the corresponding eddy diffusivities are enhanced due to the direct influence of roughness elements on the flow. Correspondingly, the vertical gradients of different scalars are reduced in the RSL. This affects the near-surface concentrations that are derived using the flux–gradient relationship, the traditional MOST in principle resulting in an underestimated concentration, if applied within the RSL.

The importance of the MOST-based profile correction for near-surface concentrations has been demonstrated earlier (Tuovinen, 2000) and, as explained above, is acknowledged in the MM (Mills, 2004). Even though the uncertainty related to the RSL is recognised in the MM, no guidance is provided for dealing with the problem. Obviously, the MM methodology and the related European-scale risk assessments can never aim to cope with all the uncertainties associated with predicting the above-canopy ozone concentrations and fluxes, including those traditionally involved in biosphere–atmosphere studies (e.g. Raupach, 1995). These difficulties are exacerbated by the complexity and variability of the natural systems to be studied and mapped, and further compounded when trying to make assessments over large areas such as for the whole of Europe (e.g. Erisman et al., 2005). It is important, however, that the possible sources of uncertainty are identified and quantified as far as possible.

In the present work we derive a simple calculation method for estimating the influence of RSL on the canopy-top concentration, and further on the exposure and dose indices. The method is applied here in the context of the EMEP CTM, but is not limited to this particular model; it can be used for measured ozone concentration data as well. By employing model-derived ozone concentrations and fluxes and related meteorological data for different geographical locations and vegetation types in Europe, we quantify and assess the importance of this RSL correction for the AOT*X* and A$F_{st}Y$ indices. Finally, we discuss the uncertainties related to the suggested method.

2. Material and methods

2.1. Deposition parameterisation

Within the EMEP model, as in most Eulerian CTMs, the dry deposition fluxes are calculated as a vertical boundary condition of the equations describing the dynamics of atmospheric processes (Simpson et al., 2003a,b). The mass flux density of ozone (Q_c, positive away from the surface) is expressed as being proportional to the dry deposition velocity (V_d),

$$Q_c = -V_d(z)c(z) \tag{1}$$

where c is ozone concentration and z is the height above the ground. The dry deposition velocity is parameterised as