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Towards a model of ozone deposition and stomatal uptake over Europe.

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Preface and Acknowledgements

This EMEP Note has been prepared for presentation at the twenty fourth session of the Steering Body of EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe). It presents an overview of the status of work concerning the development of a consistent methodology to model both the total deposition of ozone to ground surfaces and the stomatal uptake of ozone by vegetation within the EMEP oxidant model. Stomatal ozone uptake is believed to be much more closely related to expected vegetation damage than the Level I AOT40 exposure index (based on ambient ozone concentrations) that is currently used to assess ozone impacts to vegetation. As such, the development and application of the model presented in this document can provide a basis for a Level II approach to assessing risks of ozone damage, in which differences in land-cover, climate and soils are incorporated.

This work builds upon projects funded by the UK Department of the Environment, Transport and the Regions, the Scottish Executive, the National Assembly for Wales and the Department of the Environment (in Northern Ireland); the Nordic Council of Ministers and the Finnish Meteorological Institute, as well as EMEP.

PREFACE AND ACKNOWLEDGEMENTS **2**

DEFINITION OF TERMS **4**

1. INTRODUCTION **5**

2. OVERVIEW AND LAND-COVER **8**

2.1 LAND-COVER CLASSES **9**

3. STOMATAL RESISTANCE (R_{STO}) **11**

3.1 Maximum stomatal conductance (g_{max}) *12*
3.2 Minimum stomatal conductance (g_{min}) *12*
3.3 Leaf-age (g_{age}) *12*
3.4 Irradiance (g_{light}) *12*
3.5 Temperature (g_{temp}) *13*
3.6 Leaf to air vapour pressure deficit (g_{VPD}) *13*
3.7 Soil water status (g_{SWP}) *13*

4. NON-STOMATAL DEPOSITION **16**

4.1 External plant resistance (R_{ext}) *16*
4.2 Soil resistance (R_{ext}) and in-canopy aerodynamic resistance (R_{inc}) *17*
4.3 Land-cover classes with a bulk surface resistance *19*
4.3.1 Tundra and wetlands 19
4.3.2 Desert 19
4.3.3 Water 20
4.3.4 Ice and snow-covered areas 20
4.3.5 Urban 21

5. PRELIMINARY MODEL ANALYSIS **22**

5.1 MODELLING AND PARAMETERISATION USED FOR PRELIMINARY MODEL ANALYSIS **22**
5.1.1 Growing season *22*
5.1.2 Leaf Area index *23*
5.1.3 Up-scaling from leaf to canopy *25*
5.1.3.1 Needle Age 26
5.2 COMPARISONS OF MODELLED VS MEASURED DATA. **27**
5.2.1 Comparison of modelled data with site-specific measured values *31*
5.2.2 Comparison of modelled data with published data *32*
5.2.2.1 Temperate/boreal coniferous forests 33
5.2.2.2 Temperate/boreal deciduous forests 37
5.2.2.3 Mediterranean needleaf forests 39
5.2.2.4 Temperate crops 39
5.2.2.5 Mediterranean crops 39
5.2.2.6 Moorlands 40
5.2.2.7 Grasslands 40
5.2.2.8 Mediterranean Broadleaf forests 41

6. SUMMARY **43**

7. REFERENCES **44**

APPENDIX A: **53**

Definition of terms

Stomatal Flux/Uptake /Absorbed dose

Refers to the instantaneous flux or cumulative dose/uptake of ozone through the stomata into the sub-stomatal cavity within the leaf/needle

Exposure

Refers to the ambient ozone concentration (ppb) or the accumulated ozone concentration exceeding a given threshold, e.g. AOT40 (ppb.hours).

Canopy flux

Refers to the total ozone flux to a vegetative canopy, i.e. to the internal and external plant surface and soil surface beneath the canopy.

AOT40	The accumulated ozone exposure over a threshold of 40 ppb
d	Zero plane displacement (m)
EMEP	Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants
GIS	Geographical Information System
LAI	Leaf Area Index
MSC-W	Meteorological Synthesizing Centre-West
PAR	Photosynthetically Active Radiation, 400-700nm (typically about 45-50% of total global radiation) (μmol m^{-2} s^{-1})
PPFD	Photosynthetic Photon Flux Density (μmol m^{-2} s^{-1})
SEIY	Stockholm Environment Institute at York
SMD	Soil Moisture Deficit (m or mm)
SWP	Soil Water Potential (MPa)
UN ECE	United Nations Economic Commission for Europe
VPD	Vapour Pressure Deficit between leaf/needle and ambient air (kPa)
z_0	Roughness length (m)

g_s	Stomatal conductance (mmol O_3 m^{-2} s^{-1})
g_{max}	Maximum stomatal conductance (mmol O_3 m^{-2} s^{-1})
g_{min}	Minimum daytime stomatal conductance (fraction, 0-1)
g_{age}	g_s relationship with leaf age (fraction, 0-1)
g_{light}	g_s relationship with irradiance (fraction,0-1)
g_{temp}	g_s relationship with leaf temperature (fraction,0-1)
g_{VPD}	g_s relationship with leaf to air vapour pressure deficit (fraction 0-1)
g_{SWP}	g_s relationship with soil water potential (fraction,0-1)

R_a	Aerodynamic resistance to mass transfer of ozone (s m^{-1})
R_b	Boundary layer resistance for ozone transfer by diffusion (s m^{-1})
R_{sur}	Total surface resistance to ozone transfer (s m^{-1})
R_{inc}	In-canopy resistance to ozone transfer (s m^{-1})
R_{gs}	Ground surface resistance to ozone transfer, soil+mosses, etc. (s m^{-1})
Rsto	Canopy stomatal resistance to ozone uptake (s m^{-1})

1. Introduction

Level I ozone critical levels for forest trees, agricultural crops and semi-natural vegetation were established at a series of three UN ECE workshops during the 1990s, with the values currently being used in policy evaluation deriving from the final workshop, held in Kuopio, Finland (Kärenlampi & Skärby, 1996). These critical levels were based upon the AOT40 concept (Fuhrer et al., 1997), in which daytime ozone concentrations exceeding 40 ppb are summed over the growing season (hence AOT: Accumulated Over Threshold). AOT40 maps have been used to indicate those areas of Europe where ozone damage may occur (e.g. Amann et al., 1999). However, this Level I approach has a number of serious problems if the aim is to assess likely ozone damage to vegetation. Not least, AOT40 is calculated only on the basis of ambient ozone concentrations regardless of whether that ozone is actually absorbed by the plant or not. It is well established that plant response is more closely related to ozone flux, whereby ozone enters the plant through the stomata, than to atmospheric concentrations. Sensitivity to ozone is known to be dependent on plant species, phenology, climate and soils.

Ozone flux is a function of the ozone concentration above the plant canopy and the resistance to ozone transfer from there into the sub-stomatal cavity of an individual leaf. This resistance is not constant, but is a function of a number of factors, including atmospheric turbulence, canopy height and structure, species-specific phenology, and the effects of factors such as irradiance, soil moisture deficit and vapour pressure deficit on the stomatal component of the resistance. Although the stomatal flux of ozone is the component most closely related to effects, external plant surfaces and soil are also important sinks for ozone; thus ozone deposition has both stomatal and non-stomatal components. Modelling total deposition as a function of land-cover and climate is important for two reasons: firstly, it may provide a better description of ozone loss processes than the current deposition velocity module used in the EMEP photochemical models and, secondly, it is essential in calculating stomatal flux to individual leaves. The resulting inter-relationship between total deposition and stomatal flux means that the development of a consistent methodology for modelling both processes, integrated with an appropriate database on land-cover, is crucial to the production of internally consistent ambient ozone concentration and absorbed ozone dose fields across Europe.

The pan European feature of the modelling means that the model parameterisation has to be sufficiently robust to be applied generically across Europe. As such, general assumptions regarding growth habits (phenology and canopy structure) and physiological behaviour of particular vegetation groups to prevailing climatic conditions have to be made. Such assumptions cause significant uncertainties in model results when assessed on a local scale (i.e. under site-specific conditions) or when applied to particular species. However, on the 50 x 50 km EMEP grid scale the model should be capable of describing, at least in relative terms, the pan European

spatial variability in total ozone deposition and stomatal flux to the major types of land-cover.

Participants at the recent UN-ECE workshop held in Gerzensee, Switzerland (Fuhrer & Achermann, 1999) recognised that environmental conditions and species-specific characteristics which influence the temporal and spatial variation in the sensitivity of vegetation to ozone across Europe need to be incorporated if a more sophisticated (Level II) assessment of risks of ozone damage, including economic evaluation, is to be developed. The workshop also recognised the need for further work to develop such Level II assessments, and that a method based on estimates of ozone flux should be a long-term goal of such a level II approach.

This Note presents current progress on developing, testing and implementing such a methodology for the EMEP oxidant model. This deposition module aims to improve on the existing formulation by incorporating biological characteristics of land-cover, particularly with regard to phenology and stomatal conductance. This work builds strongly on previous research that concentrated on development of a model to calculate stomatal ozone flux (Emberson et al. 1996, 1998, 2000a&b). The main objective of this research is to develop a methodology for mapping absorbed ozone dose. The results and conclusions from this research should, in the longer term, provide a sounder basis for the analysis of the environmental benefits of different European ozone control strategies than the currently employed exposure based approach.

It should be emphasised that this research represents a first attempt in moving towards such a pan-European flux model. The methods presented here involve a significant increase in complexity in deposition modelling for the ozone model and it is not clear at this stage if this will improve the actual results of the model with regard to ambient ozone concentrations or AOT40. However, the increased complexity enables a much better linkage of the model output to vegetation characteristics; it thus surely represents a step closer to providing the data needed for evaluating effects of ozone on vegetation across Europe. One of the main aims of presenting a methodology at this stage is to stimulate feedback from the biology/deposition/effects communities as to the realism of the proposed methods and their appropriateness for routine EMEP modelling. Improvements and simplifications can hopefully be incorporated into future versions of the model for routine use.

In this Note we first present (Section 2) a general overview of the methodologies used for the modelling of total ozone deposition and describe which of the processes involved in the deposition calculation are important in determining stomatal flux. Sections 3 and 4 present, in turn, further details of the formulations of the stomatal and non-stomatal components of ozone deposition. These sections also discuss some of the assumptions and simplifications that have been necessary to link the deposition module with the EMEP oxidant model. Section 5 describes preliminary results of the deposition model. Although some aspects of the modelling are still under development, provisional methods have been used to enable the presentation of some preliminary results of this deposition module, run in an off-line mode. This allows an evaluation of the important components of the modelled total deposition and stomatal flux values against comparable values reported in the literature for selected different

land-cover classes, and hence provides an initial assessment of the predictive capabilities of this new ozone deposition model and its component parts.

It is important to note that this report deals with the methodology and results of the deposition module for well-watered, cloud-free conditions. The effects of water-stress are very important for ozone deposition, but the modelling of soil-water (and not least the evaluation of any methodology) presents a number of challenges, which require further work. At this stage we prefer to present and evaluate the model for well-watered conditions. Extension to water-stressed conditions will form the next phase of work on this module.

2. Overview and land-cover

A graphical summary of the resistance components that are included in this deposition module is given in Figure 1.

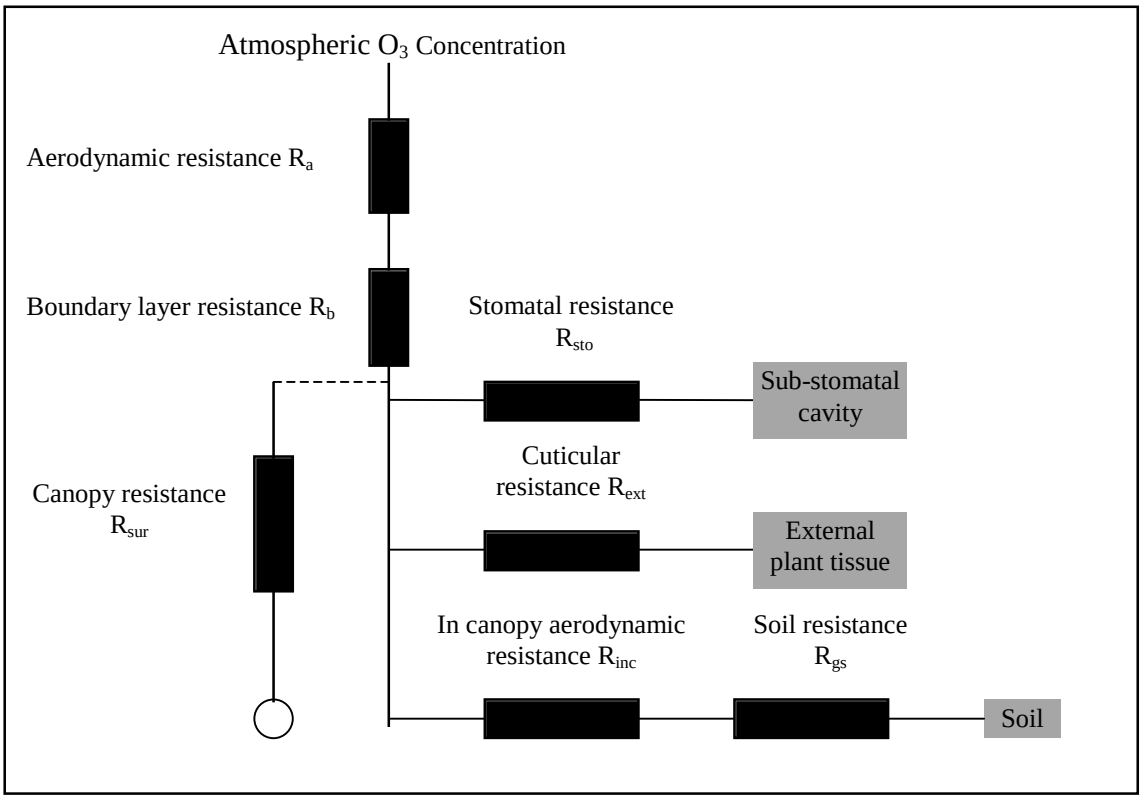


Figure 1 Resistance components included in the evaluation of ozone deposition to vegetated surfaces. The dotted line indicates that the parallel resistances given by R_{sto}, R_{ext}, $R_{inc}+R_{gs}$ can be also represented by one "canopy" surface resistance R_{sur}.

The calculations of R_a and R_b are largely based upon previously developed methods (Jakobsen et al., 1996) and not discussed further here. The only difference between the methods used is that the 3D model meteorology now employed by EMEP includes an estimation of wind-speed (u) for the lowest grid point (at about 45 m) of the numerical weather prediction model, from which the meteorological input data are obtained. This means that the calculations described by Jakobsen et al. (1996) to estimate the reference height wind-speed are not necessary.

The most important component of the above scheme is the surface resistance, since this is the part of this new deposition model that differs most significantly from previous methods to estimate surface ozone deposition. The surface resistance is calculated as follows: -

$$R_{sur} = \frac{1}{\frac{LAI}{R_{sto}} + \frac{SAI}{R_{ext}} + \frac{1}{R_{inc} + R_{gs}}} \quad [1]$$

Where,

R_{sto} is the land-cover specific leaf/needle stomatal resistance that is the resistance to ozone uptake through the stomata

R_{ext} is the external resistance that is the resistance of the exterior plant parts to uptake or destruction of ozone

R_{inc} is the land-cover specific in-canopy aerodynamic resistance that accounts for the resistance to transport of ozone within the canopy towards the soil and lower parts of the canopy

R_{gs} is the soil resistance that accounts for the resistance to destruction or absorption at the ground surface (e.g. soil, litter, moss, etc.)

LAI is the leaf area index

SAI is a surface area index, set equal to LAI in the growing season and 1 outside the growing season when leaf material is not present, used for deciduous forest

The various components of this surface resistance are described in more detail in sections 3-4.

2.1 Land-cover classes

Ozone deposition to a landscape varies strongly with the aerodynamic, physical and chemical properties of the land-surface. Some surfaces show little diurnal or seasonal variation and a reasonable estimate of ozone deposition can be made by assuming a simple bulk surface resistance for that landscape. However, for most types of vegetation, ozone deposition is strongly linked to stomata. Stomatal conductance (g_s) data are required to model this, but these vary strongly from species to species. Therefore, it has been necessary to identify vegetation groups, which comprise species with similar aerodynamic and stomatal conductance characteristics. To achieve this, g_s data have been extracted from the literature for as many species as possible (although complete parameterisation of the g_s model was only possible for a limited number of species), and these were grouped into representative land-cover classes.

Table 1 gives the main land-cover classes chosen for the deposition modelling, along with an indication of whether a bulk-surface resistance or stomatal modelling approach is used.

For forest trees, the vegetation groupings include species for which a complete g_s model parameterisation was available and which are representative of some of the more common and hence widespread European species. In addition to modelling deposition to broad forest categories, it is also possible for us to model stomatal flux to the individual species listed in Table 1. For crops the situation is rather different, largely because of the limited data available for mapping crop distribution across Europe. Such mapping has been performed by SEIY using data obtained from crop yield statistics (Eurostat, 1994) but the data limitations result in a lack of detail in terms of spatial resolution and differentiation between species.

The most frequently occurring crop species are wheat, barley and maize. Of these crops, a complete g_s parameterisation only exists for wheat and maize. Therefore, for deposition modelling, wheat g_s parameters are used to characterise temperate crop species and maize g_s parameters to characterise Mediterranean crop types. Root crops have also been treated as a separate class based upon data existing for potato.

Moorlands and heathlands have been treated somewhat differently. The variable mix of species present, and the lack of g_s data in the literature, has meant that we have adopted an empirical approach, based on deposition studies. This approach uses a modified version of stomatal conductance modelling in which g_{VPD} and g_{SWP} are excluded from the calculation (in effect this means that it is assumed that VPD and SWP will not limit ozone uptake via the stomata). The parameterisation of g_{age}, g_{min} and g_{light} is based on that collected for grasslands whilst g_{temp} is assumed similar to temperate/boreal coniferous forest. The value of g_{max} was assigned so as to produce model results in accordance with published deposition velocities for this land-cover type.

Table 1: Land-cover classes chosen for deposition calculations and representative species for which stomatal conductance (g_s) data were available. A "Y" in the g_s column indicates classes for which stomatal conductance modelling is performed.

Code	Deposition land-class	g_s	Representative species (for which g_s data were available)
CF	Temp./boreal coniferous forests	Y	Norway Spruce (*Picea abies*), Scots Pine (*Pinus sylvestris*)
DF	Temp./boreal deciduous forests.	Y	Oaks (*Quercus petraea Q. robur*), Beech (*Fagus sylvatica*), Birch (*Betula pendula*)
NF	Medit. needleleaf forests	Y	Allepo pine (*Pinus halepensis*), Maritime pine (*Pinus pinaster*), *Abies* spp.
BF	Medit. broadleaf forests	Y	Oaks (*Q. ilex, Q. suber, Q. coccifera*)
TC	Temp. crops	Y	wheat (*Triticum aestivum*)
MC	Med. crops	Y	Maize (*Zea Mays*)
RC	Root crops	Y	Potato (*Solanum tuberosum*)
V	Vineyards	Y	Grapevine (*Vitis vinifera*)
TO	Temp. orchard	Y	Apple (*Malus sylvestris*)
MO	Med. orchard	Y	Citrus (*Citrus sinensis & C. paradisi*)
GR	Grassland	Y	*Lolium* spp.
SNL	Semi-natural	Y*	Moor/heathland*
MS	Med. scrub	Y	*Q. ilex*
WE	Wetlands	-	
TU	Tundra	.	
DE	Desert	.	
W	Water	.	
I	Ice	.	
U	Urban	.	

* Empirical approach – see text above

3. Stomatal resistance (R_{sto})

The modelling approach for stomatal resistance is based on the multiplicative model described by Jarvis (1976) and modified by Körner et al. (1995). This approach assumes that there is no interaction between the different parameters in equation 2 described below. The mean land-cover- or species-specific leaf/needle stomatal resistance (R_{sto}), in units of s m^{-1}, is given by: -

$$R_{sto} = [(g_{max} * g_{age} * \max \{g_{min}, (g_{light} * g_{temp} * g_{VPD} * g_{SWP})\}) / 41000]^{-1} \quad [2]$$

Where :-

g_{max} is the maximum stomatal conductance in units of mmol O_3 m^{-2} s^{-1} expressed on a projected leaf/needle area basis

g_{age} is the relative g determined by leaf/needle age

g_{min} is the minimum daytime stomatal conductance observed under field conditions

g_{light} is the relative mean canopy g determined by irradiance

g_{temp} is the relative g determined by temperature

g_{VPD} is the relative g determined by the leaf-to-air vapour pressure deficit (VPD)

g_{SWP} is the relative g determined by the soil water potential (SWP), (related to soil moisture deficit, SMD)

41000 is the factor to convert from mmol m^{-2} s^{-1} to m s^{-1} (Jones, 1992)

(the relative g factors are expressed on a scale of 0-1 and used to modify g_{max}).

It should be noted that in order to use the derived species-specific R_{sto} to calculate the canopy resistance in equation 1, the following assumptions have been made:-

- Species-specific maximum stomatal conductance is constant with leaf/needle position within the canopy.
- Stomatal conductance relationships with environmental parameters are constant within the canopy.
- The within canopy values of temperature and VPD are assumed constant with height and equal to ambient air values (taken from the 2 m height level of the NWP model)
- LAI is evenly distributed over the whole canopy.

The parameterisation of the land-cover specific g_s data (g_{max}, g_{age} and g_{min}) and g_s relationships with environmental variables (g_{light}, g_{temp}, g_{VPD} and g_{SWP}) was achieved through collecting and pooling information available from the scientific literature. To ensure the comparability and validity of the collected g_s data rigorous criteria were set regarding the procurement and recording of the data before they were accepted for use in establishing the g_s dataset (Emberson, 1997). The following text describes the parameterization of the g factors. g_{max} and g_{min} are constants and the simple functions and parameters given in Figure 2 describe the remaining g factors. Details of the species-specific values of coefficients for these functions are given in Appendix A.

3.1 Maximum stomatal conductance (g_{max})

The maximum stomatal conductance is a constant for each species, and establishes the ceiling value that is modified by the other g factors. The values given in Appendix A, Table A: 1, are in terms of the projected leaf area since LAI is used to scale up from leaf to canopy. To calculate projected needle area for the coniferous species a factor of 2.6 is used to convert from total needle surface area (Oren *et al*. 1996). In order to ensure that the that conversion between projected and total leaf area is performed correctly, Table A: 1 also categorises vegetation according to whether the stomata are found over the entire leaf surface (amphistomatous) or just on one side of the leaf (hypostamatous).

3.2 Minimum stomatal conductance (g_{min})

The minimum stomatal conductance sets the baseline g_s (as a fraction of g_{max}) that may occur during the daytime in the field. This value is important since its inclusion as a modelling term means that stomatal ozone uptake, albeit limited will still occur even during periods of severe environmental stress.

3.3 Leaf-age (g_{age})

Maximum stomatal conductance will only occur for a particular period in a species' growing season. At the start, and towards the end of the growing season, stomatal conductance will be lower than the absolute maximum value since during these periods either the leaves are not yet fully developed or are beginning to senesce. The g_{age} component describes this phenological modification to g_{max} and is described for selected land-cover types in Figure 2. The parameterisation for g_{age} is given in Appendix A: Table A1 where gage_a, gage_b_and gage_c are land-cover specific parameters representing, in turn, the minimum g_{age}, the number of days for g_{age} to reach its maximum and the number of days during the decline of g_{age} for the minimum to again be reached. A slightly modified methodology has been developed for coniferous forests, to take into account the effects on canopy conductance of older needles. This is discussed in section 5.1.3.1.

3.4 Irradiance (g_{light})

The g_s relationships with irradiance (g_{light}) for each vegetation group have been collected from the literature and are given in Appendix A, Table A: 1. The functional relationship is:

$$g_{light} = 1 - \exp(-\alpha.PAR) \qquad [3]$$

Where PAR is the photosynthetically active radiation covering the wavelength range 400-700nm (typically about 45-50% of total global radiation). The calculation of PAR is discussed in section 5.

3.5 Temperature (g_{temp})

The g_s relationships with temperature (g_{temp}) collected from the literature have been approximated by the polynomial function:

$$g_{temp} = 1 - [(T - T_opt) / (T_opt - T_min)]^2 \quad [4]$$

Where T is the temperature in °C, T_opt is the temperature of maximum conductance, and T_min is the temperature at which conductance falls to zero. The function is symmetrical, such that the maximum temperature T_max could also be used in eqn. [4]. Although not strictly needed, Appendix A: Table A1 gives the values of T_max and T_min as well as T_opt for the different land-classes.

As stated previously, temperature is assumed constant within the canopy and equal to that at 2 m height above all the vegetation surface even though the g_{temp} functions are representative of stomatal conductance relationships with leaf temperature. This assumption may be a significant source of uncertainty, but avoids having to model the energy balance of the canopy.

3.6 Leaf to air vapour pressure deficit (g_{VPD})

The g_s relationships with VPD (g_{VPD}) collected from the literature are described by the functions shown for selected land-cover types in Figure 2 with the parameterisation for each cover type given in Appendix A: Table A2. Similar to temperature, it has also been necessary to assume that VPD is constant throughout the canopy and equal to a surface VPD value derived from data describing the specific humidity in the lowest model layer and surface temperature. The method calculates the air vapour pressure (VP) and the vapour pressure within the substomatal cavity (SVP) assuming saturation and that leaf temperature is equal to air temperature. VPD is then calculated as SVP - VP.

3.7 Soil water status (g_{SWP})

The g_{SWP} relationships require that soil water status be described as soil water potential (SWP) in units of MPa. The g_s relationships with soil water potential (g_{SWP}) collected from the literature are represented by the functions shown for selected species in Figure 2 with the parameterisation for each cover type given in Appendix A: Table A2.

As noted in the Introduction, the methodology for calculating SWP within the EMEP model is still undecided and further research is necessary before including this component. Therefore, in order to present the preliminary estimates of deposition velocities described later in this report it has been assumed that g_{SWP} =1. This assumption is probably, for the most part, realistic for Northern Europe although water-stress is sometimes quite common even in the Nordic countries. However, for central and southern Europe g_{SWP} is likely to be below 1 for significant periods, especially during the summer months.

Figure 2 **Generic functions for stomatal conductance modifiers (g_{age}, g_{light}, and g_{temp}) and examples for 4 land-cover types.**

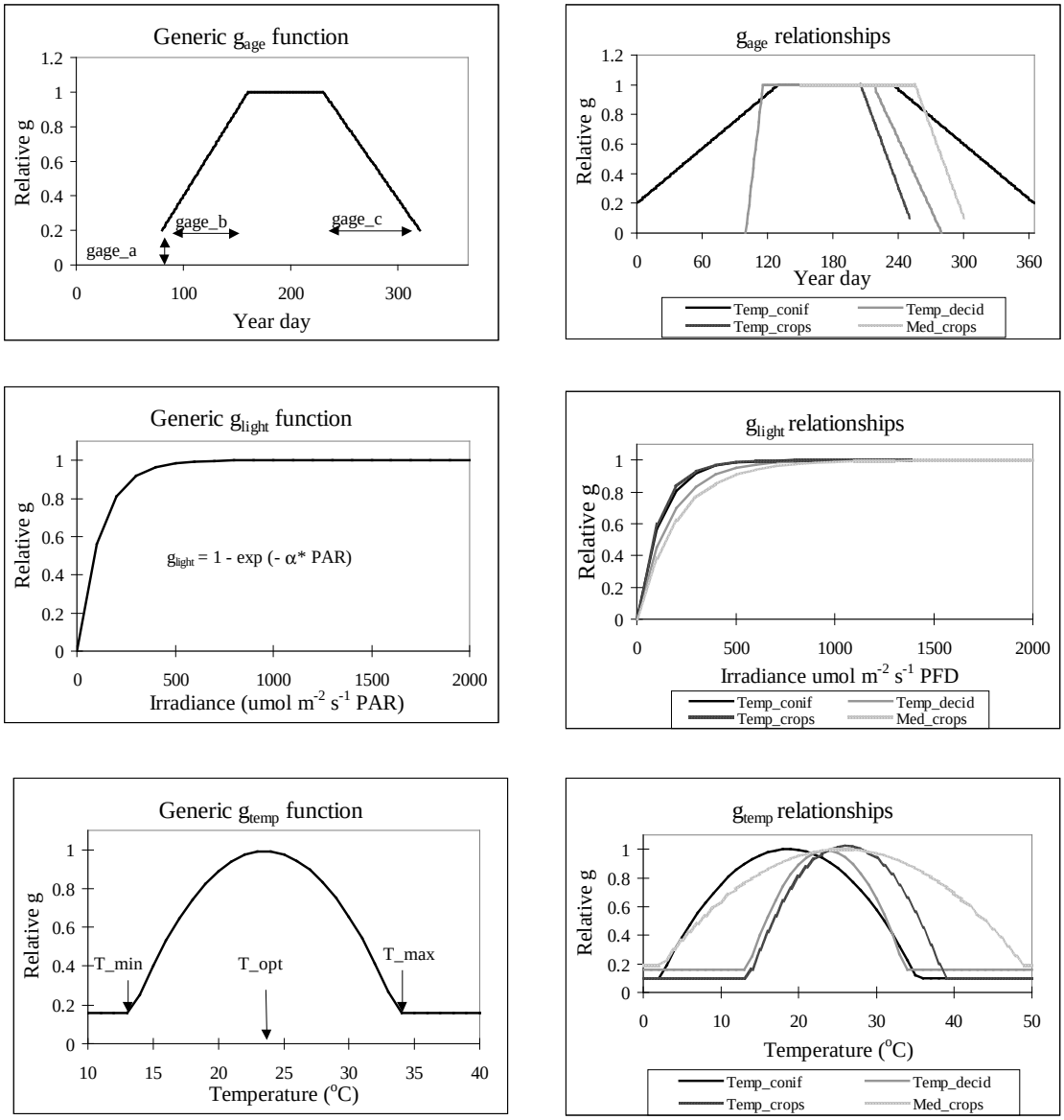
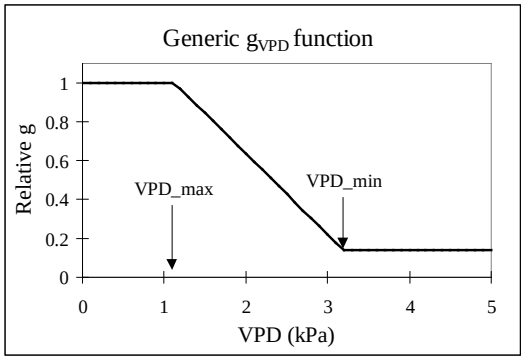
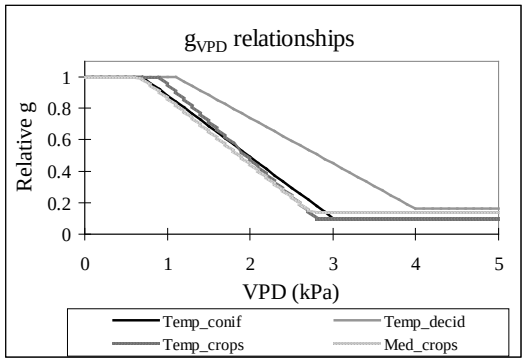
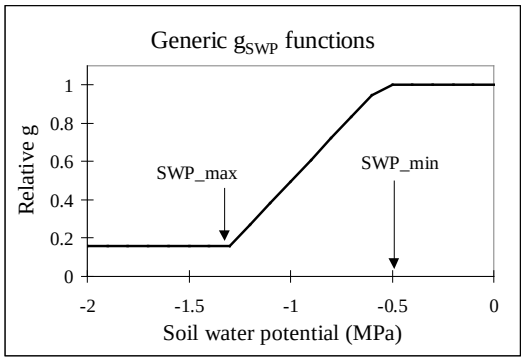
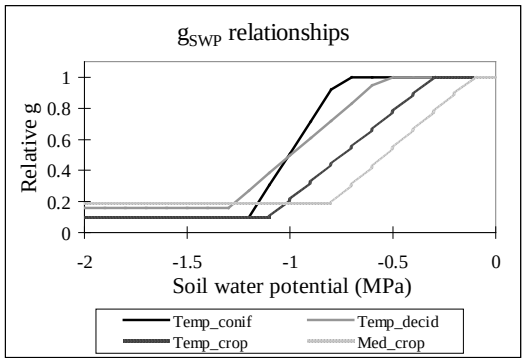


Figure 2 cont. Generic functions for stomatal conductance modifiers (g_{vdp}, g_{swp}) and examples for 4 land-cover types.









4. Non-stomatal deposition

In addition to the stomatal uptake, which has a specific biological significance, external plant surfaces and the soil underlying the vegetation must be considered as a potential sink for ozone. For the lower boundary condition and hence the overall mass balance of the transport model, it is therefore necessary to include also these non-stomatal pathways in the parameterisation.

Unfortunately, the observational evidence is somewhat mixed as to the actual mechanisms and controls behind the non-stomatal deposition, and the relative importance of different deposition pathways. This is related to problems in interpreting flux measurement data. From micrometeorological measurements that integrate on an ecosystem scale, for instance, it is not straightforward to partition the different sinks, even though the stomatal component can be estimated based on water vapour fluxes. Aerodynamic in-canopy effects further complicate the situation, especially for tall vegetation types. However, in the present application the separation between the different non-stomatal components is not crucial, as long as their sum is modelled reliably enough.

The approach adopted here is that the non-stomatal resistances are selected on the basis of the literature. Since large variability is reported for some of the inferred component resistances, the total surface resistance values are also broadly checked for consistency with observations. For land-cover types with a relatively constant and/or uncertain deposition velocity, a single bulk surface resistance is chosen as described previously in section 2.1.

4.1 External plant resistance (R_{ext})

This resistance represents all the external parts of the plants, including cuticles, twig, bark, mosses, etc. The traditional view based on early chamber studies (e.g. Rich et al., 1970; Turner et al., 1974) is that the deposition to leaves is predominantly via stomata, and thus any non-stomatal deposition observed can be interpreted as being deposited to the underlying soil. Investigations of cuticular permeability (e.g. Kerstiens & Lendzian, 1989) also support this idea.

In contrast to this, some recent studies suggest that there is a large non-stomatal component in the deposition to plants. These include branch cuvette studies of Scots pine and Norway spruce growing in Sweden, carried out by Rondón et al. (1993) and Granat & Richter (1995). By comparing ozone and water vapour fluxes, it was observed that the total ozone deposition flux to leaves often was 2 to 6 times the stomatal flux estimated based on evaporation fluxes. The cuvette technique eliminates the possibility of deposition to soil. The excess deposition was dependent on solar radiation, and it was suggested that photochemical reactions at the surface may be responsible for this sink. Some cuticular deposition was also observed in the dark. Efficient cuticular deposition was also suggested by Coe et al. (1995), who measured deposition to a dense (LAI = 10) Sitka spruce forest in Scotland during four days. There was a clear difference in the canopy conductance

between water vapour and ozone during daytime, the latter being higher by a factor of up to three. The importance of soil as a parallel sink was not addressed directly, but it was argued that the transport through such a dense canopy is restricted. A clear difference between the water vapour and ozone conductance values was also observed for a sub-arctic mountain birch forest by Tuovinen et al. (1999). The studies summarised here show that one cannot rule out the possibility of an efficient cuticular deposition. However, we do not have available a parameterisation that could be used for this.

It is often considered that the relatively low solubility of ozone in water would result in a low conductance for wetted plant surfaces (e.g. Hicks et al., 1987; Erisman et al., 1994). However, recent observational evidence shows that the situation is more complex and the effect of wetness depends on several competing processes. (Fuentes & Gillespie, 1992; Fuentes et al., 1992; Fuentes et al., 1994ab; Padro 1993; 1994; Padro et al., 1991, 1992, 1994; Massman et al., 1994; Grantz et al., 1995, 1997; Pleijel et al., 1995). According to these studies, surface wetness may limit deposition by masking reactive sites at the surface and by occluding stomatal pores, but it may also enhance deposition via heterogeneous reactions in the water film. As a net effect, the conductance may be either enhanced or retarded, depending on plant species (stomatal distribution, effect on leaf water chemistry) and origin of wetness. i.e. dew or rain (chemical composition, coverage of water, washing of reactive substances). It can be concluded from these studies that there is no basis for universally increasing the surface resistance for wet surfaces. Unfortunately, no suitable parameterisations are available to account for the variable effects. Existing parameterisations (Padro et al. 1991; Wesely, 1989) do not seem to be consistent with the recent observations.

In view of the uncertainties surrounding deposition rates to canopies, either dry or wet, we have assigned a single value to describe the external plant resistance to ozone deposition, irrespective of the land-cover category and water status of the cuticles. This value is preliminarily set at R_{ext} = 2500 s m^{-1}. For a canopy with LAI = 5, this corresponds to a conductance of 0.2 cm s^{-1}.

4.2 Soil resistance (R_{ext}) and in-canopy aerodynamic resistance (R_{inc})

A substantial amount of material can be deposited to the soil below vegetation. For instance, studies on deposition to a maize crop have estimated that typically 20–50% of the total deposition during the daytime in midsummer is non-stomatal and probably to the soil (Wesely et al., 1978; Leuning et al., 1979; van Pul & Jacobs, 1994). This deposition pathway is controlled by the transfer through the canopy and depends therefore on the density and height of the surface elements. The turbulent transport in a forest canopy is a complex process related to intermittent penetration of flow into the canopy. We have included a highly simplified parameterisation for this in-canopy resistance in the present deposition module. This parameterisation has been suggested by Erisman et al. (1994) based on the analysis of maize field data by van Pul & Jacobs (1994). The in-canopy resistance can be written as

$$R_{inc} = b\ SAI\ h/u_*, \qquad [5]$$

Where b = 14 m^{-1} is an empirical constant and h is the vegetation height taken as constant for each land-cover class. The leaf area index in the original formula has been here replaced by the surface area index, SAI to account in a simple way for leaves, twigs, bark, etc.. For grasslands R_{inc} is set to zero. It must be emphasised that this parameterisation is based on one data set for a maize field with a rather limited range of SAI h/u_*.

For bare soil a large range of resistance values has been observed. For instance, Turner et al. (1973), Galbally & Roy (1980) and van Pul (1992) have measured resistances well below 100 s m^{-1} for dry sandy soil, whereas Güsten et al. (1996) observed resistances of >3000 s m^{-1} for desert sand at night. It is considered that the resistance depends on the type and water content of the soil (Galbally & Roy, 1980). Owing to the low solubility of ozone in water, soil water limits the deposition by reducing the effective reactive surface. For instance, Wesely et al. (1978) measured a soil resistance of 1000 s m^{-1} for water-saturated silt loam soil in a ploughed field. On the other hand, Meyers & Baldocchi (1992) obtained a high resistance of 2000 s m^{-1} to deposition to the floor of a deciduous forest and reported no clear dependence on soil moisture.

As for the external plant resistance, we conclude that the data are too inconclusive for a detailed treatment of this deposition pathway and therefore choose preliminarily a single value of R_{gs} = 200 s m^{-1} for all land-cover classes. This corresponds to a conductance of 0.5 cm s^{-1}, i.e. a potentially rather efficient deposition velocity. However, as discussed above, deposition is limited by the in-canopy resistance in series with R_{gs}.

Figures 3 and 4 show the total non-stomatal surface conductance, $SAI/R_{ext} + (R_{inc} + R_{gs})^{-1}$, as a function of the surface area index for forests and crops, respectively. It can be noted that in the present parameterisation of non-stomatal resistances, the canopy density has a twofold role; the in-canopy resistance increases whilst the cuticular resistance decreases with increasing SAI. If the intensity of turbulent mixing, here parameterised in terms of u_*, is strong enough, the non-stomatal surface conductance shows only a weak dependence on SAI. For a forest with full leaves, the deposition to soil is efficiently limited by the aerodynamic in-canopy resistance, regardless of the value of R_{gs}, and the non-stomatal surface conductance is close to SAI/R_{ext} (Figure 3). For a leafless canopy, turbulent mixing largely determines the non-stomatal deposition by controlling transport to the soil. For crops, the assumed in-canopy resistance is smaller, and the underlying soil provides a significant sink for any SAI and u_*> 0.1 m s^{-1} (Figure 4).

4.3 Land-cover classes with a bulk surface resistance

4.3.1 Tundra and wetlands

The land-cover classes "Tundra" and "Wetlands" are taken to represent treeless areas with a low productivity. There are a few micrometeorological data sets available for these kind of ecosystems. The only European measurements are those by Tuovinen et al. (1998), who measured ozone deposition to an open sub-arctic fen in northern Finland. The mean surface bulk resistance during the active season was rather constant, being 400 s m^{-1} during the daytime and 480 s m^{-1} at night. Similar results have been obtained for a fen in Quebec, Canada (Moore et al., 1994), while the only data from tundra (mixed wet/dry tundra area in Alaska) shows a slightly lower mean resistance but also a similar, rather weak diurnal variation (Jacob et al., 1992). Based on these data, we choose a constant surface resistance of R_{sur} = 400 s m^{-1} for these land-cover types.

4.3.2 Desert

Ozone deposition to desert sand with no organic matter has been measured by Güsten et al. (1996). Their observations showed a mean resistance of 800 s m^{-1} during daytime and about 3000 s m^{-1}. The reason for the strong diurnal variation was not studied, but surface moisture effects were suggested. We have chosen a constant surface resistance of R_{sur} = 2000 s m^{-1} for this land-cover type.

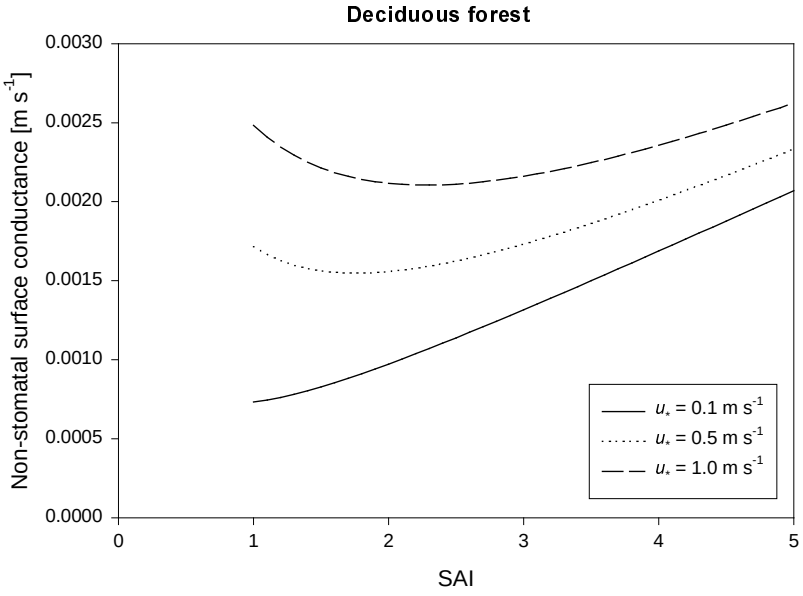


Figure 3. The non-stomatal surface conductance, $SAI/R_{ext} + (R_{inc} + R_{gs})^{-1}$, as a function of the surface area index for forests.

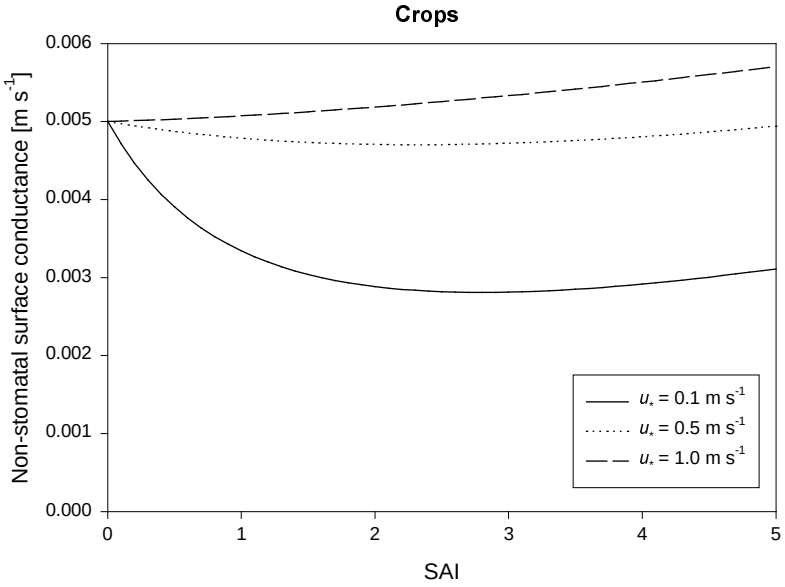


Figure 4. The non-stomatal surface conductance, $SAI/R_{ext} + (R_{inc} + R_{gs})^{-1}$, as a function of the surface area index for crops.

4.3.3 Water

A rather extensive set of observational data is available for water surfaces, both fresh water (Aldaz, 1969; Galbally & Roy, 1980; Wesely et al., 1981) and sea water (Aldaz, 1969; Regener, 1974; Garland & Penkett, 1976; Galbally & Roy, 1980; Garland et al., 1980; Lenschow et al., 1982; McKay et al., 1992). These data show that the surface resistance is larger than 1000 s m^{-1} and values in excess of 10,000 s m^{-1} have been determined in the laboratory for unstirred water (McKay et al., 1992). The resistance seems to depend on the surface roughness and may be larger for fresh water than seawater. Assuming rough surfaces to be typical in natural conditions, we choose from the data a lower end value of R_{ext} = 2000 s m^{-1} for all water surfaces.

4.3.4 Ice and snow-covered areas

Several studies have reported on measurements of ozone deposition to different types of snow surfaces (Aldaz, 1969; Galbally & Allison, 1972; Galbally & Roy, 1980; Wesely et al., 1981; Stocker et al., 1995). All observations show a rather inefficient deposition to snow. Fresh snow seems to have a lower surface resistance than old snow (Wesely et al., 1981; Stocker et al., 1995), but since our input data does not include this information we choose a single value of R_{sur} = 2000 s m^{-1}. This value is applied to the land-cover class "Ice" and snow-covered areas, as defined in the meteorological input data.

4.3.5 Urban

There seem to be no observations for non-vegetated urban areas. We assume a limited vegetation cover with a relatively inefficient overall deposition for this land-cover class and adopt the same constant resistance of R_{sur} = 400 s m^{-1} as Wesely (1983, 1989).

5. Preliminary Model Analysis

5.1 Modelling and parameterisation used for preliminary model analysis

At the present time there are some components of the modelling and land-cover schemes that are in the process of being developed. The most important modelling problem concerns soil-water, and as noted previously we confine this report to the study of well-watered vegetation, with $g_{SWP}=1$. For land-cover, work is still needed to define LAI and its seasonal variation in an optimal way. However, it is considered that the bulk of this deposition module is now far enough evolved to provide preliminary model outputs to be produced and tested against existing measured data. The assumptions that have been used in conjunction with the model components that are still under development will, in the near future, be tested and where appropriate improved, so that these components can eventually be incorporated into the overall deposition module.

The following section describes the methods currently being used to calculate these model components still under development which include a) estimation of growing season; b) estimation of leaf area index and c) methods used to up-scale from the leaf/needle to the entire canopy. These descriptions are included so as to give a complete documentation of the methods used to achieve the preliminary model results. These results are described and compared with measured data, collected either from published papers or available (but as yet unpublished) data from field campaigns.

5.1.1 Growing season

The growing season is defined as that part of the year when the leaves are physiologically active and hence allowing significant ozone uptake. Of the land-cover types considered in this study, only the temperate/boreal coniferous forests, moorlands/heathlands and grasslands will have needle or leaf areas outside the period of the growing season. During this period it is assumed that R_{sto} will be equal to $(g_{min} / 41000)^{-1}$ (Körner, 1994). For all other land-cover types, either the leaves are not present (LAI=0) or the growing season is assumed to continue throughout the year. The Surface Area Index (SAI), which allows for the fact that the woody plant material will still provide a significant sink to ozone deposition after senescence, is included only for deciduous forests. SAI is set equal to LAI in the growing season for these forests, or to 1 $m^2 m^{-2}$ outside the growing season.

The preliminary model runs described here used fixed growing season length and timings based upon published studies which have documented such data. The fixed dates used for each land-cover type are shown in Table 2. Although the use of a fixed growing season is not ideal, it does give an indication of the variability in length and timing of growing seasons and hence the seasonal differences in ozone deposition between the individual land-cover types.

Table 2 Start (SGS) and end (EGS) dates (day numbers) of fixed growing seasons used for model comparisons

Land-cover Class	SGS	EGS	References
Temp./boreal coniferous forest	0	365	Körner (1995)
$*g_{age}$	0	485	Beadle *et al*. (1982)
Temp./boreal deciduous forest	90	270	Abdulla & Lettenmaier (1997), Olson *et al*. (1985), Padro (1996), Jakobsen et al. (1996)
Medit. needleleaf forests	0	365	Hassika et al. (1997)
Medit. broadleaf forests	0	365	Sala & Tenhunen (1994), Gratani (1993), Sala & Tenhunen (1996)
Temp. crops	105	197	Olson *et al*. (1985), Boumann (1995)
Med. crops	150	300	Studeto et al. (1995), Bouman (1995)
Root crops	130	250	Pers. comm. Vandemeiren (EU CHIP Project)
Vineyards	120	300	Padro (1994), Mascart *et al*. (1991)
Temp. orchard	90	270	Tustin et al. (1988); Palmer et al. (1992)
Medit. orchard	0	365	Padro (1994), Mascart *et al*. (1991)
Grasslands	0	365	Mascart *et al.* (1991), Olson *et al*. (1985)
Semi-natural	0	365	Mascart *et al.* (1991), Olson *et al*. (1985)
Med. scrub	0	365	Pio et al. (2000)

N.B. The Temp./boreal coniferous forest group has two different parameterisation. The second parameterisation ($*g_{age}$) is used in conjunction with the provisional methodology, described in section 5.1.3.1, which estimates the canopy conductance according to needle age. The EGS of 485 enables the use of the generic g_{age} calculation incorporating the fact that the current year needles are assumed to emerge on 1st April and then become "older" needles on 1st April of the following year.

In the future, thermal time models, which estimate growing seasons according to land-cover type specific temperature sum thresholds will be investigated as they should generate a more realistic spatial distribution of LAI changes, as well as allowing for year-to-year variability.

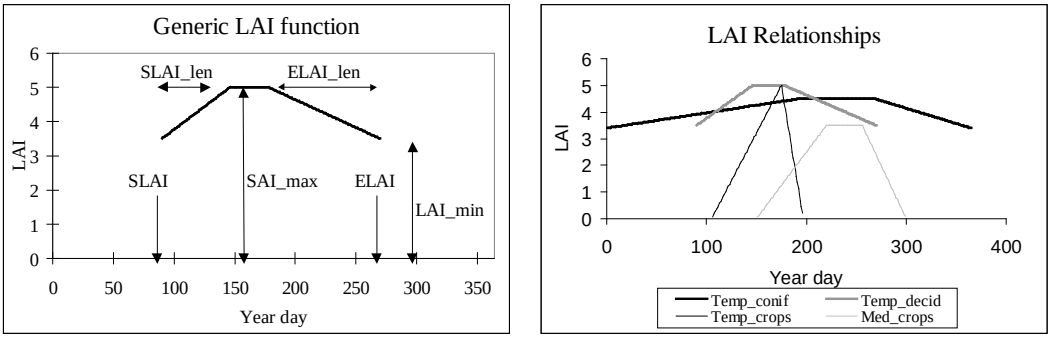
5.1.2 Leaf Area index

Default values of LAI are needed for the model evaluations. LAI is calculated according to the functions plotted in Figure 5. Table 3 summarises the parameter values used for each of the different land-cover types. The necessary values were established from published data collected from the literature for representative species of each land-cover type.

Table 3 Maximum LAI and course of LAI throughout the growing season for the different land-cover categories.

Land-cover Class	SLAI	ELAI	LAI_min	LAI_max	SLAI_len	ELAI_len	References
Temp./boreal coniferous forest	0	365	3.4	4.5	192	96	Abdulla & Lettenmaier (1997), Neilson & Marks (1994), Beadle *et al*. (1982)
Temp./boreal deciduous forest	=SGS	=EGS	3.5	5	56	92	Abdulla & Lettenmaier (1997), *Olson et al*. (1985), Padro (1996), Jakobsen et al. (1996)
Medit. needleleaf forests	0	365	-	3.5	-	-	Hassika et al. (1997)
Medit. broadleaf forests	0	365	-	4.5	-	-	Sala & Tenhunen (1994), Gratani (1993), Sala & Tenhunen (1996)
Temp. crops	=SGS	=EGS	0	5	70	22	Olson *et al*. (1985), Boumann (1995)
Med. crops	=SGS	=EGS	0	3.5	70	44	Studeto et al. (1995), Bouman (1995)
Root crops	=SGS	=EGS	0	6	35	65	Pers. comm. Vandemeiren (EU CHIP Project)
Vineyards	0	365	-	3	-	-	Padro (1994), Mascart *et al*. (1991)
Temp. orchard	=SGS	=SGS	1	3.5	60	100	Tustin et al. (1988); Palmer et al. (1992)
Medit. orchard	0	365	-	3	-	-	Padro (1994), Mascart *et al*. (1991)
Grasslands	0	365	2	5.5	140	135	Mascart *et al.* (1991), Olson *et al*. (1985)
Moor/heathland	0	365	2	5	192	96	Abdulla & Lettenmaier (1997), Neilson & Marks (1994)
Med. scrub	0	365	-	4.5	-	-	Pio et al. (2000)

Figure 5 Generic function for Leaf Area Index (LAI) and examples of seasonal course of LAI for selected land-cover types.



5.1.3 Up-scaling from leaf to canopy

The stomatal resistance model described in section 3 calculates R_{sto} for an individual young fully developed leaf or needle. To calculate the stomatal resistance of the entire canopy it is necessary to scale up from the leaf/needle to the canopy level. For the preliminary model runs described in the following section, this is achieved by calculating g_{light} according to the appropriate visible radiation value as it varies with cumulative LAI within the canopy. The radiation transfer within the canopy is calculated according to the method devised by Norman (1982), that estimates diffuse and direct irradiance on sunlit and shaded leaves/needles within vegetative canopies. The calculations of direct (I_{dir}) and diffuse (I_{diff}) solar irradiance (W m^{-2}) and solar elevation ($\sin\beta$) are made according to Jakobsen et al. (1996) where sin β is the complement of the zenith angle of the sun. Note that I_{dir} and I_{diff} are converted from W m^{-2} to μmol m^{-2} s^{-1} by multiplying by 4.57 for use within the following equations. The sunlit leaf area (LAI_{sun}) of the canopy is calculated according to: -

$$LAI_{sun} = [1 - \exp(-0.5 * LAI / \sin\beta)] * 2\sin\beta \quad [6]$$

The proportion of the total LAI that is shaded (LAI_{shade}) is then simply calculated as: -

$$LAI_{shade} = LAI - LAI_{sun} \quad [7]$$

PAR_{sun}, which is dependant on the mean angle between leaves and the sun, is calculated using a modified "big leaf" version of the canopy radiation transfer model of Norman (1982) where the flux density of PAR on sunlit leaves is: -

$$PAR_{sun} = I_{dir} * \cos(\theta) / \sin\beta + PAR_{shade} \quad [8]$$

Where I_{dir} is the flux density of direct PAR above the canopy and θ is the angle between a leaf and the sun. For these calculations it is assumed that the canopy has a spherical leaf inclination distribution (θ) constant at 60 degrees.

PAR_{shade} is calculated semi-empirically by: -

$$PAR_{shade} = I_{diff} * \exp(-0.5 * LAI^{0.7}) + 0.07 * I_{dir} * (1.1 - 0.1 * LAI) * \exp[-\sin\beta] \quad [9]$$

.

The g_{light} values, calculated as described previously in equation 3, for these sunlit (g_{light}sun) and shaded (g_{light}shade) leaves are weighted according to the fraction of sunlit and shaded leaf area and summed to give the total irradiance-dependant canopy conductance (g_{light}). This method has been simplified so that rather than integrating g_{light} over the canopy a "big leaf" approach has been employed. This means that g_{light} will be underestimated since the model does not allow for the variability in direct and diffuse irradiance within the canopy. However, since these parameters vary only slightly the model under-estimations are relatively small.

$g_{light}sun = [1 - \exp(-\alpha * PAR_{sun})]$ [10]

$g_{light}shade = [1 - \exp(-\alpha * PAR_{shade})]$ [11]

Finally, g_{light} is calculated as: -

$g_{light} = g_{light}sun * LAI_{sun} / LAI + g_{light}shade * LAI_{shade} / LAI$ [12]

This mean canopy g_{light} value is used in equation [2] to calculate mean canopy leaf/needle R_{sto}. The canopy R_{sto} is then calculated in equation [1] using the cover-type specific LAI to upscale from the leaf/needle to the canopy level.

5.1.3.1 Needle Age

The stomatal conductance of leaves and needles decreases with age. For those vegetation groups whose canopies comprise of leaves/needles that emerge and senesce within a single year the g_{age} function described in Figure 2 accounts for the variability in stomatal conductance with leaf age. However, for certain vegetation groups, namely the needle bearing forest groups (conif_temp and med_needle) needles remain on the tree for a number of years. Since these older needles comprise a significant proportion of the total LAI, the effect of needle age on canopy conductance needs to be incorporated into the model for these vegetation groups. A method, described below, has been devised to account for the effect of needle age and has been used in the calculations of ozone deposition to conif_temp.

The canopy LAI is divided into two needle classes a) current needles and b) older needles. The respective ratio of these two classes varies over the course of the year as described by Beadle *et al*. (1982) and shown in Table 4. In addition, the stomatal conductance of current year needles, $g_{age}C$, is influenced by age. This decreases from that time when $g_{age}C$ first drops below g_{max} (as defined for conif_temp species by Körner, (1995)) to a value of half this maximum conductance once the needles are 1 year old (Wallin et al., 1990, 1992a; Beadle *et al*., 1982). The relationship for $g_{age}C$ follows functions the generic form shown in Figure 2, using the values given in Appendix A: Table A1. No further reduction in the maximum potential stomatal conductance is assumed with increasing age past 1 year (i.e. all needles greater than or equal to 1 year old are assigned a maximum potential stomatal conductance, $g_{age}O$, of 0.5 g_{max} .

Table 4 Parameterisation used to calculate effect of needle age on canopy conductance. Proportion (Pc) of current year needles in canopy

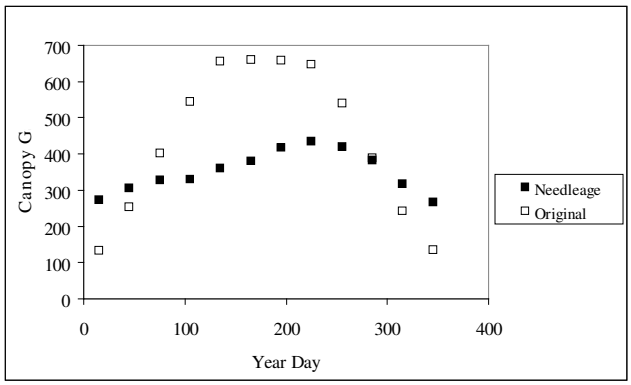
Month	J	F	M	A	M	J	J	A	S	O	N	D
Pc	0.53	0.535	0.54	0.545	0.1	0.15	0.27	0.36	0.42	0.48	0.5	0.5

The overall g_{age} can then be calculated by equation [13] and then be used in equation [2] described previously in this document.

$$g_{age} = Pc * g_{age}C + (1-Pc) * g_{age}O \quad [13]$$

An example of the above calculation performed for the conif_temp vegetation group, giving midday values for each month assuming cloudless conditions is shown in Figure 6 (Needleage). As a comparison, data are also shown which describe the light dependent canopy conductance assuming all needle age classes have equal potential maximum conductance values (Original).

Figure 6 Canopy conductance (Gs canopy) as a function of canopy radiation and needle age for the conif_temp vegetation group.



5.2 Comparisons of modelled Vs measured data.

The following sections describe some comparisons of the results obtained from preliminary model runs which have been performed using the deposition model as described in sections 3 to 4 with the provisional assumptions described above in section 5.1. These comparisons are made in one of two ways: - 1) by comparing modelled values against site-specific measured values and 2) through comparison with published data collected from the literature.

It is important to note that model data for these comparisons has not generally been available for the time-period of the measurements. Model data from the 50 x 50 km^2 NWP model with 6-hourly resolution was available for 1996, and 3-hourly resolution for 1997. Thus, these comparisons should be interpreted with care. The comparisons of model outputs with published data are made as far as possible with those results that most closely match the time of year, time of day, prevailing climate, land-cover type and geographical location. However, the comparisons described below should still give a good general idea of the model performance in terms of the models capability to predict output values within the range of comparable published data. Two other points should be made with reference to the comparisons with published data. Firstly, it should be noted that the comparisons of canopy conductance values described in the following sections are invariably made with published data for water vapour converted to ozone using a diffusivity ratio of 0.6. Secondly, the fact that the VPD calculation was made using air rather than leaf temperature may result in a tendency to underestimate the VPD and hence the g_s response to this environmental variable. Such under-estimations are likely to be greater for the shorter broadleaf species since larger leaf blades coupled with relatively lower wind-speeds associated with shorter vegetation types tend to result in higher leaf to air temperature values.

The site-specific studies include two investigations. The first performed by Tuovinen (2000) for a Scots pine forest in Finland where default canopy parameters were modified according to local conditions and the model was run using in-situ meteorological observations. The second site-specific study investigated the performance of the stomatal component of the model comparing measured and modelled stomatal conductance to ozone using site-specific meteorological input data with Norway spruce gs parameterisation (Emberson et al. 2000a).

Figures 7-8 illustrate some calculated values of deposition velocity, canopy stomatal conductance, and g-factors for a number of different land-cover types. Results are illustrated here for a location in Scotland, but calculations have been performed for several other locations in Europe, using meteorological data from the EMEP 50x50 km^2 data sets, with 3-hourly resolution. As noted earlier, all results are calculated for the well-watered situation, i.e. assuming $g_{SWP}=1$. The example sites were chosen so as to represent different climatological conditions. These grid squares are named according to specific sites located within the square at which field measurements of ozone fluxes have been performed. The sites are: -

Petsikko, Finland (latitude 69^oN)
Auchencorth Moss, Scotland (latitude 56^oN)
Payerne, Switzerland (latitude 47^oN)
Montemor, Portugal (latitude 39^oN)

At each site the calculations are carried out for each land-cover type included in the model that employs the parameterisation of the stomatal conductance. This means that, except for a few cases, the data do not refer to actual ecosystems. We discuss here some initial observations on the model results, including both stomatal and non-stomatal pathways.

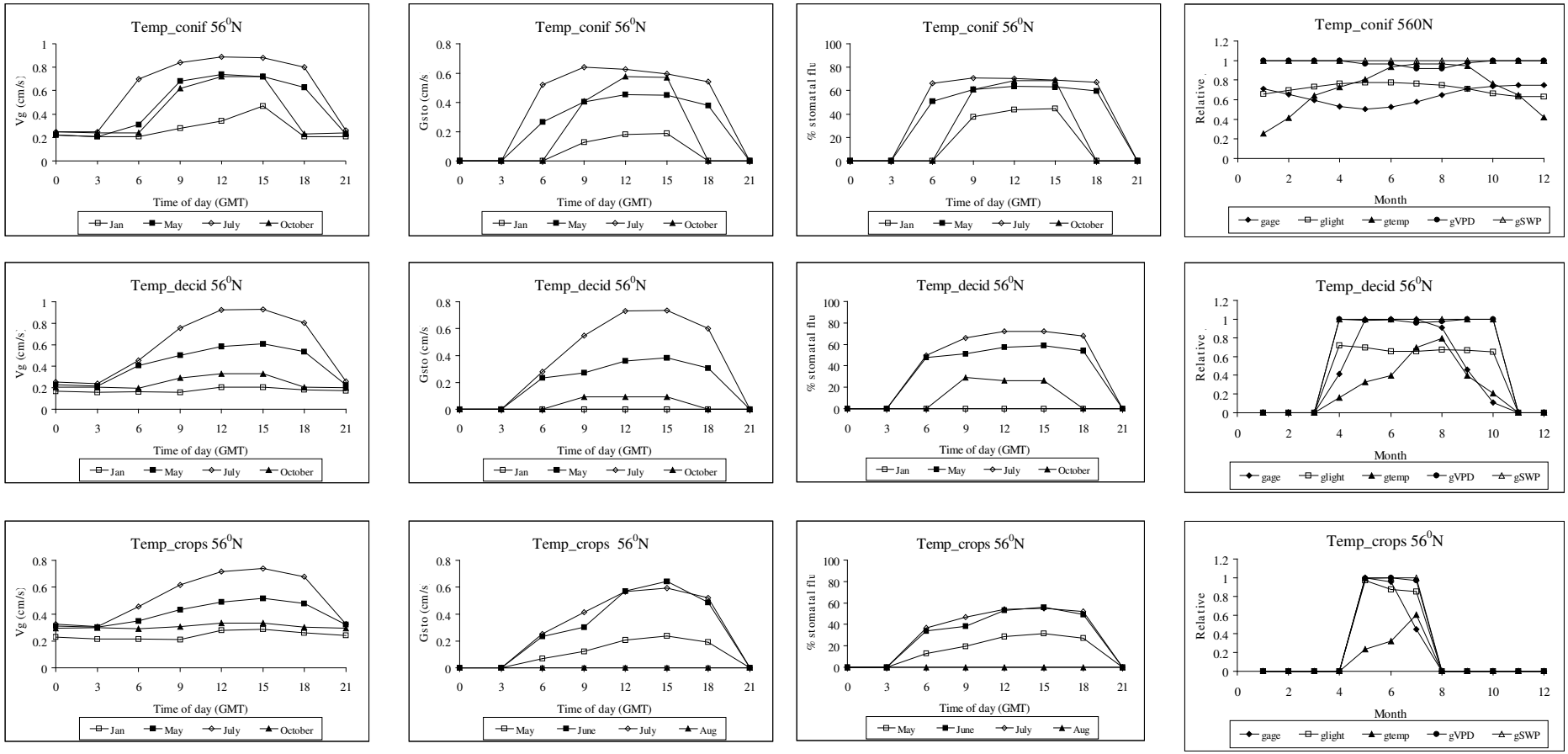


Figure 7 **Calculations for Auchencorth Moss, Scotland. From left to right: (a) near surface deposition velocities (Vg) (1/(Ra(d+3m)+Rb+Rsur)), (b)canopy stomatal conductance (Gsto), (c) % of canopy stomatal component of surface deposition, (d) noon-time g-factors. Results given as monthly averages, calculated when LAI > 0 for 5 days or more during a month.**

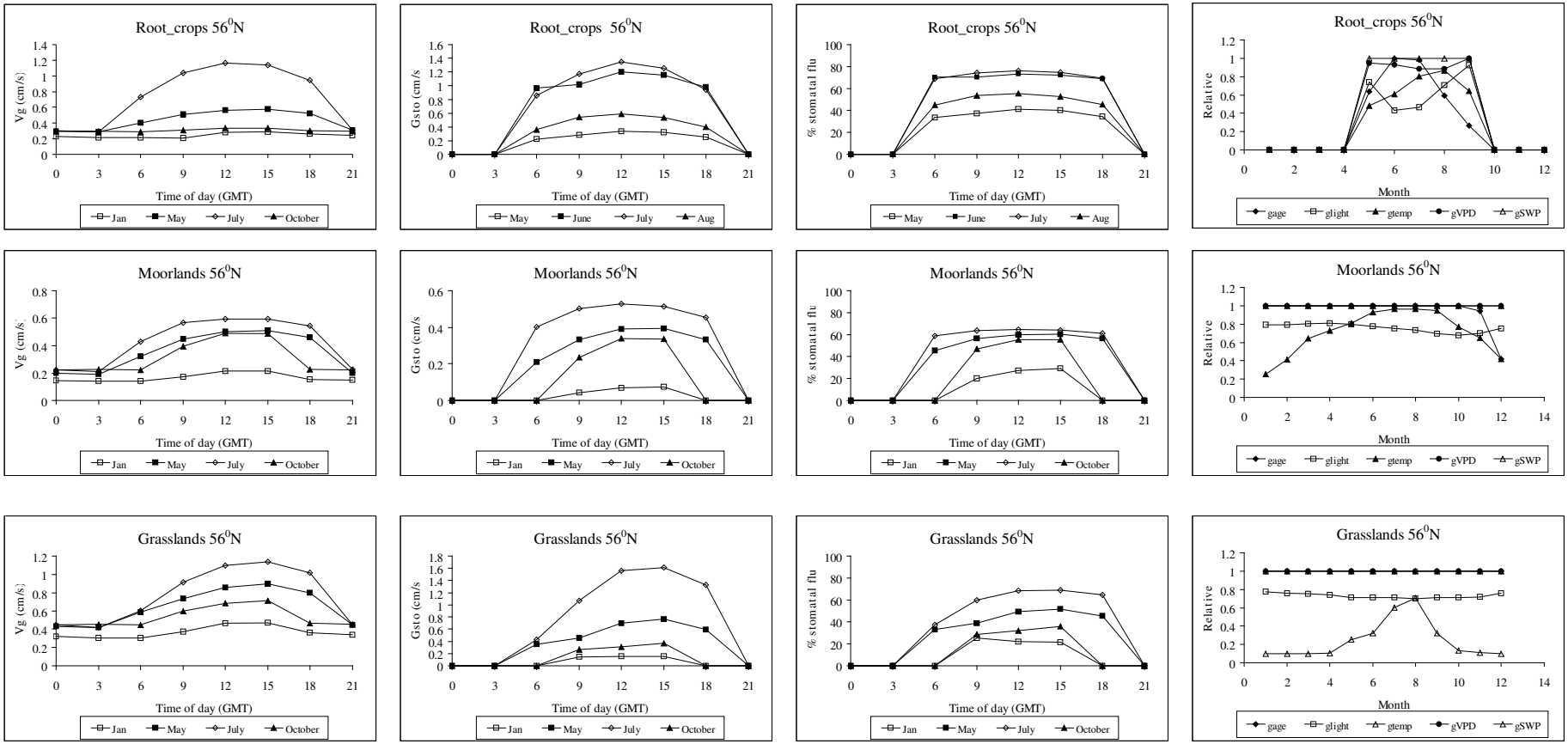
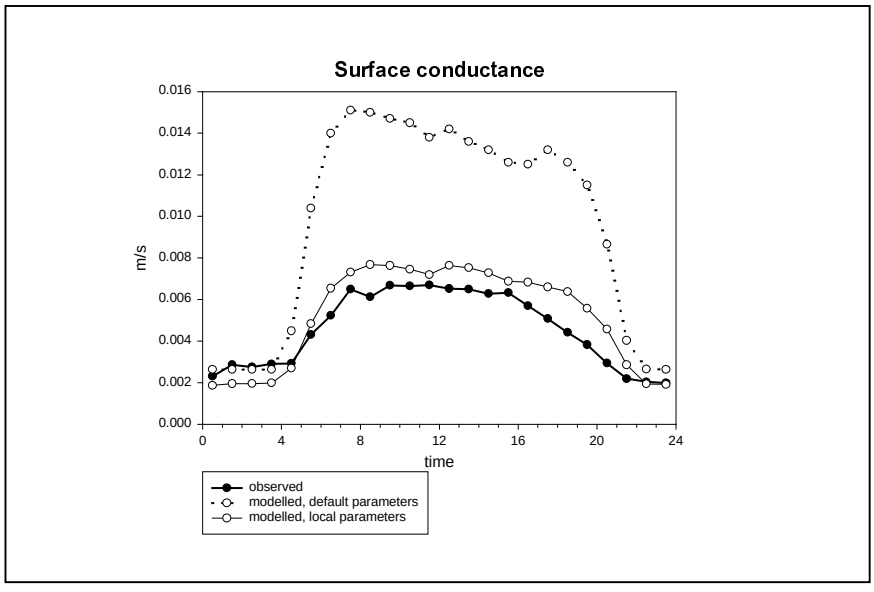


Figure 8 **Calculations for Auchencorth Moss, Scotland. From left to right: (a) near surface deposition velocities (Vg) (1/(Ra(d+3m)+Rb+Rsur)), (b)canopy stomatal conductance (Gsto), (c) % of canopy stomatal component of surface deposition, (d) noon-time g-factors. Results given as monthly averages, calculated when LAI > 0 for 5 days or more during a month.**

5.2.1 Comparison of modelled data with site-specific measured values

The results shown in Figs 7-8 are calculated by using the default land-cover specific values of canopy height and leaf area index. For a sparse forest, these values are not representative and are expected to lead to overestimated deposition rates. This has been demonstrated with an earlier version of the model by Tuovinen (2000), who compared the model results with observations made in a relatively sparse (LAI ≈ 2) pine forest in Finland (63°N). It is important to note that since this comparison used an earlier model version the effects of needle age on canopy conductance were not incorporated, therefore the results presented in Figure 9 should not be directly compoared with those presented in Figure 7. The comparison showed that at this site the mean midday maximum of the surface conductance in July 1995 was 0.67 cm s^{-1}, which is about 50% of the model prediction. However, when tested in a site-specific mode, adjusting the canopy parameters according to local conditions and also using *in situ* meteorological observations, a satisfactory fit with observations was obtained, as shown by the mean positive bias of 16% in the deposition velocity (Tuovinen, 2000). The results of this comparison are shown in Fig 9, in which where observed and modelled surface conductance values are shown. The modelled G_{sur} (in m s^{-1}) values are similar to the observed values when the local input data and LAI value is used in place of the EMEP meteorological data and default LAI parameterisation.

Figure 9 Surface conductance to ozone for a sparse Scots pine forest growing in Finland. Comparisons are made between observed and modelled data using a) default model values and b) using local vegetation parameters and meteorological input.



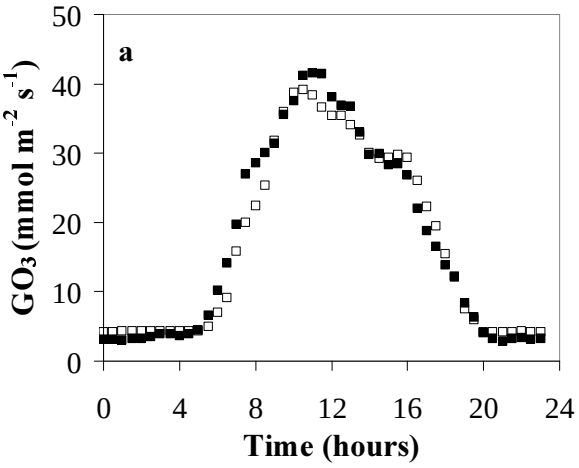
There was a tendency for the model to over-predict the deposition rate, except for highest rates that were under-predicted. The residual between the observed and modelled surface conductance did not depend on air temperature, PAR or VPD. However, the under-prediction of G_{sur} coincided with the highest friction velocities, which may be related to the simple parameterisation of the aerodynamic in-canopy resistance. Overall, this example demonstrates that the model is capable of predicting

the mean summertime deposition velocities, but also that considerable uncertainties result from aggregating forests with a wide density range into a single land-cover category.

Because of the role of LAI in the parameterisation, a corresponding under-prediction could be expected at sites with a LAI larger than the default value. For coniferous forests, this should be true for spruce stands. Pilegaard et al. (1995a) measured a mean daytime surface resistance of 150 s m^{-1} (G_{sur}= 0.7 cm s^{-1}) for a 12-m Norway spruce plantation in Denmark in June 1994 and a much higher value of 370 s m^{-1} (G_{sur}= 0.3 cm s^{-1}) for the dry month of July 1992. These correspond to a considerably lower surface conductance than predicted by the model. The reason for the differences is not clear. On the other hand, the measurements during a winter month show a mean daytime surface resistance of 210 s m^{-1} (Pilegaard et al., 1995a), which is close to the model predictions.

In a separate study performed by Emberson et al. (2000a), modelled values using Norway spruce g_s parameterisation were compared against field measurements of Norway spruce g_s. In this instance a direct comparison of the modelling techniques was possible as the meteorological input used in the modelling were those recorded as the g_s measurements were performed. The model performed reasonably well accounting for 66 % of the variation in stomatal conductance to ozone (GO_3) to an individual needle. In addition, the model was capable of describing monthly mean diurnal variation in stomatal conductance with reasonable accuracy, an example of which is shown in Figure 10. However, this study highlighted the importance of assigning the correct g_{max} value, since the use of a value consistent with local conditions improved the predictive capabilities of the model.

Figure 10 Comparison of modelled and measured average diurnal values of GO_3 for Norway spruce (*Picea abies*) during the 1989[(a)] investigation period (Emberson et al. 2000a). The measured and modelled values are represented by filled and open squares respectively.



5.2.2 Comparison of modelled data with published data

Table 5 describes ozone deposition velocities (collated in a recent paper by Brook et al. (1999)) and canopy conductance values collated within this project with comparable model results (shaded columns). It should be noted that the deposition

velocity values described by Brook et al. (1999) present data collected from North America as well as Europe. In contrast, this section only gives details of European studies, some of which have been published since 1999. Therefore, the information in the table is not a summary of the dicussion presented below.

5.2.2.1 Temperate/boreal coniferous forests

During the growing season, the modelled deposition is largely determined by stomatal uptake, as generally assumed (e.g. Fowler et al., 1989). In summer, VPD limits the stomatal conductance during daytime. In northern Europe, low temperatures are also an important limiting factor during other seasons. The value set for the external plant resistance results in a small but significant deposition at night, consistent with observations for Norway spruce by Pilegaard et al. (1995a) and for Scots pine by Tuovinen et al. (1999). This deposition pathway is however parameterised in the present module as being less efficient than the results of Rondón et al. (1993), Granat and Richter (1995) and Coe et al. (1995) suggest, as discussed above. In winter, the surface conductance is considerably smaller and the non-stomatal component dominates.

In addition to the longer-term measurements cited above, several short campaigns have been carried out. In some of these, very low surface resistances have been observed. Even though Coe et al. (1995) report a mean R_{sur} of 180 s m^{-1} for a dense Sitka spruce forest in Scotland for a five-day period in May, the results also show that for three days the daily minimum was as small as 20 s m^{-1}. Values significantly lower than 100 s m^{-1} were occasionally observed at a 20-m high Douglas fir forest in the Netherlands (Choularton et al., 1994) and at a forest dominated by mature Norway spruce in southern Germany (Enders, 1992).

In terms of the ability of the model to describe the stomatal component, Slovik et al. (1996) modelled canopy conductance values for German Norway spruce stands calculating g_s using a similar multiplicative model and up-scaling according to an effective LAI. They plotted mean annual time courses for canopy stomatal conductance over the year, which is compared in Figure 11 with equivalent modelled data from the Payerne grid square to give an indication of the models ability to predict the seasonal profile of canopy conductance. The canopy conductance datasets for published and modelled values are standardised (presenting values relative to the maximum conductance found within the year) to provide a direct comparison of the seasonal profile. Figure 11 shows that the deposition models seasonal profile compares well with that modelled by Slovik et al. (1996) with only slight differences in Relative G_{sto} at the start and end of the year, these are probably related to the different parameterisations of the phenological influence on canopy conductance.

Table 5 Comparison of measured values with modelled estimates for a) total ozone deposition velocity and b) canopy stomatal conductance. All values are given as ozone conductances in units of cm s^{-1}.

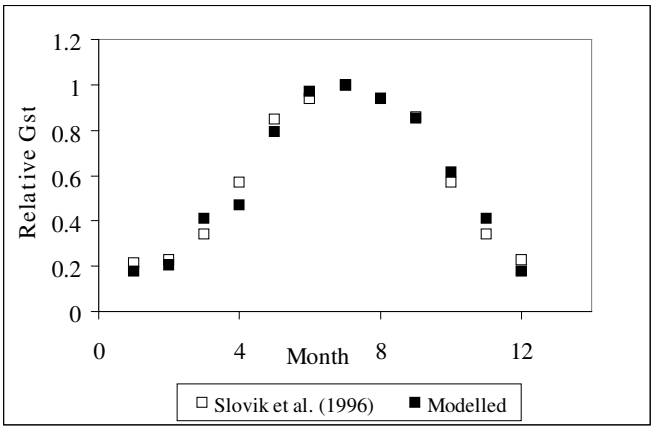
a) Deposition velocity comparisons

Surface	Observation				Modelled		
	Mean	Range	Condition	Reference	Land-cover type	Mean	Range
Beech	0.4	0.1 – 0.7	April, May	Pilegaard et al (1995b)	DF	0.41	0.22 – 0.78
Deciduous forest	1.0	0.0 – 1.8	Dry day summer	Padro et al. (1992, 1994)	DF	0.5	0.25 – 0.82
		0.0 – 1.2	Wet day summer				
	0.2	0.0 – 1.2	Night summer			0.24	
		0.0 – 0.5	Dry winter			0.18	0.12 – 0.25
		0.0 – 0.4	Wet winter				
		0.11 – 0.45	Winter	Wesely et al. (1983)		0.18	0.12 – 0.25
		0.23-0.45	Day winter				0.15 – 0.23
Grape		0.02 – 0.92	No dew	Massman et al. (1994)	V	0.7	0.1 to 1.3
		0.01 – 1.02	Dew				
Grass		0.05 – 0.2	Summer	Padro (1996)	GR	0.58	0.3 – 0.89
	0.56	0.06 – 1.0	Daytime	Delany & Davies (1983)		0.67	0.58 – 0.89
		0.0 – 0.56	No dew	Massman et al. (1994)			
	0.24		Summer	Meyers et al. (1998)		0.58	
Pine forest		0.0 – 1.16		Sanchez & Rodriguez (1997)	CF	0.39	0.18 – 0.73
	1.0		Summer	Lenschow et al. (1982)		0.48	0.22 – 0.74
Spruce		0.0 – 0.7	June	Pilegaard et al. (1995a)	CF	0.51	0.22 – 0.74

b) Canopy stomatal conductance comparisons

Surface	Observation	Condition	Experimental apparatus, Location	LAI	Calculation	Reference	Land-cover type	Mean	Range
Scots pine (*Pinus sylvestris*)	May: 0.6 June: 2.4	Daytime	England	7.5 – 11.3	Calculated from gs and LAI allowing for height within the canopy and needle age	Roberts et al. (1982)	CF	May: 0.38 June: 0.49	
Sitka spruce (*Picea sitchemsis*)	Max: 0.5 Range: 0.016 – 0.5 (Daytime)	Diurnal	Field, Scotland	10.2	Calculated using eddy correlation techniques with Penman Monteith equation	Coe et al (1995)	CF	Max: 0.45	0.26 – 0.45 (daytime)
35 yr. old Scots pine (*Pinus sylvestris*)	Max: 0.31 Range: 0.0 – 0.31	June, Diurnal	Field, Germany	3	Calculated from sapflow	Sturm et al. (1998)		Max: 0.58 Mean: 0.33	Range: 0.0 – 0.58 (diurnal
40 - 140 yr old Norway spruce (*Picea abies*)	Max: 0.24 (10.00 Hrs) Mean: 0.15 (Daytime) Range: 0.01 – 0.24	Diurnal	Field, Germany	6.5	Calculated from sapflow	Köstner et al. (1998)	CF	Max: 0.61 Mean: 0.5 (Daytime)	0.0 – 0.61
35 yr old Beech (*Fagus sylvatica*)	Mean: 0.3 Range: 0.015 - 0.66	Daytime, June to September	Field, Italy	3.8	Calculated using Penman-Monteith equation.	Magnani et al. (1998)	DF	Mean: 0.23	0.0 – 0.86
32 yr old Sessile oak (*Quercus Petraea*)	Max: 2.5	Summer	Field, France	6	Calculated using Penman-Monteith equation.	Breda et al. (1993a)	DF	Mean: 0.23	0.0 – 0.86

Figure 11 Comparison of relative G_{sto} values from published data (Slovik et al. 1996) for German Norway spruce stands and modelled data for conif_temp land-cover type from the Payerne grid square.



Roberts et al (1982) made calculations of canopy conductance for a 26 yr. old Scots pine (*Pinus sylvestris*) stand from measurements made of LAI and g_s at different heights in the canopy and on needles of different classes. These measurements are made in May and June when LAI of individual trees within the stand ranges between 7.5 and 11.3. The published daily maximum values of canopy conductance are in the range of 0.6 to 2.4 cm s^{-1}. In comparison, the modelled mean daily maximum for May and June predicted for the Auchencorth location are significantly lower with values of 0.45 and 0.58 cm s^{-1} for May and June respectively. This may be partly explained by the larger LAI of Scots pine in the published study (LAI of the modelled data ranges from 4.2 to 4.4) but even so, the published canopy conductance values reported are still very high.

In a separate study, Coe et al. (1995) used eddy correlation techniques to calculate deposition velocities for ozone and as well as the canopy resistance to ozone. These field measurements were made in a Sitka spruce (*Picea sitchensis*) plantation in Scotland with a LAI of 10.2. Measurements were made over the course of 5 days during the end of May. The deposition velocities calculated gave night-time values of less than 0.2 cm s^{-1} with daytime deposition velocities reaching a peak of between 0.7 and 1.4 cm s^{-1} remaining at between 0.4 and 1.0 cm s^{-1} throughout the day. The measured values of canopy stomatal conductance were found to rise sharply to 0.5 cm s^{-1} as stomata opened in response to full sunlight. In the afternoon conductance decreased steadily to between 0.025 and 0.016 cm s^{-1} when evaporative losses of water caused stomatal closure. Stomatal canopy conductance then rose again in the early evening to 0.025 with brief stomatal opening. These data compare favourably with model results that predict mean maximum canopy conductance values in May of between 0.4 to 0.5 cm s^{-1}.

Sturm et al. 1998 measured canopy conductance values of 35 yr. old Scots pine (*Pinus sylvetris*) in Germany during the summer of 1993 (LAI = 3) and 1994 (LAI = 1.9). During periods when soil water was not limiting, maximum canopy conductance values of 0.3 cm s^{-1} were observed during the morning period. These conductance values decreased with increasing VPD over the course of the day to values of 0.075 cm s^{-1} during the afternoon. The modelled values predict mean

maximum canopy conductance values for June 1997 of 0.56 cm s^{-1} occurring in the afternoon i.e. there appears to be no decrease in conductance with increasing VPD. However, Sturm et al. (1998) also detail the corresponding VPD climate which indicates that canopy conductance begins to decrease once VPD reaches approx. 1.1 kPa. This is in agreement with the stomatal conductance parameterisation assigned to the conif_temp land-cover type. This would suggest that that the model should be capable of predicting the observed lower canopy conductance values but that in the 1997 model runs described the VPD climate is not severe enough to produce this diurnal variation.

In summary, it would appear that the model is predicting canopy conductance values that are in general agreement with published values when differences in LAI are taken into account, and allowing for differences in model and measurement time-periods. It should be noted that the default LAI values for this cover type have been assigned a maximum of $5m^2$ m^{-2}. As has been described above, LAI values for coniferous species can be well in excess of this value (with LAI values reaching 10 and above) and this aspect of the variation of LAI with geographical location needs further investigation and ideally to be represented within the land-cover map. In addition, it should be noted that the up-scaling from needle to canopy uses a canopy radiation transfer model and information describing the relative proportions and conductance values of current and older needle age classes. The data to parameterise this model have been taken from Scots pine trees with relatively low LAI. An investigation by Skärby et al., (1995) showed that the proportion of current to older needles present on Norway spruce trees decreased with age. This study compared an 8 year old trees (with an LAI of 2) and 89 year old tree (with an LAI of 10) and estimated that current year needles made up 72% and 16% respectively of the canopy. The variability in needle age class proportions will need to be taken into account once it is possible to describe the European variation in LAI within cover-types.

5.2.2.2 Temperate/boreal deciduous forests

Stomatal conductance is also assumed to control the deposition to deciduous forests in summer. In July, for example, the model predicts the stomatal to total surface conductance to be about 70%. Due to the stronger response to temperature, the stomatal conductance is however somewhat lower than that of conifers. Deposition is not fully prevented in the absence of leaves, as the reduced in-canopy resistance makes deposition to the underlying ground surface possible. This is in accordance with observations made in Ontario, Canada, where a mean deposition velocity of 0.3 cm s^{-1} was observed at 15 m above a 18-m high mixed (red maple, poplar) forest during a leafless spring period (Padro et al., 1992). The modelled surface conductance also fits reasonably well the strong diurnal cycle observed at this site in summertime (LAI=5), although the mean midday canopy stomatal conductance is somewhat smaller than the value of 1.0 cm s^{-1} estimated from the measurements (Padro, 1996).

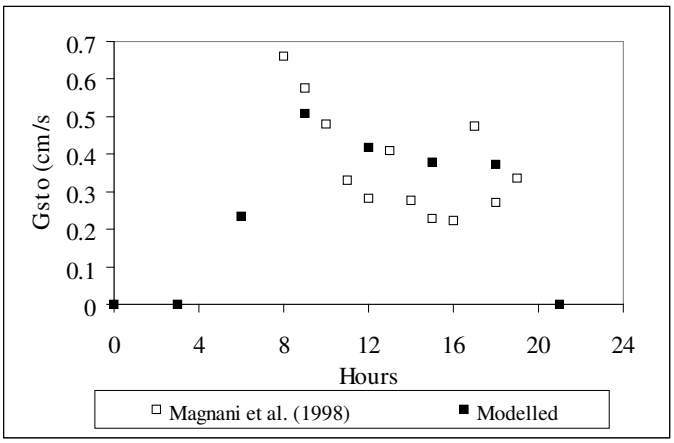
On the other hand, Pilegaard et al. (1995b, 1997) measured higher resistances for a beech forest in Denmark. In May, with fully unfolded leaves, the mean daytime (06:00-18:00) surface resistance was 270 s m^{-1} ($G_{sur} \approx 0.4$ cm s^{-1}), which surprisingly was not very different from R_{sur} = 330 s m^{-1} observed before the bud burst in April. This again indicates that deposition to the forest floor may play a

significant role, even though it is not clear why the effect of stomatal activity remains relatively small (Pilegaard et al., 1995b). The mean nocturnal surface resistance was 690 s m^{-1} and 600 s m^{-1} for April and May, respectively.

The measurements carried out in a subarctic mountain birch forest in northernmost Finland (69°N) (Tuovinen et al., 1999; Aurela et al., in press) represent an extreme in terms of the distribution of deciduous forest within the modelling domain. The fluxes to this ecosystem exhibit a striking seasonal variation, demonstrating the shortness of the growing season in the north. Even up to late June, the dry deposition velocity of ozone was low and rather constant (0.1 cm s^{-1}). Once the leaves emerged, a much higher uptake rate was rapidly attained, the mean midday V_d exceeding 0.6 cm s^{-1}. During 19th to 24th June 1996, at an early stage of leaf expansion, the mean surface resistance was 560 s m^{-1}, which for the foliated period was reduced to 180 s m^{-1} (25–30 July). These values are broadly consistent with the model predictions, even though the forest has a considerably lower LAI than the default value.

Investigating the stomatal component, Magnani et al (1988) modelled canopy conductance of a mature beech forest in Italy. The beech stand had a LAI of 3.8 and canopy conductance was modelled according to a multiplicative model not dissimilar to that used in the ozone deposition model reported here. Canopy conductance was found to be typically large early in the morning under conditions of sufficient irradiance and still low vapour pressure deficit, and decreased steadily during the day, mirroring the time course of air humidity. A second maximum of canopy conductance was sometimes observed late in the afternoon. Figure 12 compares the diurnal pattern of this Italian study with the predicted model values for the grid square located in Portugal which would be expected to have the most similar environmental conditions of the four grid square locations. Fig 12 shows that the model is able to predict, at least to some extent, the decrease in conductance during the afternoon. A similar strong limiting effect of VPD on canopy conductance was also reported by Breda et al. (1993).

Figure 12 Comparison of canopy stomatal conductance data measured by Magnani et al. (1998) in Italy for beech (*Fagus sylvatica*) during June, July and August (1992) with modelled G_{sto} data (the mean for June, July and August, 1997) for the Montemor grid square.



5.2.2.3 Mediterranean needleaf forests

Measurement data corresponding to this land-cover type have been reported for a maritime pine dominated forest in SW France. Affre et al. (2000) show that the daily maximum deposition velocity at 12 m above the mean canopy height of 24 m is typically within 0.7–0.9 cm s^{-1} (late June to early July), as measured by the eddy covariance technique. This is less than the model predictions, but the comparison is inconclusive in that the LAI of this forest is lower (2.1) than the default value of the model. There are also significant differences between these measurements and those taken by using the gradient method (Sánchez et al., 1997).

5.2.2.4 Temperate crops

Grimm & Fuhrer (1992a) measured deposition velocities for ozone to wheat grown in open top chambers (OTC) located at Zimmerwald, Switzerland. They recorded mean maximum values ranging between 1.1 and 1.4 cm s^{-1} over the two measurement periods. This compares with modelled values of 1.1 cm s^{-1} for equivalent G_{sur} values for Payerne grid square. These values compare favourably although care should be taken when comparing OTC measurements with field conditions due, most importantly, to the modifications to microclimatic conditions but also given additional deposition that will occur to the OTC chamber surfaces.

5.2.2.5 Mediterranean crops

The modelled deposition velocities compare favourably with the observations made on a maize field in the Netherlands (van Pul & Jacobs, 1994). From these data a mean daytime surface conductance of 0.64 cm s^{-1} can be calculated for July–August. The modelled stomatal to total surface conductance ratio for that period is also in accordance with that of 75% estimated by van Pul & Jacobs (1994) from the measured water vapour fluxes.

5.2.2.6 Moorlands

The moorland category was modelled using a different approach from the other land-cover classes. The literature data on stomatal responses of representative species were insufficient for deriving a parameterisation for this land-cover type, but there is an exceptionally long-term flux measurement data set of four years available for an ombrotrophic mire in southern Scotland (Fowler et al., 1999). Therefore, the maximum stomatal conductance and the total non-stomatal conductance were tuned based on these observations.

The field measurements indicate that the mean midday near-surface V_d is 0.6–0.7 cm s^{-1} in spring and summer, 0.4–0.5 cm s^{-1} in autumn, and varies from 0.3 to 0.6 cm s^{-1} in winter (Fowler et al., 1999). The mean nocturnal V_d was typically 0.2–0.3 cm s^{-1}. The tuning approach made it possible not only to reasonably estimate the mean diurnal cycles of the deposition velocity and the surface conductance including the stomatal component observed in summer, but also to model the seasonal development in a consistent way. Even though the annual variations were not tested, it is probable that the year-to-year differences in the observations are not fully explained by the model. This may be related to surface wetness effects, which are not included in the model, as discussed above.

5.2.2.7 Grasslands

For grasslands the model predicts relatively high surface conductance values and thus deposition velocities. Except for the location in southern Europe, the example calculations do not indicate a strong limitation by VPD, as is the case for many other land-cover types (cf. Table A2). The observations made in Germany however show a clearly asymmetric cycle for the deposition velocity reported as an average over a five month vegetation period (May–September 1990 and 1991), VPD being suggested as the most likely candidate for producing such an effect (Grünhage et al., 1994). Within the mean diurnal cycle, the maximum deposition velocities are about 0.8 cm s^{-1}, which is reduced to 0.6 cm s^{-1} in the afternoon, and further to 0.1 cm s^{-1} at night. The model seems to somewhat overestimate the deposition velocity, though it must be noted that these long-term data warrant a site-specific comparison to properly test the model.

Observations made in a meadow in Portugal indicate that the seasonal variation of ozone deposition velocities in southern Europe may be very different from that in the rest of the continent. Pio *et al.* (2000) measured ozone fluxes from February to March, observing that the highest values of the surface conductance occurred at the beginning of this period (mean midday $G_{sur} \approx 0.5$ cm s^{-1}), while the lowest ones ($\approx$ 0.2 cm s^{-1}) were observed in August. The present version of the model that lacks the soil moisture module is unable to predict these seasonal differences, and also over-predicts the maximum rates. The agreement is somewhat better with the results of another Iberian study in which ozone fluxes were measured on a 25-40 cm high grass during a five-day period in late July (de Miguel & Bilbao, 1999). The average daytime dry deposition velocity was 0.6 cm s^{-1} and the surface resistance was between 100 and 150 s m^{-1} ($G_{sur} \approx 0.7$–1.0 cm s^{-1}), with a remarkably strong short-term variability.

A study by Cieslik & Labatut (1997) at an Italian grassland site found significant differences in the contributions of the stomatal component to total ozone deposition. Micrometeorological measurements calculated total and stomatal conductance values for June 1993 during a period of drought and May 1994 when the vegetation was still active and receiving rainfall. During June the total conductance values were low (≈ 0.3 cm s^{-1}) and the stomatal conductance values accounted for about 20 to 30 % of the total. In May of the following year, the total conductance values were in the range of 0.4 cm s^{-1} and the stomatal conductance values accounted for about 60 % of the total. This compares with modelled daytime values that range between 45 to 70% during March. Therefore, in those instances when SMD is not limiting (i.e. gSWP = 1 as has been used in these preliminary model runs) the stomatal component of deposition is described reasonably well for grasslands found in Mediterranean regions.

5.2.2.8 Mediterranean Broadleaf forests

The exclusion of the influence of SMD on the modelled stomatal conductance is especially important to bear in mind for vegetation growing in the Mediterranean, where dry conditions will often result in a reduction of g_s. This is highlighted in Figure 13, which describes standardised published seasonal profiles of g_{max} for Holm oak (*Quercus ilex*), grouped within the Mediterranean broadleaf cover type.

Figure 13 Seasonal course of standardised midday g_s for *Quercus ilex* in different European locations. The Caldwell data describes the course of g_{age} over the year i.e. that when no environmental limitation to gs is being experienced.

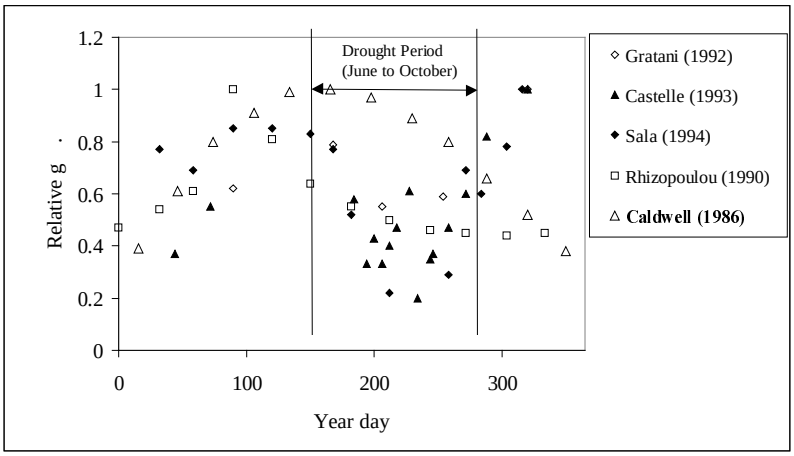


Figure 13 shows that stomatal conductance is significantly reduced between the months of June to October. This coincides with periods of drought and therefore, reflects the influence that reduced soil moisture availability will be likely to have on g_s, canopy conductance and subsequently ozone deposition.

Although Figure 13 describes the reduction in stomatal conductance for Holm oak, the previous grasslands section (5.2.2.7) also reported reductions in deposition velocities and associated components during the same June to October period. This would suggest that for vegetation growing in Southern Europe, soil water shortage

is an important factor significantly affecting ozone deposition through the reduction of stomatal ozone flux. Therefore, the inclusion of the soil moisture component of the stomatal conductance calculation (g_{SWP}) will be crucial in future applications of this deposition model to provide realistic simulations of ozone deposition across the whole of Europe.

6. Summary

This Note has presented an overview of the deposition methodology planned for introduction into the EMEP oxidant model, in order to enable the explicit calculation of ozone fluxes into stomata. This flux calculation is an essential step in addressing so-called level II mapping which is intended to provide a much better basis for vegetation damage estimates than the previous AOT40 concept.

The model development and testing is a complex process, not least because of the number of land-cover classes involved, and the difficulties in evaluating the different possible pathways for ozone loss from the atmosphere.

Here we have presented some preliminary results showing calculated deposition velocities and stomatal conductance values. Only well-watered conditions are addressed as the soil-moisture component of the model is still under development and evaluation.

The brief comparisons of the modelled values for both the stomatal and non-stomatal components show mixed but promising results. When local values of such key parameters as LAI are known, the model seems to do a reasonable job of predicting the deposition pathways for forest ecosystems at least. The overall deposition rates seem somewhat high, however, so further investigations are needed to understand the reasons for this. Comparisons for the stomatal component alone show mixed results: the model may over- or under-estimate measured g_s values.

It seems that the model is able to predict the seasonal and diurnal patterns of g_s in a realistic manner (allowing for our omission of soil-water effects in this evaluation). This is promising for the intended usage of this deposition module in full seasonal runs of the EMEP oxidant models, and seasonal flux-estimates.

As well as further investigation of the parameterisations of the g_s module, it is clear that improved land-cover maps, with realistic descriptions of the seasonal change in factors such as LAI, will be critical for the application of this methodology.

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APPENDIX A:

Tabulation and sources of data for land-cover specific parameters used in stomatal conductance model.

The following tables give the parameter values associated with the stomatal conductance modifiers of Figure 2. Note that data are given for more land-cover classes than anticipated for the regional ozone modelling, in order to enable some offline processing for a few important species with individual g_s data. Data for the regional model are assigned a code consistent with Table 1of the main report. Thus, the Temperate crops of Table 1 are associated with barley and wheat below, Mediterranean crops with maize. Shaded values indicate where g_s data for the particular species / species group could not be found within the literature and data from a generically similar species has been used as a surrogate.

Table A1:Land-scape specific parameters for g_{max}, g_{min}, g_{age}, g_{light} and g_{temp}. A/H gives whether stomata are found over entire leaf (A=amphistomatous) or one one side (H=hypostomatous). Shaded values indicate data obtained by analogy from other land-cover category. Sources of data given at end of Tables.

		g_{max}	A/H	g_{min}	g_{age}			g_{light}	g_{temp}		
Code		mmol O_3 m^{-2} s^{-1} Projected			gage_a	gage_b	gage_c	α	T_min	T_opt	T_max
				frac.	frac.	days	days		°C	°C	°C
CF	Temp. conif.	146	-	0.1	0.5	130	130	0.0083	1	18	36
	$*g_{age}$				0.2	-	245				
DF	Temp. decid.	141	H	0.16	0	16	63	0.006	12	23	34
NF	Med. needle	170	-	0.13	0.2	130	130	0.013	4	20	37
BF	Med. broadleaf	213	A	0.14	0.2	130	130	0.013	4	20	37
TC	Wheat	296	A	0.1	0.1	0	45	0.009	12	26	40
	Barley	296	A	0.1	0.1	0	45	0.009	12	26	40
MC	Maize	156	A	0.19	0.1	0	45	0.0048	0	25	51
RC	Root crops	360	A	0.2	0.2	20	45	0.0023	8	24	40
V	Grape	270	A	0.19	0.2	110	70	0.0076	5	20	45
TO	Temp. orchard	265	A	0.1	0.2	60	80	0.006	10	30	40
MO	Med.orchard	137	A	0.14	0.14	130	130	0.013	5	20	45
	Olive	165	A	0.14	0.2	130	130	0.0035	5	20	45
GR	Grassland	270	A	0.1	1	0	0	0.009	12	26	40
SNL	Seminat.	60		0.1	0.1	0	45	0.009	1	18	36
MS	Med. scrub	213	A	0.14	0.2	130	130	0.012	4	20	37

Table A2: Land-scape specific parameters for g_{VPD}, g_{SWP}. Shaded values indicate data obtained by analogy from other land-cover category. Sources of data given at end of Tables.

		g_{VPD}		g_{SWP}	
		VDP_{max}	VDP_{min}	SWP_{max}	SWp_{min}
		kPa	kPa	Mpa	Mpa
CF	Temp. conif.	0.7	3	-0.76	-1.2
DF	Temp. decid.	0.93	3.4	-0.55	-1.3
NF	Med. needle	0.4	1.6	-0.4	-1
BF	Med. broadleaf	1.1	3.2	-1.1	-2.8
TC	Wheat	0.9	2.8	-0.3	-1.1
	Barley	0.9	3.2	-0.3	-1.1
MC	Maize	1	2.5	-0.11	-0.8
RC	Potato	0.31	2.7	-0.44	-1.0
V	Grape	1.6	3.5	-0.4	-0.6
TO	Temp. orchard	0.6	2	-0.55	-1.3
MO	Med.orchard	1	2.5	-2	-2.6
	Olive	1	2.5	-1.1	-2.8
GR	Grassland	1.3	3	-0.49	-1.5
SNL	Seminat.	nd	nd	nd	nd
MS	Med. scrub	1.3	2.4	-1.1	-3.1

Notes

The data describing the relationship for Mediterranean evergreen trees was fairly robust at the higher end of the temperature range. However, between 0 and 15^{o}C no data could be found. Therefore, other forest tree relationships, which are fairly similar over this temperature range, were used as a surrogate. For orchards, the G_{temp} data shows that between approximately 20 and 30^{o}C g_s remains fairly constant. No data was found describing how quickly g_s changed with temperature at either end of this range so again, the other forest tree vegetation group relationships were used as a surrogate. The relationship for grasslands is defined by g_s values measured over the range of 10 to 30^{o}C. The curve gives the best fit to these data but probably mis-represents the response of g_s to temperatures higher than 30^{o}C. However, at such high temperatures VPD will also be high and hence the environmental factor most likely to be limiting ozone uptake. As such, the G_{temp} relationship is considered suitable for describing response within the modelling procedure. For seminatural vegtation no data were available for g_{VDP} - for simplicity g_{VDP} was set very high.

A3: Sources of data for stomatal conductance g factors.

The sources for each land-cover type, represented here by the land-cover codes **CD**, **DF**, **BF**,etc., are as follows:

g_{max} :-
CF: *Norway spruce* : Korner *et al*. (1995); Dixon *et al*. (1995); Zimmermann *et al*. (1988); Mikklesen & Ro-Poulsen (1994); Wallin *et al*. (1992b) *Scots pine* : Beadle *et al*. (1985a); Troeng & Linder (1982); Korner *et al*. (1995); Whitehead *et al*. (1984); Hellkvist *et al.* (1980); **DF:** *Oak*: Epron & Dreyer (1993b); Breda et al. (1993a); Breda et al (1993b); Epron & Dreyer (1993b); Breda et al. (1993b); **NF:** *Aleppo pine*: Anttonen et al. (1998), *Maritime pine*: Loustau et al. (1996), Guehl et al.(1995), Picon et al. (1996), Guehl et al.(1991), *Abies spp.*: Guicherd (1994); **BF:** *oak*: Acherar & Rambal (1992); Gratani (1993),Sala & Tenhunen (1994); Sala et al. (1994); Rhizopoulou & Mitrakos (1990) Acherar & Rambal (1992); Tenhunen *et al*., (1984); Oliviera *et al*., 1992; Tenhunen *et al*. (1987); Tenhunen *et al*., (1987), Caldwell *et al*., (1986); Rhizopoulou & Mitrakos, (1990); **W:** Gruters et al. (1995); Araus et al. (1989); Araus & Tapia (1987); Lehnherr et al. (1988); Grimm & Fuhrer (1992a); **B:** as wheat; **M:** : Tardieu & Katerji (1991); Tardieu *et al.* (1993); Tardieu *et al.,* (1992); **P:** Jeffries, 1994; Vos & Groenwald, 1989; Marshall & Vos, 1991; **S**: Bogaert & Lemur (1994), Geiger et al. (1991), Catsky et al. (1996), Huzulak & Matejka (1992) **V**: Winkle & Rambal (1993), Correia et al. (1995); **TO:** *apple:* Green, & McNaughton (1997), Giulianiet al (1997), Campbell et al (1992); **MO:** *orange:* Bañulus & Primo-Millo (1992), Fereres *et al*. (1979); **O:** Bongi & Loreto (1989); **GR:** *Lolium spp.* : Ferris et al. (1996), Nijs et al. (1989), Gay et al. (1986), Jackson et al. (1994) **MS :** *Holm oak*: Acherar & Rambal (1992); Gratani (1993), Sala & Tenhunen (1994); Sala et al. (1994); Rhizopoulou & Mitrakos (1990)

g_{min}:-
CF : *Norway spruce & Scots pine*: Korner *et al.* (1995); **DF:** *Birch*: Osonubi & Davies (1981), Ranney *et al*. (1991), Tognetti (1995), *oak*: Epron & Dreyer (1993b), Breda et al. (1993a), Breda et al. (1993b), Epron & Dreyer (1993a), Epron & Dreyer (1990), Vivin *et al*. (1993), Epron & Dreyer (1993b), Breda *et al*. (1993b); **NF:** *maritime pine*: Loustau et al. (1996), Picon et al. (1996), Guehl et al.(1991), *abies* spp.: Guicherd (1994) ; **BF:** *oak*: Epron & Dreyer (1990), Acherar & Rambal (1992), Sala & Tenhunen (1994); **W** :Korner (1994); **B:** as wheat; **M:** *maize*: Tardieu *et al.* (1992a), Davies *et al*. (1994); **P** : Vos & Groenwald (1989); **S:** as potato; **G :** Correia *et al*. (1995), Quick *et al.* (1992), During (1987); **TO:** *apple:* Giulianiet al (1997); **MO:** *orange:* Reiger (1995), Fereres *et al*. (1979), Save *et al.* (1995); **Olive :** as med_broad; **GR:** Korner (1994); **MS:** *Holm oak*: Sala & Tenhunen (1994)

g_{age}:-
CF : Korner (1995), Beadle et al. (1985); **DF:** *oak* : Breda *et al*. (1993b), *beech*: Pearson & Mansfield (1993), Taylor & Dobson (1989); **NF:** as med_braod*;* **BF** *oak*: Caldwell et al. (1986) **W:** Gruters et al. (1995); Araus & Tapia (1987); Grimm & Fuhrer (1992b); **B:** as wheat; **M:** as wheat; **P:** Vos & Oyarzun (1987), Vos & Groenwald (1989), Jeffries (1994); **S:** as potato; **G:** Winkle & Rambal (1993), Correia *et al*. (1995); **GR:** Assume Gpot=Gmax through season; **MS:** *holm oak*: Caldwell et al. (1986).

g_{light}:-
CF: *Scots pine*: Beadle *et al* (1985), Korner *et al* .(1995); Ng (1979); *Norway spruce*: Theone *et al*. (1991), Korner *et al*. (1995); **DF:** *Birch* :Osonubi & Davies (1980b); *Beech*: Eamus (1991); *Oak*: Breda *et al.* (1993a); **NF***: maritime pine:* Brahim et al. (1996), Loustau et al. (1996)*;* **BF**: *oak*: Tenhunen *et al*. (1985); Sala & Tenhunen (1994); **W:** Machado & Lagôa (1994), Weber & Rennenberg (1996), Gruters et al. (1995); **B:** as

wheat; **M:** *maize*: Bethenod & Tardieu (1990), Turner & Begg (1973); **P:** Vos & Oyarzun (1987), Ku et al. (1977), Dwelle et al (1983) Vos & Groenwald, (1989); Stark (1987); **S:** as potato; **G:** Winkle & Ramble (1990); **TO:** *apple*: Giuliani et al (1997), Campbell et al (1992); **MO:** *orange***:** Brakke & Allen (1995); **O:** Bongi & Loreto (1989); **GR:** *as wheat* **MS:** *holm oak*: Sala & Tenhunen (1994)

g_{temp}
CF : *Scots pine*: Beadle *et al* (1985), Ng (1979); **DF:** *Birch* :Osonubi & Davies (1980b); **NF:** as med_broad; **BF:** *oak*: Tenhunen *et al*. (1985); Sala & Tenhunen (1994); **W:** Gruters *et al*. (1995); **B:** as wheat; **M:** *maize*: Rodriguez & Davies (1982); **P:** Ku et al (1977), Dwelle et al (1981); **S:** as potato; **G:** as med_orchard; **TO: :** *apple*: Giuliani et al (1997); **MO:** *orange* : Khairi & Hall (1976); **O:** as med_orchard; **GR :** as crops_temp; **MS:** *holm oak*: Sala & Tenhunen (1994)

g_{VPD}:_
CF : *Scots pine*: Beadle *et al* (1985), Ng (1979); Korner *et al*. (1995); *Norway spruce* : Korner *et al*. (1995), Weiser & Havranek (1993), Zimmermann *et al*. (1988); **DF:** *Beech* : Kersteins (1995); *Birch :* Osonubi & Davies, (1980a); **NF :** *maritime pine*: Loustau et al. (1996), Picon et al. (1996), Guehl et al.(1991), *abies* spp.: Guicherd (1994); **BF** *oak:* Sala & Tenhunen (1994); **W:** Weber & Rennenberg (1996), Teubner (1985); **B:** Tattari et al. (1995); **M:** as orange; **P:** Teubner (1985); **S:** as potato; **G :** During (1987), Correia *et al*. (1995); **TO :** *apple*: Giuliani et al (1997); **MO:** *Orange* :Khairi & Hall (1976); **O:** as med_orchard; **GR:** *Lolium spp*. : Ludlow (1980); **MS:** *holm oak*: Sala & Tenhunen (1994)

g_{SWP}:-
CF : *Scots pine*: Ng (1979); Jackson *et al*. (1995); *Norway spruce* : Dobson *et al*. (1990); Wallin & Skarby (1992a), Dixon *et al*. (1995); **DF :** *Beech* :Tognetti *et al*. (1995); *Oak* : Breda (1993a), Epron & Dreyer (1993b), Breda et al (1993a), Breda et al. (1993b), Vivin et al. (1993), Breda et al. (1993b), Epron & Dreyer (1993b); **NF :** *maritime pine***:** Picon et al (1996); **BF** : *oak*: Sala & Tenhunen (1996), Epron & Dreyer (1990), Acherer & Rambal (1992) ; Acherer & Rambal (1992) **W:** Weber & Rennenberg (1996), Teubner (1985); **B:** as wheat **M:** Tardieu *et al*. (1992a), Davies *et al*. (1994); **P:** Vos & Oyarzun (1987), van Loon (1981); **S:** as potato; **G :** Winkle & Rambal (1993), Quick *et al*. (1992); **TO:** as temp_decid; **MO :** *orange*: Save *et al*. (1995), Fereres *et al*. (1979), Kaufmann & Levy (1976); **O**: as med_broad; **GR**: *Lolium* spp. Neilson (1995) **MS***: holm oak*: Sala & Tenhunen (1996), Epron & Dreyer (1990), Acherer & Rambal (1992)