Comparison of Measurements of Ozone Dry Deposition to Crops and Grassland with the Dry Deposition Model Results

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Introduction

The field studies were designed primarily to obtain high quality flux measurements of O_3 flux averaged over a field scale ($\geq 10^4$ m^2) and also provide data for comparison with the deposition model. Measurements are reported from 2 sites: Sutton Bonnington with 4 years of semi-continuous flux measurements over a range of crops; and a single season of measurements over *lolium perenne* at Easter Bush, close to the CEH laboratories, which included measurements of the major components of the surface energy balance, net radiation, sensible (or corrective) heat flux, latent heat and soil heat fluxes to provide clear estimates of the stomatal resistance of the grass canopy.

The objectives of the measurements were:

- To measure full-scale O_3 deposition fluxes with a time resolution of 1 hour over a range of crops at Sutton Bonnington.
- To measure field scale O_3 fluxes with hourly time resolution over grass at Easter Bush, and to provide sufficient additional measurements of R_a, C, λE and G to quantify the canopy resistance for H_2O (and hence) O_3 uptake by stomata.
- To separate stomatal (Rc_1) and non-stomatal (Rc_2) canopy resistance components and quantify the effects on Rc_2 of radiation and surface temperature.

To estimate stomatal ozone uptake the following method is used to relate the stomatal resistance for a trace gas (eg R_{stO3}) to the bulk canopy resistance to water vapour transfer (R_{cwv}). As transfer into the stomata is by diffusion the stomatal resistance for one gas can be calculated from another by simply scaling by their molecular diffusivities:

$$R_{sO3}D_{O3} = R_{swv}D_{wv}$$

R_{swv} can be readily estimated from measurements of the water vapour flux and saturation vapour pressure using either the Penman-Monteith equation (Monteith and Unsworth, 1990):

$$R_{swv} = \left[\frac{\Delta C(R_a + R_b)}{\gamma\lambda E}\right] + \frac{\rho c_p}{\lambda E}[e_s(T(z)) - e(z)] - (R_a + R_b)$$

or the more simple formula (Coe *et al*., 1995):

$$R_{swv} = \frac{\rho\varepsilon}{p}\frac{e_s(T(z_{o'})) - e(z_{o'})}{E}$$

where Δ = rate of change of saturation vapour pressure with temperature, ie $\delta e_s(T)/\delta T$
γ = psychrometer constant, ε = ratio of the molecular weights of water vapour and air (0.622), es($T(z_{o'})$) = saturation vapour pressure at the surface temperature, kPa ($T(z_{o'})$), $z_{o'}$ = height of the canopy's surface, $e(z_{o'})$ = vapour pressure at $z_{o'}$, kPa, E = water vapour flux, g m^{-2} s^{-1}

However there will be periods where the water vapour flux is from sources other than plant respiration (evaporation from soil for example) and so the measurements used have to be restricted to periods when: the surface is dry and there's no rainfall; during daylight hours when the vegetation is active and should be respiring; when humidity is low (< 60 - 70%).

Field Sites and Instrumentation

Measurements at Sutton Bonnington, near Nottingham in the English Midlands, provide long term, field scale fluxes of O_3 at the same location as the SO_2 flux monitoring station. The measurements rely on the aerodynamic, flux-gradient technique in which the vertical flux is inferred from the vertical profiles in concentration, wind velocity and temperature, which develop over extensive uniform terrain. The vertical profile in ozone concentration is monitored using a UV absorption gas analyser, which samples sequentially from a 3-point profile mast, which extends to a height of 3 m above the surface. The wind velocity profile and temperature profiles are monitored from the same mast and are logged continuously. A more detailed description of the theory of gaseous pollutant flux measurement can be found in (Monteith and Unsworth, 1990) or (Flechard, 1998).

The instrument mast is on the boundary between two fields, which are planted in rotation with different crops and so the data are split into two fetch sectors, one for the west field and one for east. Typically, the data capture with site and atmospheric properties which satisfy the boundary conditions for flux gradient analysis amount to about half the time, with the majority in the west field and the minor fraction in the east field. Measurements over sugar beet/wheat in 1998 and oats/wheat in 2000 where selected for comparison with the deposition model.

The Easter Bush field site is located close to CEH-Edinburgh, ~10 km south of Edinburgh in the foothills of the Pentlands. There are two fields, separated by a wire fence and hedge, both of which are mainly covered by lolium perenne (rye grass) with a few other species mixed in. They are managed for silage, with harvests twice during the summer. The fields are fertilized immediately after the cut grass is lifted and livestock are allowed on to graze a few weeks after the second cut. The instrumentation used at the site allows the eddy-correlation method to be used for flux measurement as well as the aerodynamic-gradient method (see (Monteith and Unsworth, 1990)). The site has suitable fetches for micrometerology across both fields and as the management is the same they can be treated as one big field. In some wind directions the fetch is disrupted by the fence or tow-a-van and hedge, so these data have to be excluded. Measurements made from the 25th of May 2001 to the 1st October 2001 are used for comparison with the deposition model.

Results: Comparison of measurements to the deposition model

For comparison with the measurements the model was implemented using site specific measurements of wind speed (u), momentum flux (τ), heat flux (H), surface ($z_{0'}$) temperature (T_s), air pressure (p), solar radiation (S_r) and surface ($z_{0'}$) vapour pressure (v_p) (where available). Standard parameters for the appropriate vegetation type where used, although for the grassland and sugar beet local measurements of the canopy height were also introduced to give a more realistic profile of canopy growth.

Sutton Bonnington

Measurements over sugar beet/wheat in 1998 and oats/wheat in 2000 where selected for comparison with the deposition model. As it is not possible to segregate stomatal from non-stomatal deposition at this site, results for the whole canopy are considered.

Sugar Beet

The standard model parameterisation for root crops is based on potatoes rather than sugar beet and so the standard model canopy height differs significantly from the actual field data, therefore the model was adjusted to give more realistic canopy growth (Figure 1a). In general the model underestimates large values of the measured deposition velocity (Figure 2a & Figure 3a) although for some periods they agree quite well (Figure 4a), particularly during the night.

Oats

In this case the standard parameterisation for temperate crops was used, which is based on data from wheat. The modelled profile of canopy height again differs from the observed and so in this case a time period was selected when the two corresponded fairly closely, as illustrated in Figure 1b. The model shows the best agreement with the oats data (Figure 3b & Figure 4b) from Sutton Bonnington although it tends to underestimates large and overestimates small values of deposition velocity (Figure 2b).

Wheat

In this case the standard parameterisation for temperate crops was used and a time period selected when the model canopy height corresponded to the observed (Figure #c & d). As the wheat was planted in the east field during both years under consideration there is little data for comparison with the model. During 1998 the model agrees fairly well (Figure 3c) although it again underestimates the larger values (Figure 2c). In 2000 it overestimates in comparison to the measured values (Figure 2c & Figure 3d).

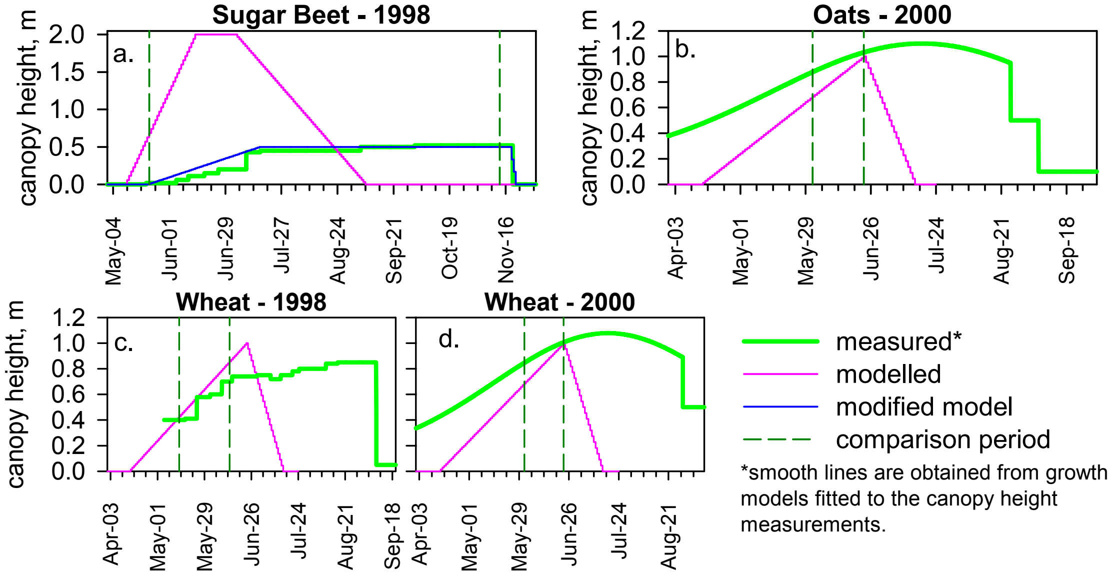

Figure 1. Time series profiles of measured and modelled canopy heights for the crops at Sutton Bonnington, showing the periods of comparison for each crop.

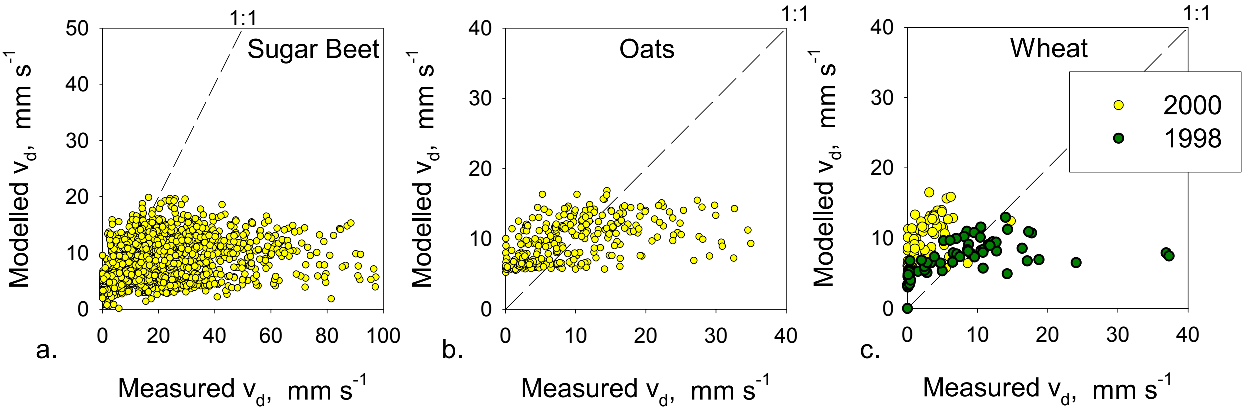

Figure 2. Measured versus modelled hourly deposition velocities for Sutton Bonnington: a, sugar beet during 22nd May 1998 to 13th November 1998; b, oats during 6th to 23rd June 2000; c, wheat during 14th May to 13th June 1998 and 6th to 23rd June 2000.

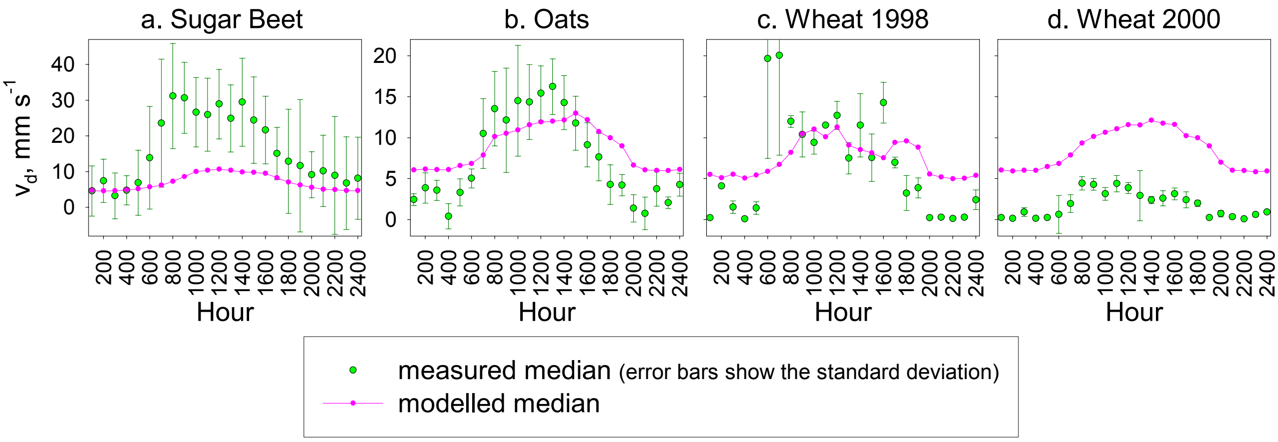

Figure 3. Median diurnal cycles of hourly measured and modelled ozone deposition velocity over (a) sugar beet and (b) oats (c) wheat in 1998 and (d) wheat in 2000, at Sutton Bonnington.

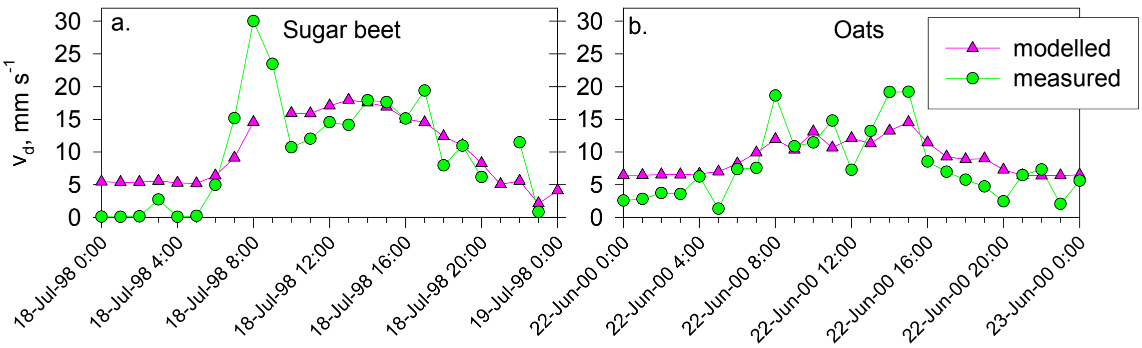

Figure 4. Diurnal cycles of hourly measured and modelled ozone deposition velocity over (a) sugar beet on the 18th of July 2000 and (b) oats on the 22 June 2000 at Sutton Bonnington.

Easter Bush: grassland

As described earlier, the field was cut for silage twice during the measurement period and so the standard modelled canopy height profile for grassland does not represent the measurements. Hence, two versions of the model were considered, one using all the standard parameters and a second using the actual canopy height and LAI (Figure 5).

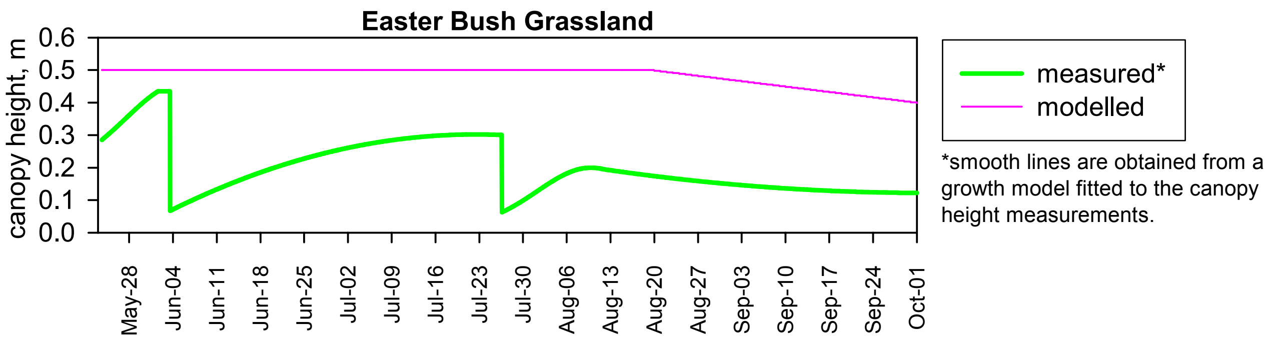

Figure 5. Measured and modelled canopy height for grassland at Easter Bush.

The model reproduces the basic meteorological parameters quite well, even when using the standard canopy height profile, as shown in the plot of measured and modelled u_* (Figure 6a). However, it tends to underestimate large values of the total canopy resistance (Rc) or overestimate small values of the canopy conductance (Gc) as shown in Figures 6b and c respectively. As the water vapour flux is measured at this site we can also compare measured and modelled stomatal resistance or conductance. Figure 7 shows a plot of the stomatal conductance, in general the model overestimates stomatal conductance by about a factor of 2 using the site-specific model and a factor of 3 using the standard model. However, as at Sutton Bonnington, there are periods where the measurements and model agree quite well during the day-time at least, as shown in Figure 8.

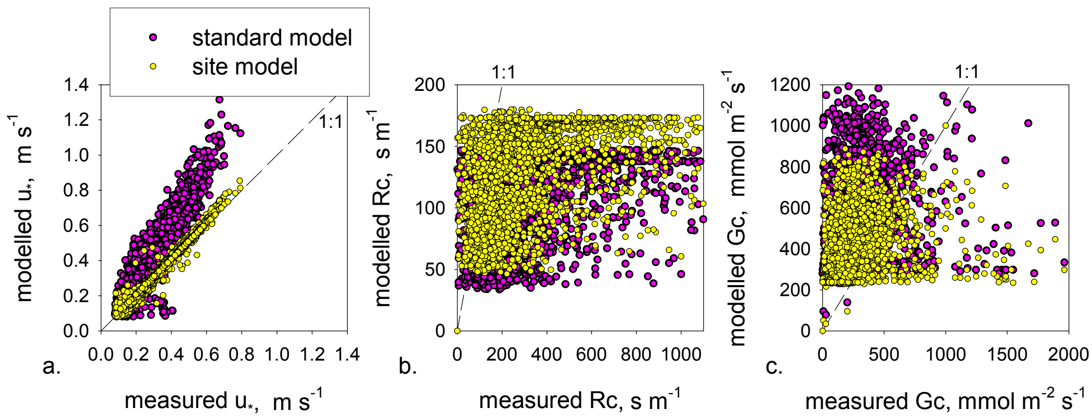

Figure 6. Measured and modelled (a) friction velocity, u_*, (b) total canopy resistance, Rc, and (c) canopy conductance, Gc, for grassland at Easter Bush.

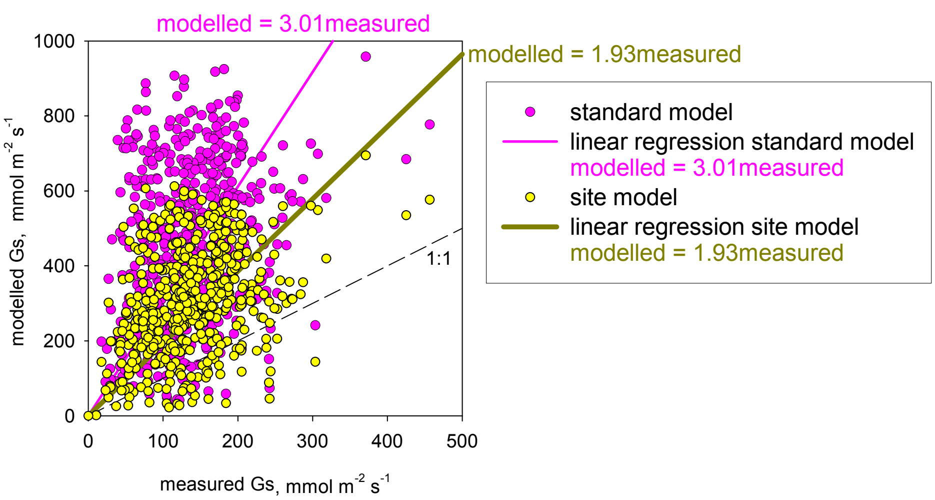

Figure 7. Measured versus modelled stomatal conductance for grassland at Easter Bush.

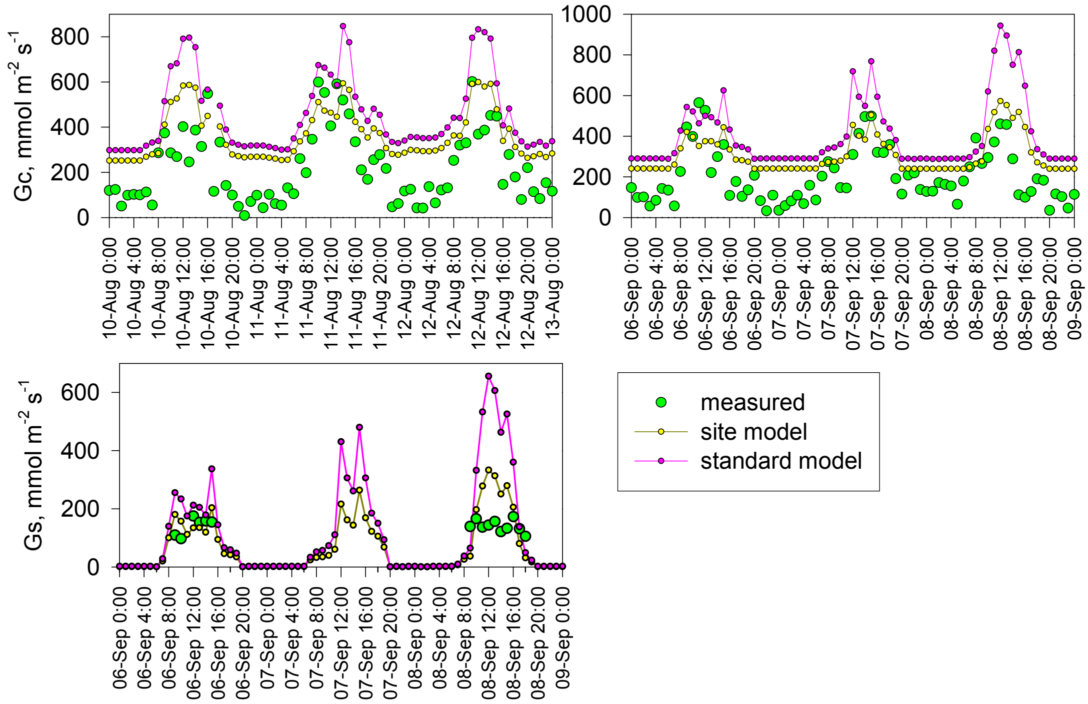

Figure 8. Example of periods when the total canopy conductance (top) and stomatal conductance (bottom) measurements and models agree fairly well during the daytime.

Discussion

At Sutton Bonnington the model tends to underestimate ozone deposition whereas at Easter Bush it tends to overestimate, particularly at night. However there are periods where the model agrees very well with the measurements, indicating that it can potentially model the deposition at these sites quite well. Further examination of the data to understand the models performance and tuning the parameters for the specific sites and crops would provide better agreement. Also, the model assumes that the non-stomatal ozone flux is fairly constant as although it has been shown to be affected by factors such as surface wetness and temperature (Fuentes, 1992, Fuentes *et al*., 1994, Grantz *et al*., 1995, Pleijel *et al*., 1995, Rondon *et al*., 1993), their effects cannot be well characterised in the model at present. This accounts for the some of the differences between model and measurements, in particular the overestimation of night-time deposition at Easter Bush. (Rondon et al., 1993) found R_{ns} declined with PAR and temperature while (Fowler et al., 2001) found that R_{ns} declined logarithmically with solar radiation and temperature. Preliminary analysis of the Easter Bush measurements indicate a similar relationship with solar radiation as shown in the plot in Figure 9.

In summary:

- The model reproduces the basic meteorological resistances and variables satisfactorily.
- Model performance varies for each site and crop, although for each data set periods can be found when the measurements and model agree quite well.
- The best agreement was found for oats at Sutton Bonnington.
- Total canopy and stomatal conductance are, in general, over-estimated by a factor of 2 at Easter Bush.

- The measurements indicate the non-stomatal component is controlled by factors other than LAI and so it is not well reproduced by the model.Further analysis and tuning of the model will improve its performance with these data sets.
- Continuing measurements of total and stomatal ozone deposition are required to improve and validate the model, particularly for non-stomatal deposition.

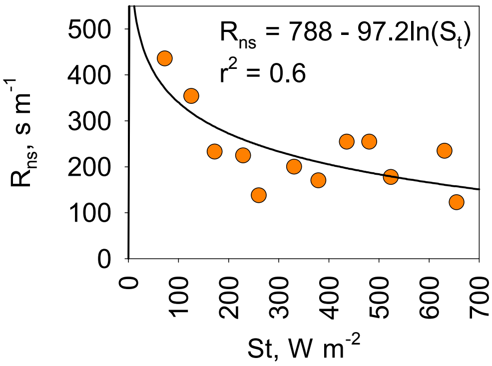

Figure 9. Average R_{ns} against St (solar radiation) when LAI > 3.5 (full canopy).

References

Coe, H., Gallagher, M.W., Choularton, T.W., Dore, C., 1995. Canopy scale measurements of stomatal and cuticular o3 uptake by sitka spruce. Atmospheric Environment 29 (12), 1413-1423.

Flechard, C.R., 1998. Turbulent Exchange of Ammonia Above Vegetation. Thesis Thesis, University of Nottingham, 231 pp.

Fowler, D., Flechard, C., Cape, J.N., Storeton-West, R.L., Coyle, M., 2001. Measurements of ozone deposition to vegetation quantifying the flux, the stomatal and non-stomatal components. Water Air and Soil Pollution 130 (1-4), 63-74.

Fuentes, J.D., 1992. Effect of foliage surface wetness on the deposition of ozone. Dissertation Thesis, The university of Geulph, 145 pp.

Fuentes, J.D., Gillespie, T.J., Bunce, N.J., 1994. Effects of Foliage Wetness on the Dry Deposition of Ozone onto Red Maple and Poplar Leaves. Water Air and Soil Pollution 74 (1-2), 189-210.

Grantz, D.A., Zhang, X.J., Massman, W.J., Denhartog, G., Neumann, H.H., Pederson, J.R., 1995. Effects of stomatal conductance and surface wetness on ozone deposition in field-grown. Atmospheric Environment 29 (21), 3189-3198.

Monteith, J.L., Unsworth, M., 1990. Principles of Environmental Physics. Edward Arnold, London.

Pleijel, H., Karlsson, G.P., Danielsson, H., Sellden, G., 1995. Surface wetness enhances ozone deposition to a pasture canopy. Atmospheric Environment 29 (22), 3391-3393.

Rondon, A., Johansson, C., Granat, L., 1993. Dry Deposition of Nitrogen-Dioxide and Ozone to Coniferous Forests. Journal of Geophysical Research-Atmospheres 98 (D3), 5159-5172.