Ozone deposition to a temperate coniferous forest in Norway: measurements and modelling with the EMEP deposition module

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Abstract: Estimates of diurnal and seasonal variation of ozone deposition to a temperate coniferous forest in Southern Norway are presented. The estimates are based on the gradient method. Ozone deposition velocities are also produced by the EMEP deposition module for the same site with measured meteorology as input. There is good correspondence for diurnal cycles in summer and winter, suggesting that the module is able to provide characteristic results for this site. On the other hand, there is a discrepancy in the diurnal average data that needs to be investigated further. Annual average deposition velocity estimated by the gradient method is 1.3 mm/s while average deposition velocity calculated by the deposition module is 1.8 mm/s.

Introduction

Establishing level II critical ozone levels for forest trees requires long term monitoring of ozone deposition at a variety of locations in Europe. Knowledge about characteristic seasonal and diurnal cycles of deposition velocities and resistances will be crucial when developing a new generation of complex modelling tools with the ability to provide detailed deposition maps[1-2]. Such tools are required to improve estimation of vegetation exposure to ozone. Wesely and Hicks (2000)[3] have recently described dry deposition processes and the current status of knowledge in an extensive review. An overview of dry deposition of ozone studies in particular with emphasis on European conditions and policy applications is in preparation by Tuovinen et al (2002)[4].

Several authors have reported measured and modelled ozone deposition to coniferous forests in Europe[5-10] and comparisons with the EMEP[1] deposition module results have also been presented[11]. In this paper we report winter and summer diurnal cycles of ozone deposition velocities above a coniferous forest in Southern Norway. Deposition velocities at 25 m above ground estimated by the gradient method are compared with those produced by the EMEP deposition module[1,2].

Site description and methods

Since 1 July 2000 monitoring of ozone deposition has been undertaken by the Norwegian Institute for Air Research (NILU) in a Norway spruce forest (*Picea abies*) in Hurdal, South-East Norway (60^{o} 22' N, 11^{o} 4' E)[12]. The area is relatively homogeneous in tree height and topography and was clear cut about 35 years ago. Average tree height is now around 13 m. The climate in the area is continental with winter January normal temperature of –7.2 ^{o}C and July normal temperature of +15.2 ^{o}C.

Wind and temperature profiles are measured using a 25 m tower. Temperature difference between 15 and 25 m, wind speed and direction at 25 m, and relative humidity at 25 m is averaged and sampled every hour by standard procedures. Ozone concentrations at 15 and 25 m above ground is measured by a UV absorption probe (API 400 O_3 analyser) switching from intakes at the two heights in 5 minute cycles. All data are stored as 1 hour averages.

Ozone deposition velocity at 25 m above ground (i.e. 12 m above tree the tops),

[1] Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe.

V_d(25m), is presented here because the flux at this height will be less influenced by Roughness Surface Layer (RSL) effects[13] than the flux at 15 m. In this paper no correction for RSL effects is implemented. Thus these data are more suitable for comparison with model output, but the presented velocities will be somewhat smaller than some of those previously reported. V_d has been estimated by the gradient method,

$$F_c = \div \frac{\mathrm{k}\, u_* \left(c(z_2) - c(z_1)\right)}{\ln\left(\frac{(z_2 - d)}{(z_1 - d)}\right) + \psi_h\left(\frac{(z_1 - d)}{L}\right) - \psi_h\left(\frac{(z_2 - d)}{L}\right)} \tag{1}$$

$$V_d(z) = \div \frac{F_c}{c(z)} \tag{2}$$

where F_c is vertical ozone flux, k is von Kármáns constant c is ozone concentration, d is displacement height, L is the Monin-Oboukhov length and ψ_h is the integral form of the Monin-Obukhov stability function for heat. The stability functions are calculated with profile parameterisations from Holtslag[14]. The roughness length is estimated from the wind profiles and previous measurements to be 0.5 m, and the displacement height for the dense forest is set to 10 m. Figure 1 shows the ozone concentrations a 25 m in 2001. Due to instrument failure there was a significant loss of data (46 %) in the summer (June-August).

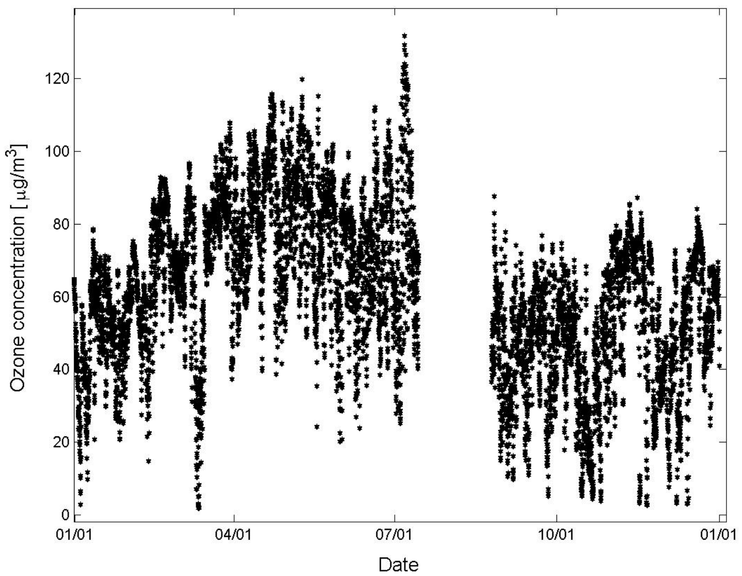

Figure 1: Ozone concentration at 25 m at the Hurdal site in 2001.

EMEP deposition module

Since the EMEP deposition module[1,2] has only been available for about one week before preparing this paper, a rather limited analysis has been carried out so far. Meteorological input to the model has been provided by the measurements described above. The code has been run as provided by the EMEP MSC-W[15] except that parameters such as calculation height for V_d, tree height, latitude/longitude and seasonal snow cover has been set appropriate for the Hurdal site. Also the relative humidity has been measured directly instead of calculated from the absolute humidity. Model output is provided for every hour.

Results

Previous analysis[12] has shown that there is a pronounced diurnal cycle in ozone deposition velocity in summer (June-August), a much smaller amplitude in spring and autumn and no diurnal cycle in winter (December-February). In this paper the summer and winter diurnal cycles for 2001 are compared with modelled cycles. In winter the ground is snow covered continuously and the trees will be covered with snow and rime in long periods. Figure 2 shows that V_d(25m) estimated from Eq. 1 in winter varies only between 0.3 and 0.5 mm/s. The model shows a weak diurnal cycle with a peak of almost 1.1 mm/s.

Figure 3 shows the summer diurnal cycle for 2001. In this case the modelled values are somewhat higher than those estimated by the gradient method. The nocturnal minima also correspond well.

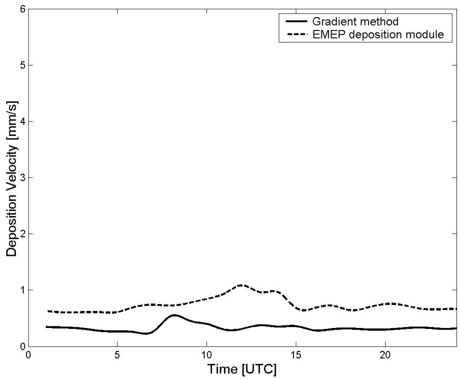

Figure 2: Winter (January, February and December) diurnal cycle of ozone deposition velocity at 25 m. above ground in Hurdal 2001.

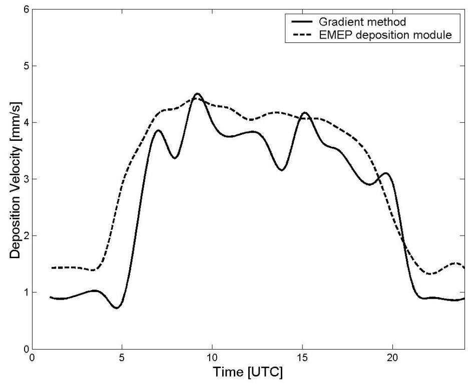

Figure 3: Summer (June, July and August) diurnal cycle of ozone deposition velocity at 25 m. above ground in Hurdal 2001.

Although seasonal diurnal cycles seem to correspond rather well and that the model provides characteristic results for the site, a closer analysis of the data reveals a day to day variation in the results (Figure 4). In this figure the diurnal average deposition velocity for 2001 are presented. Yearly average deposition velocity estimated by the gradient method for the whole year is 1.3 mm/s while average deposition velocity form the EMEP deposition module is 1.8 mm/s.

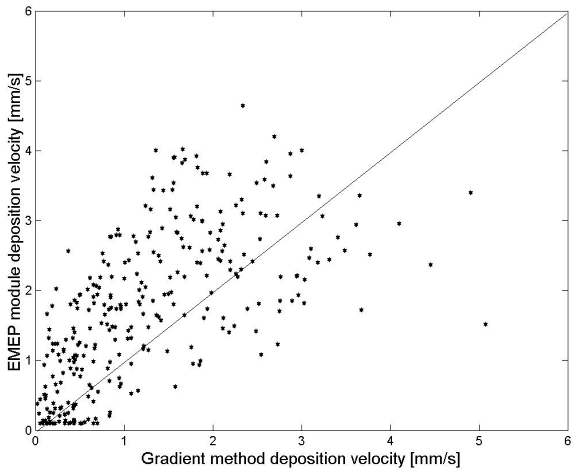

Figure 4: Comparison of modelled and gradient method diurnal average ozone deposition velocities for 2001.

Table 1 is the seasonal average values for most of the resistances that are calculated by the deposition module. Due to dynamically stable atmospheric conditions, the aerodynamic resistance, R_a, has an occurrence of infinite values of 65 % in winter and 19 % in summer. Also, in winter the soil resistance is infinite in 47% of the cases.

Table 1: Seasonal average resistances for the Hurdal site. Average values for R_a in summer and winter and R_{gs} in winter are not provided because of the occurrence of infinite values.

	Aerodynamic R_a **(s/m)**	**Boundary layer** R_b **(s/m)**	**Exterior plant parts** R_{ext} **(s/m)**	**Stomatal** R_{sto} **(s/m)**	**Soil** R_{gs} **(s/m)**	**Surface** R_{sur} **(s/m)**
Summer	-	161	465	407	200	228
Winter	-	396	525	448	-	411

Concluding remarks

A limited comparison of measured and modelled ozone deposition velocities above a coniferous forest in Norway has been presented. The average diurnal cycles for the winter and summer seasons of 2001 correspond satisfactorily while there is a significant day to day variation in the results. The reasons for these discrepancies will be investigated further in the near future and a more thorough analysis of the seasonal variation of resistance factors will be carried out. The instrumentation at the Hurdal site will be significantly extended and improved in the autumn of 2002 with a sonic anemometer to provide stability parameters and better resolution of the wind profiles. This will allow for a more detailed analysis of the different resistances and ozone pathways in the future.

References

[1] Emberson, L.D., D.Simpson, J.-P. Tuovinen, M.R. Ashmore and H.M. Cambridge, *Towards a model of ozone deposition and stomatal uptake over Europe.* EMEP MSC-W Note 6/2000.

[2] Simpson, D. , J.-P. Tuovinen, L.D. Emberson and M.R. Ashmore, *Characteristics of an ozone deposition module.* Water Air Soil Pollut. Focus 1, 253–262, 2001.

[3] Wesely, M.L., and B.B. Hicks, *A review on the current status of knowledge on dry deposition.* Atmospheric Environment **34**, 2261-2282, 2000.

[4] *Dry deposition of ozone: advances in the process understanding and policy applications in Europe*, in prep.

[5] Lamaud, E., A. Carrara, Y. Brunet, A. López, and A. Druilhet, *Ozone fluxes above and within a pine forest canopy in dry and wet conditions*. Atmospheric Environment **36**, 77–88, 2002.

[6] Klemm, O. and A. Mangold, *Ozone deposition at a forest site in NE Bavaria*. Water, Air and Soil Pollution: Focus 1, 223–232, 2001.

[7] Mikkelsen, T.N., H. Ro-Poulsen, K. Pilegaard, M.F. Hovmand, N.O. Jensen, C.S. Christensen, and P. Hummelshoej, *Ozone uptake by an evergreen forest canopy: temporal variation and possible mechanisms*. Environmental Pollution **109**, 423-429, 2000.

[8] Pilegaard, K., N.O. Jensen and P. Hummelshøj. *Seasonal and diurnal variation in the deposition velocity of ozone over a spruce forest in Denmark*. Water, Air and Soil Pollut. **85**, 2223–2228, 1995.

[9] Sánchez, M.L., R. Rodríguez, and A. López, 1997. *Ozone dry deposition in a semi-arid steppe and in a coniferous forest in southern Europe*. J. Air and Waste Management Ass. **47**, 792–799.

[10] Zeller, K., *Summer and autumn ozone fluxes to a forest in the Czech Republic Brdy Mountains.* Environmental Pollut. **119**, 269-278, 2002.

[11] Tuovinen, J-P, D. Simpson, T.N. Mikkelsen, L.D. Emberson, M.R. Ashmore, M. Aurela, H.M. Cambridge, M.F. Hovmand, N.O. Jensen, T. Laurila, K. Pilegaard and H. Ro-Poulsen, *Comparisons of measured and modelled ozone deposition to forests in Northern Europe.*Water Air Soil Pollut. Focus 1, 263-274.

[12] Hole, L.R., A.Semb and K. Tørseth, *Seasonal variation in ozone deposition to a spruce forest in Norway.* In prep.

[13] Garratt, J., *The atmospheric boundary layer, p 58*. Cambridge Univ Press, ISBN 0-521-46745-4,1999.

[14] Holtslag, A.A.M., *Estimates of diabatic wind speed profiles form near-surface weather observations,* Boundary layer meteorology **29**, 225-250, 1984.

[15] Simpson, D., pers. comm., September 2002.

Ozone deposition to a temperate coniferous forest in Norway

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Abstract:

Estimates of diurnal and seasonal variation of ozone deposition to a temperate coniferous forest in Southern Norway are presented. The estimates are based on the gradient method. Ozone deposition velocities are also produced by the EMEP deposition module for the same site with measured local meteorology as input. There is good correspondence for diurnal cycles for all four seasons, suggesting that the module is able to provide characteristic results for this site. However there are some discrepancies in the timing of the cycles. Annual average deposition velocity estimated by the gradient method as well as calculated by the deposition module is 1.8 mm/s.

Site description and methods

Since 1 July 2000 monitoring of ozone deposition has been undertaken by the Norwegian Institute for Air Research (NILU) in a Norway spruce forest (*Picea abies*) in Hurdal, South-East Norway (60° 22' N, 11° 4' E – Fig. 1). The data presented here are from the period 1 July 2000 to 31 December 2001. The area is relatively homogeneous in tree height and topography and was clear-cut about 35 years ago. Average tree height is now around 13 m. The climate in the region is continental with winter January normal temperature of –7.2 °C and July normal temperature of +15.2 °C. For the period studied, the minimum air temperature at 25 m above ground was -25.5 °C (5 February 2001) while the maximum was 26.3 °C (6 July 2001).

Wind and temperature profiles are measured using a 25 m tower. Temperature difference between 15 and 25 m, wind speed and direction at 25 m, and relative humidity at 25 m is averaged and sampled every hour by standard procedures. Ozone concentrations at 15 and 25 m above ground are measured by a UV absorption probe (API 400 O_3 analyser) switching from intakes at the two heights in 5-minute cycles. All data are stored as 1-hour averages.

Fig. 1 A. Map over Hurdal surroundings.

Fig. 1 B. Hurdal mast.

Fig 1 C. Station hut.

Ozone deposition velocity at 25 m above ground (i.e. 12 m above tree the tops), V_d(25m), is presented here because the flux at this height will be less influenced by Roughness Surface Layer (RSL) effects than the flux at 15 m (Garratt, 1992). No correction for RSL effects is implemented. Thus these data are more suited for comparison with model output, although the presented velocities will be somewhat lower than some of those previously reported. V_d has been estimated by the gradient method,

$$F = -\frac{k\,u_*\left(c(z_2)-c(z_1)\right)}{\ln\left(\frac{(z_2-d)}{(z_1-d)}\right)+\psi_h\left(\frac{(z_1-d)}{L}\right)-\psi_h\left(\frac{(z_2-d)}{L}\right)} \qquad (1)$$

$$V_d(z) = -\frac{F}{c(z)} \qquad (2)$$

where F is vertical ozone flux, k is von Kármáns constant, c is ozone concentration, d is displacement height, L is the Monin-Obukhov length and ψ_h is the integral form of the Monin-Obukhov stability function for heat. The stability functions are calculated with profile parameterisations from van Ulden and Holtslag (1985). The roughness length is estimated from the wind profiles and previous measurements to be 0.5 m, and the displacement height for the dense forest is set to 10 m.

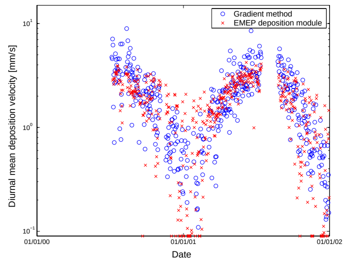

Fig. 2. Diurnal average ozone deposition velocities at Hurdal July 2000 – December 2001.

EMEP deposition module

The EMEP deposition module (Emberson et al., 2000; Simpson et al., 2001) has been run with local meteorological parameters as input. Cloud cover was set to zero since no local information was available. Meteorological input to the model has been provided by the measurements described above. The code has been run as provided by the EMEP MSC-W (Simpson, 2002) except that parameters such as calculation height for V_d, tree height, latitude/longitude and seasonal snow cover has been set appropriate for the Hurdal site. The tree height in the 'temperate coniferous forest' land cover class was set to 13 m. Snow cover was set to 100% in November-April and 0% in the rest of the year. Also the relative humidity has been measured directly instead of calculated from the absolute humidity. Otherwise default parameters were used. Model output is provided for every hour. For a general description of the module and the resistance analogy applied we refer the reader to Emberson et al. (2000) and Simpson et al. (2001).

Results

The analysis shows that there is a pronounced annual cycle in ozone deposition velocity most of the year. In Fig. 2 the diurnal average deposition velocities are presented revealing that the seasonal pattern seems to be well described by the model. In Fig. 3 average diurnal cycles for four seasons are compared with modelled cycles. In winter the ground is snow covered continuously and the trees will be covered with snow and rime in long periods. Figure 3 shows that V_d(25m) estimated from Eq. 1 in winter varies only between 0.3 and 0.7 mm/s. The model shows a weak diurnal cycle with a peak of 1 mm/s. For all seasons there is generally a good correspondence between modelled results and those estimated by the gradient method, but the diurnal peak velocities seem to arrive earlier in the model. Table 1 shows the average V_d(25m) for each season. Both methods provide an annual average V_d(25m) for the site of 1.8 mm/s, although there is some variation from season to season.

Table 1: Average ozone deposition velocities in mm/s.

	Winter	*Spring*	*Summer*	*Autumn*	*Annual*
Gradient Method	0.6	1.6	3.2	1.7	1.8
EMEP Deposition Module	0.6	2.0	2.9	1.6	1.8

The EMEP deposition module calculates the different resistances required to estimate $V_d(z)$ for the compound studied. To study the relative contribution from each resistance we have plotted for convenience the diurnal cycle of the reciprocal of the aerodynamic, quasi-laminar boundary, and canopy resistances in Fig. 4. The sum of these resistances is the reciprocal of the deposition velocity. It appears that the aerodynamic resistance is preventing ozone deposition most of the time except in the middle of day in summer when the canopy resistance, R_c, is the limiting link. It is also interesting to note that the atmospheric and boundary layer resistances are higher in autumn than in spring. A longer investigation period is required to establish whether this is a general result since only one spring was included in the investigation period. R_c is defined by,

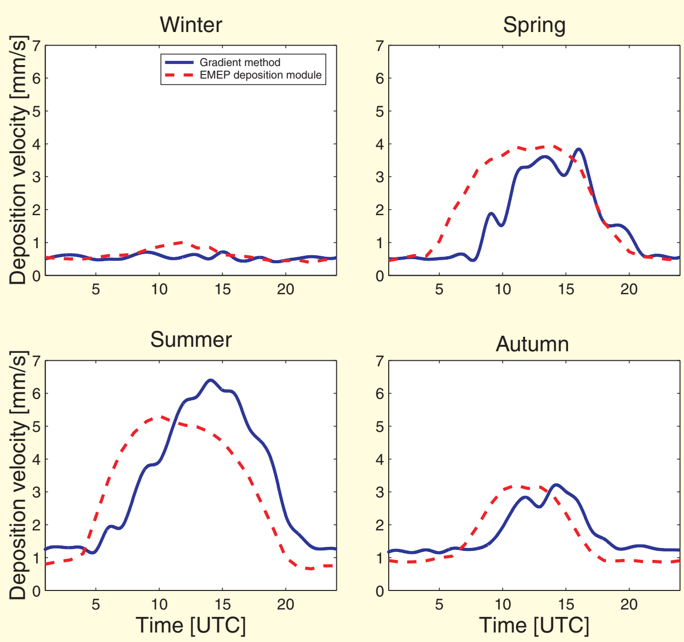

Fig. 3. Average diurnal cycles of ozone deposition velocities at the Hurdal site for winter (December-February), spring (March-May), summer (June-August) and autumn (September - November).

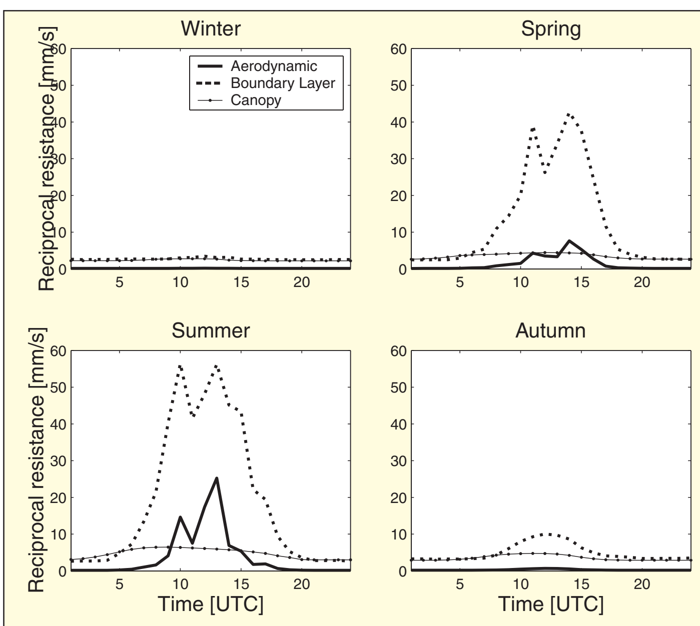

Fig. 4. Average diurnal cycles of ozone reciprocal resistances at the Hurdal site for winter, spring, summer and autumn as predicted by the EMEP deposition module.

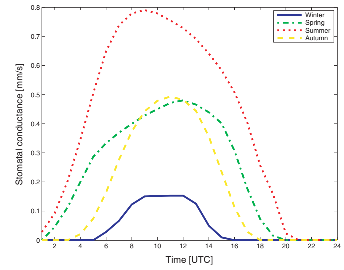

Fig 5. Average diurnal cycles of stomatal conductance as predicted by the EMEP deposition module.

$$R_c = \frac{1}{\frac{LAI}{R_{sto}}+\frac{SAI}{R_{ext}}+\frac{1}{R_{inc}+R_{gs}}} \qquad (3)$$

where R_{sto}, R_{ext}, R_{inc} and R_{gs} are the stomatal, plant exterior, land-cover specific in-canopy and ground (soil or snow) resistances respectively. *LAI* is the Leaf Area Index while the *SAI* is the Surface Area Index. For the land cover class studied here, the *SAI* varies slightly between 4.4 in January to 5.6 in July, while the LAI varies between 3.4 in January to 4.5 in July. R_{inc} is set to 1000 s/m while Rext varies between 568 s/m in winter to 454 s/m in summer. R_{gs} is approaching infinity at sub-zero air temperatures and set to 200 otherwise. R_{sto} is the resistance that has received most attention in the modelling community. It is defined by,

$$R_{sto} = \frac{LAI}{g_{sto}} \qquad (4)$$

where g_{sto} is the stomatal conductance, which is a complicated function of many factors such as solar radiation, vapour pressure deficit in the needles, soil water potential, needle age, and air temperature (Emberson et al., 2000). In Fig. 5 diurnal cycles of g_{sto} is plotted for the four seasons. The most notable feature is that the peak conductance arrives in early morning in summer, and in the early afternoon in spring. This is probably due to higher air temperatures and lower relative humidity in the summer afternoons.

Comparing Figs. 3 and 5 it seems like the early diurnal maximum of the modelled V_d (Fig. 3) in summer is associated with the very early maximum of g_{sto} (Fig. 5). The afternoon peak of g_{sto} in spring seems to result in an afternoon peak of V_d(25m).

Concluding remarks

Ozone deposition velocities above a coniferous forest in Norway have been presented. The deposition velocities have been estimated by the gradient method as well as modelled by the EMEP deposition module. Aerodynamic resistance seem to be the limiting link for ozone deposition in most seasons, except in the mid-day hours in summer when the canopy resistance is highest. Average diurnal cycles for four seasons correspond well, although there are discrepancies in the timing of the diurnal peak velocities with modelled peaks generally arriving first. There seem to be a connection between a non-zero stomatal conductance in the early morning hours and resulting high ozone deposition velocities. The reasons for these discrepancies will have to be investigated more closely. We also plan to use parameters from the EMEP CTM model as input to the deposition module.

Instrumentation at the Hurdal site will be significantly extended and improved in the near future with a sonic anemometer to provide stability parameters and better resolution of the wind profiles. This will allow for a more detailed analysis of the different resistances and ozone pathways.

Acknowledgements

We would like to express thanks to Kristine Aasarød for help with the manuscript and to Leif Håvard Slørdal for useful discussions of results. We are also grateful to David Simpson at the Norwegian Meteorological Institute for sharing the EMEP deposition module source code.

References

Emberson, L.D., Simpson, D., Tuovinen, J.-P., Ashmore, M.R., Cambridge, H.M., 2000. *Towards a model of ozone deposition and stomatal uptake over Europe.* Oslo, EMEP MSC-W Note 6/2000.

Garratt, J., 1992. *The atmospheric boundary layer.* Cambridge University Press, ISBN 0-521-46745-4. p. 58.

Simpson, D., Tuovinen, J.-P., Emberson, L.D., Ashmore, M.R., 2001. *Characteristics of an ozone deposition module.* Water Air Soil Pollut. Focus 1, 253–262.

Simpson, D., pers. comm., September 2002.

van Ulden, A.P., and Holtslag, A.A.M., 1985. *Estimation of atmospheric boundary layer parameters for diffusion application.* J. Appl. Met. 24, 1196-1207.