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Project Summary

Determination of Dry Deposition Rates for Ozone

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Measurements were taken of the rates of loss of O_3 from the atmosphere onto the earth's surface under non-precipitation conditions. This is commonly called "dry deposition" and the critical parameter is usually the "deposition velocity" V_d. Other investigators have determined that the general magnitude of V_d for O_3 is about 0.6 cm/s. The major objective of the present research was to measure ozone V_d and other meteorological parameters over a wide range of ambient conditions and to relate the values of V_d to commonly measured or estimated meteorological parameters. In this way a calculation procedure for ozone V_d could be developed for use in meteorological pollutant transport models.

The micrometeorological profile method for estimating V_d was used in this research program. Measurements were made over a soybean field in Illinois, a grain and grass field in Pullman, WA, and a hardwood forest area in south central Pennsylvania. The measurements over the soybean and grain fields show that V_d has a strong diurnal cycle and is correlated with a lateral gustiness parameter, σ u, where σ_θ is the standard deviation of wind direction and u is the average wind speed. The model is of the form $V_d = A(\sigma_\theta u)^b$ where the value of A is between 0.2 and 0.4 and b is between 0.7 and 1.3. The measurements of V_d over the Pennsylvania forest canopy did not follow this model, but the reasons are not clearly understood. However, there were some notable meteorological features of the experimental period. In particular, there was little diurnal variation in turbulence over the forest; conditions were generally turbulent over the forest canopy during the day, as might be expected, but also, unexpectedly, at night. Values of V_d over the forest area were generally larger by a factor of two or more compared to the V_d measurements over the crop surfaces.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Air pollutants are scavenged from the atmosphere largely by adsorption or reaction at the earth's surface. The effects of scavenging mechanisms usually have not been considered important factors in plume diffusion modeling because the models have been applied to relatively short distances; thus, the time periods being considered would have been too short for deposition to have had a significant impact on the system. However, diffusion and transport are now being modeled over much greater distances and covering longer time periods. Under such conditions it is no longer prudent to ignore the scavenging phase of the transport model.

The concept of *deposition velocity* (V_d) was first described in a 1953 paper by A. C. Chamberlain and R. C. Chadwick from the Atomic Energy Research

Establishment, Harwell, Great Britain, as a means of explaining the loss of material from the atmosphere to the underlying surface when the material was too small to be covered adequately by Stokes' law. By definition, V_d is the coefficient that relates air concentration, C, to the deposition rate, D:

$$D = V_d C$$

where the deposition rate, D, is essentially the downward flux of the pollutant ($\mu g\ cm^{-2} s^{-1}$); and the concentration of pollutant, C, can be expressed in $\mu g/cm^3$. Hence, the dimensions of V_d must have the units cm/s in order for the expression to balance. Since these are the dimensions of velocity, it was natural to label the coefficient *deposition velocity*.

Further study has shown that the surface loss is equal to the downward flux to the surface, F, which can be expressed in terms of well known micrometeorological variables and the vertical concentration profile.

The primary objective of the experimental program was to measure the dry deposition velocity of O_3. A second objective was to relate the deposition velocity for O_3 to a wind or a gustiness parameter, such as $\sigma\theta$, for inclusion in Gaussian-type plume models. The profile method was selected as the V_d estimation technique.

The field measurements were conducted in several major phases at three locations. In July and September, 1977 measurements were made at Robinson, IL. This was followed by a program in Pullman, WA from April to July, 1978 and near Lancaster, PA in July-August, 1979. The underlying surfaces at these three locations were different. In Illinois, the measurements involved a soybean field at two stages in its growth cycle; in Washington, the surface was grain and grass. The measurements in Pennsylvania were made over the top of a deciduous forest with a 20-m high canopy. The measurements produced an extensive set of dry deposition and meteorological data that can be applied to modeling programs.

Procedure

The field system consisted of four major components: (1) an instrumentation tower of either a scaffold type or a taller antenna type; (2) the meteorological sensor system; (3) the air sampling system; and (4) a field facility to house the instrumentation.

The Robinson IL field study began July 15, 1977 with the installation of meteorological and air sampling instruments adjacent to the Robinson airport, and continued to July 31, 1977. A similar experiment was conducted at the same site from September 5 to September 15, 1977. The scaffold instrumentation tower was erected at the eastern edge of a soybean field. Because flat agricultural lands extended several km upwind to the west, winds blowing from the directions of south through west to north were generally applicable to profile experiments; this was especially true for winds from the sector enclosed between 225° and 360°. The most frequent winds were from westerly directions satisfying the experimental requirements that the wind and pollutant flow be stabilized over an "infinite uniform" surface before reaching the tower location and profile sensors.

Commercial steel scaffold components were used to construct the scaffold instrumentation tower. Meteorological sensors were fixed at levels of approximately 25, 75, 200, and 500 cm above the crop surface. The meteorological sensors and air sampling intakes were located about 2 m from the structure in the direction of the prevailing wind. The observation levels and the types of observations on the tower are presented in Table 1.

The second phase of the study was conducted between April 1 and August 7, 1978 on a site approximately 4.8 km northwest of Pullman, Wa. At this site it was necessary to erect the scaffold instrumentation tower on the gentle slope of a hill which forms a shoulder of a shallow valley in the midst of rolling hills. The prevailing wind was from the southwest along the axis of the valley; this satisfied in a reasonable manner the requirements that the windflow be stabilized over an "infinite uniform" surface before reaching the instrumentation. Although low hills with gentle slopes rising about 30 m above the valley axis were located about 0.8 km southwest of the tower, the general terrain conformed more or less to a uniform formation which ensured a stable fetch of wind for a distance of approximately 8 km to 16 km. The crop surface was a mixed growth of grain, grass, and weeds with an average crop height of approximately 30 cm at the beginning of the April 1978 experiments. The same scaffold tower instrumentation profile given in Table 1 was used for these experiments.

The Pennsylvania forest site was located on Tower Mountain between Lancaster and York. The tower was set up at the edge of a predominantly oak forest with an estimated canopy height of approximately 20 m. To the west, in the direction of the prevailing wind, the forest surface was relatively uniform for about 2 km. The ground was cleared and leveled at the edge of the forest where the tower was located. A 34-m antenna tower was assembled on the ground with the instruments and sampling lines in place. It was then tilted into position using a gin pole and winch with the supporting guy cables used to maintain a stable attitude during the lift. The profile extended approximately 12 m above the top of the canopy. The observation levels and types of observations made at the forest site are presented in Figure 1.

At all three experimental sites air samples for O_3 analysis were drawn from six levels above the canopy surface

Table 1. *Scaffold Tower Instrumentation Profile*

Observation Level	*Profile Height**	*Type of Observation*
1	*Crop Surface (approx.)*	*Air Sample Inlet*
2	*0.25 m*	*Air Sample Inlet, Wind Speed, (WS), Temperature, (TEMP.), Dew Point (DP)*
3	*0.75 m*	*Air Sample Inlet, Wind Speed, Wind Direction, (WD), Direction Sigma, (σ_θ), Temperature*
4	*2.00 m*	*Air Sample Inlet, Wind Speed, Temperature*
5	*5.00 m*	*Air Sample Inlet, Wind Speed, Wind Direction, Direction Sigma, Temperature, Dew Point*

**Profile heights are given in relation to the top of the underlying vegetation.*

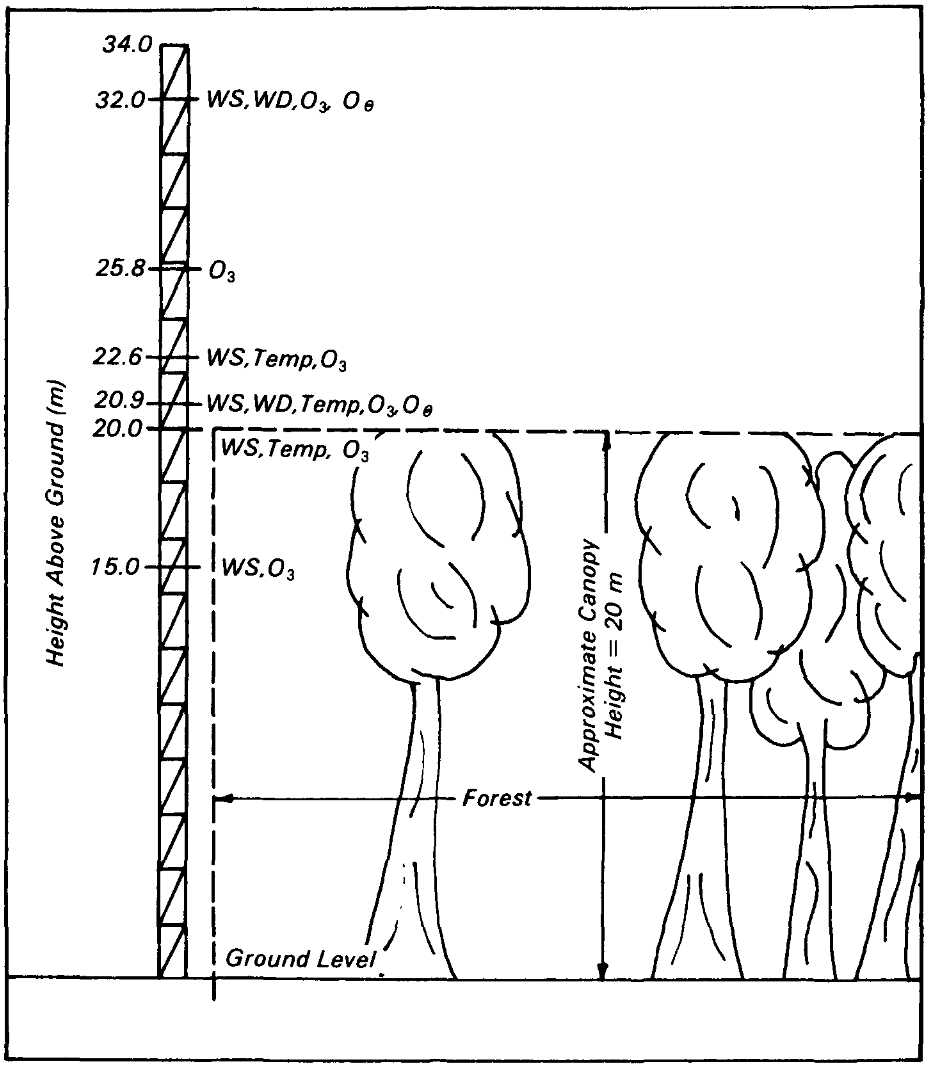

Figure 1. *Antenna tower instrumentation for forest profile studies, Pennsylvania, 1979.*

using 0.5 in O.D. (0.25 in, I.D.) Teflon tubing through a solenoid valve assembly into a common manifold leading from the tower to the mobile laboratory. A pump inside the mobile laboratory moved the sample air stream through the common manifold and the pollutant analyzer obtained its sample from this manifold. By electrically sequencing and opening one valve at a time, it was possible to draw an air sample into the common manifold successively from each of the six sampling ports. Each valve was kept open for 5 minutes. Line loss of O_3 through the manifold was determined and suitable corrections were applied to the measured concentrations.

Results and Discussion

Crop Sites

The experimental data from the Washington and Illinois sites for ozone V_d values apply to a height of about 1 m above the crop surface and show a general correspondence between the three experimental periods. At night, values of V_d were often close to zero except when the nighttime winds maintained some turbulence and prevented the formation of a strong radiation inversion. The typical daytime V_d value of approximately 0.6 cm/s is similar to recent values published by investigators in England and the United States. The nighttime V_d range of 0.1 cm/s to 0.3 cm/s, under situations when the surface-based nocturnal inversion did not occur, agrees well with the range reported from measurements in England.

The trend of variation of the ground level O_3 concentration generally exhibits a diurnal cycle with clearly defined daytime maxima and nighttime minima at both crop sites. This is a normal situation and has been reported by other investigators. It is attributed to the transport of O_3 within and below the nocturnal inversion and destruction by deposition onto the underlying surface. The morning increase of O_3 concentration is attributed primarily to downward mixing of air from aloft when the radiation inversion is dissipated. In some situations, photochemical O_3 formation could play a role in morning concentration patterns.

At the Illinois and Washington sites, the vegetation characteristics were generally uniform for several hundred meters in the direction of the prevailing wind. There is no evidence that the terrain features adversely affected the profile measurements. The O_3 dry deposition velocity and O_3 flux were calculated using only profiles recorded during the time periods when the wind fetch was from a suitable sector.

The recorded profiles of wind speed, temperature and O_3 concentrations were considered for an averaging period of 30 min. A graphical procedure was followed in obtaining the average profile for O_3 concentration during the 3 min averaging period. A similarity between the transfer of heat and the transfer of pollutant was assumed in relation to ozone V_d and ozone flux estimates. The O_3 concentrations in these cropland experiments were indicative of "natural" or background conditions rather than urban areas photochemistry. This was perhaps a significant difference compared to the forest experiment.

The field data show a general correspondence between the three experimental periods and the two sites. Daytime values of V_d averaged 0.6 cm/s with a standard deviation of 0.17 cm/s. At night, V_d values were in the general range of less than 0.1 cm/s to 0.3 cm/s, with some higher values when the nighttime winds were especially strong.

The daytime average O_3 flux determined from the cropland field study data is around 6×10^{11} molecules cm^{-2} s^{-1}, and the nighttime flux is about 1.5×10^{11} molecules cm^{-2} s^{-1}. The O_3 flux reported

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by other investigators is in the general range of 1 x 10^{11} molecules cm^{-2} s^{-1} to 6 x 10^{11} molecules cm^{-2} s^{-1}.

From the basic considerations of the micrometeorology of the boundary layer, we would expect V_d to be generally related to the product G of lateral wind gustiness, σ_θ , and the mean wind, $\bar{u}$. From data at the two sites, acceptable statistical relationships between ozone V_d and G were obtained as follows:

Robinson, IL:
July, 1977: $V_d = 0.0339(G)^{0.84}$
September, 1977: $V_d = 0.0241(G)^{0.78}$
Pullman, WA:
April/May, 1978: $V_d = 0.0406(G)^{0.76}$

where $G = \sigma_\theta \bar{u}$ (deg m s^{-1}).
Although there are some differences between these three power law regressions that may be due to differences in the surfaces, they are still generally similar and have been combined into a single power law regression:

$$V_d = 0.0322(G)^{0.79}$$

This expression could be used to derive values of V_d from estimates of σ_θ and $\bar{u}$ for a variety of cropland surfaces and sites.

Forest Site

The forest experiment produced data that were not as easily interpreted as the Illinois and Washington crop site data. The top of the forest canopy apparently did not develop a strong diurnal pattern of nighttime stability and daytime turbulence, and there was a great deal of scatter in the values of all the calculated parameters. On the basis of median values of the various parameters, the boundary layer over the canopy was determined to be characteristically unstable and turbulent. Median values of V_d were about 1 cm/s with no significant diurnal cycle. Although the gustiness parameter, σ_θ $\bar{u}$, had an apparent diurnal cycle with maximum median values in the late afternoon, nighttime median values were also relatively large. The correlation between V_d and σ_θ $\bar{u}$ was much lower than for the crop experiments. It is believed that the V_d estimates showed relatively large fluctuations because the O_3 profiles were not in equilibrium with the canopy surface. This probably resulted from local formation and scavenging processes due to the influences of local and regional photochemical air pollutants. It appears that the model developed from the low crop experiments underestimates values of V_d for the forest site by 50 percent or more.

Recommendations

The application of these results to transport model calculations was a principal objective of this research and it is believed that the results described above provide reasonable process toward this goal. For large-scale transport studies, and in most other model studies, it will be necessary to estimate values of σ_θ and $\bar{u}$ from the prevailing meteorological conditions. Values of u can be obtained directly from the observed or forecast wind field. Estimates of σ_θ can be obtained from an estimate of surface layer stability and the relationships between stability and σ_θ. The stability classes can be determined from general weather conditions using generally accepted techniques.

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***W. A. Lonneman** is the EPA Project Officer (see below).*
The complete report, entitled "Determination of Dry Deposition Rates for Ozone," (Order No. PB 82-258 989; Cost: $10.50, subject to change) will be available only from:
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