Modeling of Dry Deposition over Regional Scales with Use of Satellite Data*

by

Y. Xu and M. L. Wesely
Environmental Research Division
Argonne National Laboratory
Argonne, IL 60439

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MODELING OF DRY DEPOSITION OVER REGIONAL SCALES WITH USE OF SATELLITE DATA

Yiwen Xu* and M. L. Wesely
Environmental Research Division, Argonne National Laboratory, Argonne, Illinois

1. INTRODUCTION

Dry deposition, an essential component in the atmospheric budget of many trace chemicals, can deliver a major portion of the chemicals deposited at sensitive receptors at the surface of the Earth. Dry deposition in atmospheric numerical models is often described by modules that provide estimates of the deposition velocity \( V_d \), which is the downward flux described with modules that provide estimates of the deposition velocity \( V_d \), which is the downward flux divided by concentration at a specified height. A fairly common practice in dry deposition modules is to describe surface conditions that affect dry deposition in terms of broad land use and seasonal categories. This practice can lead to unrealistic values for \( V_d \), however, when vegetative conditions for one land use category vary considerably within the domain, when abrupt changes in surface conditions are imposed by a change in seasonal category, or when environmental conditions change vegetative properties within one season. To improve this situation, surface spectral reflectances sensed by environmental satellites can be used to provide more realistic depictions of the spatial and temporal variations in surface conditions. Such an approach is explored here, by extending methods described by Gao (1995) and Gao and Wesely (1995), in conjunction with a previously developed dry deposition module (Wesely, 1989). In addition, because simulations of biogenic emissions usually rely on an adequate description of many of the surface conditions that affect dry deposition, we examine a method of using a single source of satellite data with modules for both biogenic emission rates and dry deposition velocities.

The Biogenic Emissions Inventory System (BEIS) version 2.2, which is a version similar to the model described by Geron et al. (1994), is used. Results are presented for ozone \( V_d \), isoprene emission rates, and emission rates of other monoterpenes in the eastern half of the United States and nearby areas for selected periods during 1989.

2. DERIVING LAI AND ABSORBED PAR

The dry deposition and biogenic emission of many substances in vegetative canopies depend directly or indirectly on two key parameters: the green vegetative leaf area index (LAI) and the amount of photosynthetically active radiation (PAR) absorbed in the plant canopy. Neither of these parameters is considered directly in the formulations of Wesely (1989). BEIS 2.2 assumes appropriate values of LAI for vegetative species whose amount of coverage for various locations is provided in tables; BEIS uses PAR explicitly in estimates of the emission rates of isoprene and monoterpenes. Here these parameters are treated as variables that are derived with data from advanced very-high-resolution radiometers (AVHRRs) on satellites, with the techniques described by Gao (1995) and Gao and Wesely (1995).

Radiance reflected from a canopy-soil system result from multiple scattering of solar radiation. With an increasing amount of green leaves, the total canopy reflectance in the red band usually decreases, while the total canopy reflectance in the near-infrared band increases. Gao (1995) and Gao and Wesely (1995) used a series of formulas to describe the behavior of light in canopy-soil systems, starting with an equation for the wavelength-dependent reflectance of the bulk surface:

\[
P = \frac{(p_s p_m - 1) + (1 - p_s / p_m) (1 - P)^{-2K}}{(p_s - 1 / p_m) + (p_m - p_s) (1 - P)^{-2K}}.
\]

Here the probability \( P \) of light penetration through the canopy can be expressed as

\[
P = \exp(-G(\theta) \Omega_L \cos \theta).
\]

In (1) and (2), \( \rho_s \) and \( \rho_m \) are the wavelength-dependent reflectances for soil and the bulk canopy, respectively; \( K \) is the wavelength-dependent extinction coefficient for the bulk canopy; \( G(\theta) \) is the mean projection of unit leaf area on the plane perpendicular to the solar beam at zenith angle \( \theta \); \( \Omega_L \) is the LAI for the total canopy, and \( \Omega \) is the canopy clumping index. The values of several of these, including \( \rho_s \) and \( \Omega \), are estimates based on studies reported in the scientific literature. The values of \( \Omega_L \) and \( P \) for the red \( [\rho(\lambda)] \) and near-infrared \( [\rho(\lambda)] \) bands are found by iterations in which (1) and (2) are solved, and values of the normalized-difference vegetation index, NDVI = \( [\rho(\lambda) - \rho(\lambda)]/[\rho(\lambda) + \rho(\lambda)] \), match those measured by AVHRRs on satellites. Pathfinder monthly composited AVHRR data with a horizontal resolution of 8 km were used in this study (Agbu and James, 1994), and a simple empirical scaling scheme was applied to these NDVI data to compensate partially for atmospheric effects.

Values of PAR in the canopy are computed as

\[
I_{\text{PAR}}(L) = I_{\text{PAR}0} \exp(-KL),
\]

where \( L \) is the cumulative LAI above the height of interest, and \( I_{\text{PAR}0} \) is the incident PAR above the canopy. The absorbed photosynthetically active radiation (APAR) can be found by integration of (3) from the ground surface to the top of the canopy.

*Corresponding Author address: Yiwen Xu, Environmental Research Division, Bldg. 203, Argonne National Laboratory, Argonne, IL 60439; e-mail: Yiwen_Xu@anl.gov.
3. APPLICATION IN THE MODULE

3.1 Plant Stomatal Resistances

Transfer through plant leaf stomata is the dominant pathway for the dry deposition of trace gases that are moderately soluble in water or highly reactive with substances in substomatal cavities. Although reactions with external plant surfaces and surface elements at the ground are important sites of O₃ destruction, most of the removal of O₃ by vegetative canopies during the daytime is accomplished by destruction in leaf substomatal cavities. The substomatal resistance to O₃ uptake in the leaf mesophyll cells has been shown by many studies to be practically zero. The transfer velocity or conductance through the stomata is regulated by the aperture size, location, and number of stomata. We estimate the bulk canopy stomatal conductance $G_{si}$ for gas species $i$ as

$$G_{si} = \int_0^{L_T} W_s g_{si} dL,$$  \hspace{1cm} (4)

where $W_s$ represents the effects of variations in environmental factors on stomatal conductance within the canopy. The term $g_{si}$ represents the stomatal conductance for individual leaves and is a dependent on absorbed PAR, air vapor pressure deficit $\delta e$, and soil moisture content $\theta_s$:

$$g_{si} = \frac{D_i}{D_w} \left[\frac{\alpha_1 \text{PAR}}{(\alpha_2 + \text{PAR})}\right]^1(\delta e)^2(\theta_s).$$  \hspace{1cm} (5)

Here $D_i$ is the molecular diffusivity in air of the substance of interest, $D_w$ is the molecular diffusivity of water vapor, and $\alpha_1$ and $\alpha_2$ are empirical constants. As shown by Gao and Wesely (1995), inserting (3) into (5) and integrating the resulting expression according to (4) yields an analytical expression for $G_{si}$. Hence, estimates of $G_{si}$ are made effectively on the basis of $L_T$ and APAR inferred from satellite data. Other components of surface conductances are found via the procedures described by Wesely (1989).

3.2 Dry Deposition Velocity Estimates

Estimates of ozone $V_d$ were made for each 8 km by 8 km pixel associated with the Pathfinder AVHRR data set. For these calculations, each of 26 land use classes derived from a United States Geological Survey (USGS) land cover data set for areas of 1 km by 1 km (USGS, 1990) was assigned to one of the land use categories used by Wesely (1989). The value of NDVI for each AVHRR pixel was assigned to each enclosed land use cell, for which values of $L_T$, APAR, and O₃ deposition velocities were computed and averaged for each AVHRR pixel. Figures 1a and 1b show resulting estimates of ozone $V_d$ at a height of 20 m above the local zero-plane displacement heights for January and July 1989. Incident PAR throughout the domain was assumed to have values of 100 W m⁻² in January and 500 W m⁻² in July, for midday, cloudless conditions. The average $V_d$ over the domain was calculated to be

Fig. 1. Distribution of ozone deposition velocities (m s⁻¹) modeled for (a, top) January 1989 with the current module, (b, middle) July 1989 with the current module, and (c, bottom) July 1989 with an older module version that does not use satellite remote sensing data.
0.003 m s⁻¹ for the winter months of December, January, and February and 0.004 m s⁻¹ for the season-transitional months of March, April, October, and November. For July, peaks near 0.008 m s⁻¹ for V_d can be seen (Fig. 1b) in forested areas in the Appalachian Mountains and the Ozarks, while values slightly smaller appear in large areas of agricultural lands. By comparison, significantly less spatial variation and one-third larger deposition velocities were computed with the procedures described by Wesely (1989) without use of satellite data (Fig. 1c). The highest deposition velocities seen in the simulations using the present techniques are near 0.009 m s⁻¹, during May in a region that includes the West Virginia and in another region encompassing Indiana. The location of large dry deposition velocities in the former region moved northward as the season progressed, while deposition velocities in the latter region gradually decreased as agricultural crops matured. Such spatial and temporal patterns were not seen without use of satellite-derived NDVI (Fig. 1c).

The pattern in Fig. 1b tend to conform with those for ozone G₂ shown by Gao (1995) for July 1997, suggesting that consistency in results has been achieved. The ultimate test of the worthiness of the modeled estimates of ozone V_d would be comparison to measured values, which are not readily available for large areas. The most easily found types of data are to be O₂ deposition velocities at specific sites, which tend to agree with the values in Fig. 1b. For example, midday values of ozone V_d during summer are typically 0.005-0.011 m s⁻¹ over agricultural crops but are as high as 0.012 m s⁻¹ over deciduous forests (e.g., Wesely, 1983; Padro, 1996; Meyers et al., 1998).

4. APPLICATION IN THE BIOGENIC EMISSION MODULE

4.1 Emission Rates of Isoprene and Monoterpenes

Nonmethane hydrocarbons (NMHCs) emitted from vegetation can strongly influence ozone production in the troposphere. Guenther et al. (1995) estimated that vegetation generates over 90% of the global emission of volatile organic compounds. Experiments have shown that the emission rate of isoprene from vegetation is a function of plant species, canopy leaf density, and environmental variables such as solar radiation, temperature, and soil moisture content. Oak and eucalyptus tree leaves have very high emission rates, while rates for maize, cotton, and potato are usually smaller by several orders of magnitude. To model the emission rates for isoprene, a set of formulas summarized by Geron et al. (1994) is used. The emission rates of isoprene or monoterpenes from the whole canopy can be estimated by integrating all individual leaves as follows:

\[ F_C = \int F_L dL \]  \hspace{1cm} (6)

Here \( F_L \) is the emission rate from an individual leaf, and \( F_C \) is the total emission from the canopy.

4.2 Comparison of Module and BEIS 2.2 Results

Modeled estimates of \( F_C \) for isoprene and monoterpenes during July 1989 are shown in Fig. 2, for which values of PAR = 1000 μmole m⁻² s⁻¹ (approximately 220 W m⁻²) and \( T = 320^\circ \text{C} \) were assumed. The computations of \( L_T \) and APAR were carried out in the same way as for the dry deposition module. Emission calculations were based on a table of emission factors provided by BEIS (version 2.2) for 129 plant species at standard conditions of \( T = 30^\circ \text{C} \) and PAR = 1000 μmole m⁻² s⁻¹. A data set developed for applications of BEIS 2.2 by the Ozone Transport Assessment Group (OTAG) identified the fractional coverage of each plant species within areas of 1/6 deg latitude by 1/9 deg longitude. The patterns and magnitudes of isoprene and monoterpane \( F_C \) displayed in Fig. 2 agree fairly well with those shown in Figs. 6a and 6b of Geron et al. (1994), who used a slightly earlier version of BEIS. The regions of high isoprene emission in the southern Appalachian Mountains and the Ozarks are associated with a high density of oak and gum trees. The northern Appalachians have lower isoprene emission rates because of fewer oak trees and more maple, beech, and birch trees. In much of New England, the emissions are substantial because of the abundance of spruce forest. In comparison to the results of Geron et al. (1994), the present simulation gives significantly larger isoprene emission rates in the southern portion of the domain, probably because Geron et al. (1994, in Fig. 6a) did not address emissions from nonforested vegetation. For monoterpenes, the values of \( F_C \) mapped in Fig. 2b vary between 0 and 2 mg C m⁻² hr⁻¹, in fairly close agreement with the results of Geron et al. (1994).

5. CONCLUSIONS

The dry deposition module successfully uses NDVI data derived from satellite data to infer LAI and APAR, to compute bulk canopy stomatal conductances for estimates of \( V_d \), and to compute \( F_C \) for selected hydrocarbons. The modeled dry deposition velocities are about 30% less than the those produced by Wesely's model (1989) in dry summer, and the temporal and spatial patterns appear to be more realistic than those produced in past models that rely on broad land use types or specified LAI in tables. In addition to the chemical species addressed in this paper, the module can estimate deposition velocities of SO₂, NO₂, and other substances, as well as the emission rates for a variety of NMHCs. Evaluation of model performance tends to be limited to comparisons with experimental results at specific sites and to comparisons of observed concentrations with those resulting from outputs of atmospheric chemistry models. Improvements in the module are needed in the algorithms for nonstomatal conductances. Use of more detailed descriptions of the distribution of plant species will be considered, such as the data sets currently being applied in a new version of BEIS (Pierce et al., 1998). Algorithms for soil emission rates of NO and the rapid in-air chemical reactions of NO and NO₂ need to be developed further and added to the module.
Fig. 2. Distribution of emission rates (mg C m\(^{-2}\) hr\(^{-1}\)) modeled for July 1989 for (a, top) isoprene and (b, bottom) monoterpenes.

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