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Project Summary

A Dry Deposition Module for Regional Acid Deposition

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Methods to compute surface dry deposition velocities for sulfur dioxide, sulfate, ozone, NO plus NO_2, and nitric acid vapor over much of the North American continent have been developed for use with atmospheric numerical models of long-range transport and deposition. The resulting dry deposition module, actually a FORTRAN subroutine and a landuse map, has been designed for use with Eulerian models but can also produce maps and averages of deposition velocities for other types of models. The module provides much of the data required to compute deposition velocities: a computerized landuse map, surface roughnesses keyed to landuse type and season, and similarly keyed surface resistances of pollutant uptake. The landuse map has basic grid cells with dimensions of 1/4 degree longitude by 1/6 degree latitude, over the region from 52 to 134 degrees west longitude and 24 to 55 degrees north latitude. External input data must specify geographical location, season, and height at which deposition velocity estimates are to be made, as well as provide values of atmospheric parameters such as solar irradiation, wind speed, atmospheric stability, and boundary-layer mixing height. These parameters are usually average values for gridded areas defined by the Eulerian model. A fairly general dry deposition module has been produced as well as a module adapted specifically for the Regional Acid Deposition Model being developed at the National Center for Atmospheric Research.

This Project Summary was developed by EPA's Atmospheric 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

Dry deposition results in substantial removal of trace substances from the atmosphere and accounts for a large portion of the sulfur and nitrogen compounds delivered to the surface. Atmospheric numerical models of long-range transport and deposition of such substances must take into account dry deposition. This is the case, for example, in Regional Acid Deposition Model (RADM) being developed by the National Center for Atmospheric Research for the National Acid Precipitation Assessment Program. The rates of deposition are obtained by the expedient of multiplying pollutant concentrations by deposition velocities. To improve estimation of the deposition velocities, it is necessary to incorporate the latest research findings and compile the necessary formulae and data. For RADM, the results of such work are applied in the form of a dry deposition module, which includes a FORTRAN subroutine and a landuse map for the continental United States and its surrounding regions. In addition to sulfur dioxide and sulfate particles addressed in earlier efforts, O_3, NO plus NO_2, and NHO_3 are included in the present study.

Many variables control the dry deposition velocities of airborne chemical substances. Each chemical species has distinct chemical and physical properties that strongly affect uptake at the surface. Correspondingly, each type of surface has its own influential set of physical, chemical, and biological characteristics. Indeed, deposition velocities vary widely depending on chemical species, surface type, season, and time of day. For a region as large as the contiguous United States and surrounding areas in Canada, Mexico, and bordering seas, development of an appropriate dry deposition module requires some balance between identification of the details of processes that control dry deposition and the computational time available to estimate deposition velocities over large areas in small time steps. In the present study, we address a simplified scheme to compute dry deposition velocities averaged over surface grids with typical side dimensions of tens and kilometers. Considerable generalization of results from research on dry deposition is made in order to achieve a working dry deposition module.

Procedures

The deposition velocity v_g for a gas at height z over land is computed as

$$v_g = ku_*[\ln(z/z_0) + 2(D_h/D_g)^{2/3} + ku_*r_g - \psi_c]^{-1} , \qquad (1)$$

where k is the von Karman constant, u_* is the friction velocity, z_0 is the surface roughness scale length, D_h and D_g are the molecular diffusivities for heat and the gas of interest, respectively, ψ_c is the stability correction function for the gas, r_g is the surface resistance to uptake of the gas. The deposition velocities of sulfate particles over water and land are computed from

$$v_p = ku_*[\ln(z/z_0) + ku_*r_p - \psi_c]^{-1} , \qquad (2)$$

where r_p is the surface resistance for particle uptake.

To determine deposition velocities with these equations, the parameters that must be specified are surface roughess, molecular diffusivity, stability correction function, friction velocity, and surface resistance. Molecular diffusivities are provided within the module, while friction velocity and atmospheric stability are input variables. The surface roughnesses and the surface resistances for SO_2 and O_3 are provided by lookup tables that specify landuse types and seasonal categories. The landuse types are classified as follows:

1. urban land,
2. agriculture land,
3. range land,
4. deciduous forest,
5. coniferous forest,
6. mixed forest including wetland,
7. water,
8. barren land,
9. non-forested wetland,

A. mixed agricultural and range land, and

B. rocky open areas occupied by low growing shrubs.

The seasonal categories are:

1. midsummer,
2. autumn,
3. late autumn,
4. winter, and
5. transitional spring.

The landuse data used in the present study cover an area from 52 to 134 degrees west longitude and 24 to 55 degrees north latitude. The area is divided into a matrix of 328 × 186 (longitude by latitude) grid cells with increments of 1/4 and 1/6 degree longitude and latitude, respectively. Data for each grid cell contain longitude and latitude coordinates of the cell and the percentages of the areas used by the 11 landuse types in the cell. A sample landuse map of the most prevalent landuse type in each one-degree square is shown in Figure 1.

The surface resistance tables for SO_2 and O_3 contain values partitioned according to solar irradiation during the daytime in order to account for the influence of variations of vegetational stomatal openings on surface uptake. A special category is added at night for very light winds when dew is likely to form on the surface. For NO plus NO_2, the surface resistances are computed on the basis of O_3 surface resistance coupled with selected algorithms. The simplest species to deal with is HNO_3 because the surface resistance is assumed to be 0.1 s cm^{-1} in all cases. For sulfate particles, the surface resistance tables are not used. Instead, equations provide the surface resistance as a function of friction velocity, atmospheric stability, and boundary-layer inversion height, with only a minimal dependance on surface roughness.

Parameters of input to the module must include chemical species, height at which deposition velocity is needed, friction velocity, Monin-Obukhov length (i.e., atmospheric stability), solar irradiation, atmospheric temperature, boundary-layer inversion height, and air temperature and humidity.

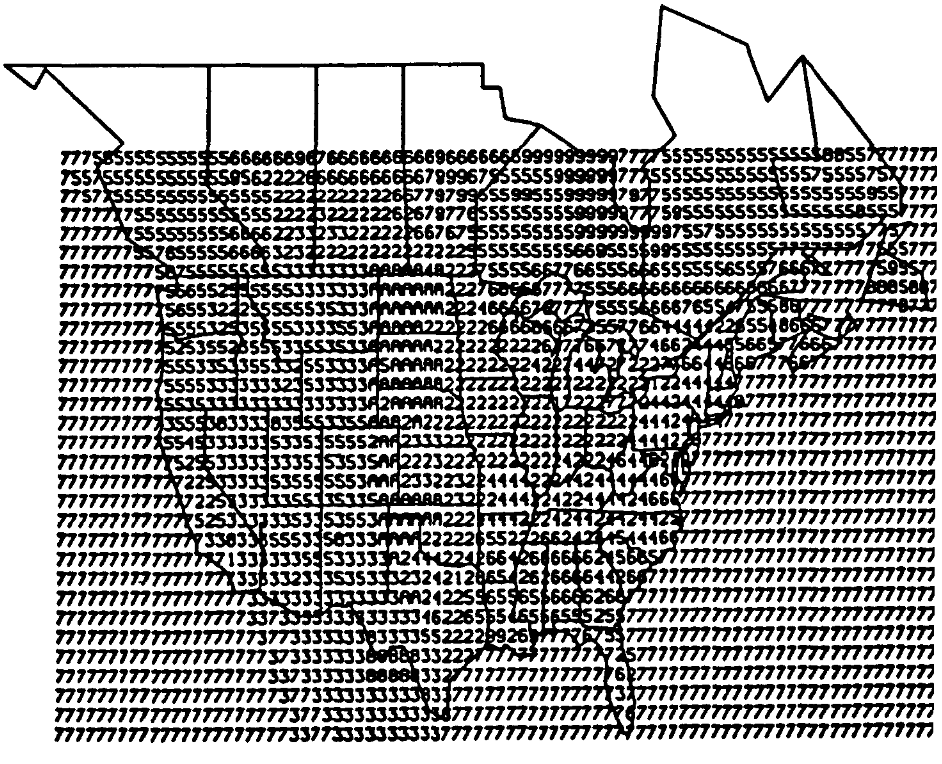

Figure 1. A landuse map of North America with locally dominant landuse types represente by alphanumeric symbols.

Results and Discussion

Sample maps of dry deposition velocities of nitric acid vapor and sulfate particles are shown in Figures 2 and 3. These assume summer daytime conditions when solar irradiation levels are greater than 400 W m^{-2} and wind speeds are moderate, corresponding to approximately 3.8 m s^{-1} at a height of 10 m above a surface with z_0 equal to 3 cm. A sensible heat flux of 150 W m^{-2} is assumed over all land surfaces and 20 W m^{-2} is assumed for water surfaces. Nitric acid vapor and sulfate particles are chosen for illustration because they have extremes in deposition velocity. At heights of 10 m above the northeastern United States during daytime summer conditions, for example, the average deposition velocity values are near 3.5 cm s^{-1} for HNO_3 but are an order of magnitude less for particulate sulfur. At night, values of deposition velocity for particulate sulfur, are typically smaller than 0.05 cm s^{-1} (not shown).

RADM has successfully utilized the dry deposition module to compute deposition of SO_2, $SO_4^=$, and HNO_3 over the eastern United States for three rainy days in the springtime. Domain averaged midday deposition velocities were found to be 0.8 cm s^{-1} for SO_2, 0.2 cm s^{-1} for sulfate, and 2.5 cm s^{-1} for HNO_3.

Most Eulerian models provide sets of atmospheric parameters that are meant to be averages over entire grid cells. For example, the mesoscale meteorology model of RADM gives one average profile of wind speed, temperature, and humidity per grid square of 80 by 80 km. From the profiles, the fluxes of momentum, heat, and moisture required for input to the dry deposition module must be derived in order to compute deposition velocities via Equations. (1) and (2). In the current version of the module used in RADM, grid-averaged fluxes are derived from the profiles with semiempirical equations designed to avoid time-consuming iterative calculations necessary with conventional micrometeorological formulae.

For each grid cell in RADM, a new average friction velocity is estimated on the basis of a grid-averaged wind speed and a surface roughness computed as the logarithmic average of values weighted by the fraction of area covered by each landuse type. The products of wind speed and friction velocity are then assumed constant over all surfaces within the grid, at a specified height near 40 m. This allows computation of the local friction velocity and wind speed above each landuse type, via the equation of the logarithmic wind profile and the surface roughness for each landuse type. This provides both realistic variations in local friction velocity above each grid cell and a distribution of wind speed that, when averaged, is consistent with the grid-averaged wind taken from RADM. The heat and moisture fluxes important in computing the Monin-Obukhov length are assumed constant and equal to the grid averages, which is a deficiency, but a small one compared to the practice of assuming constant friction velocity, or alternatively, wind velocity.

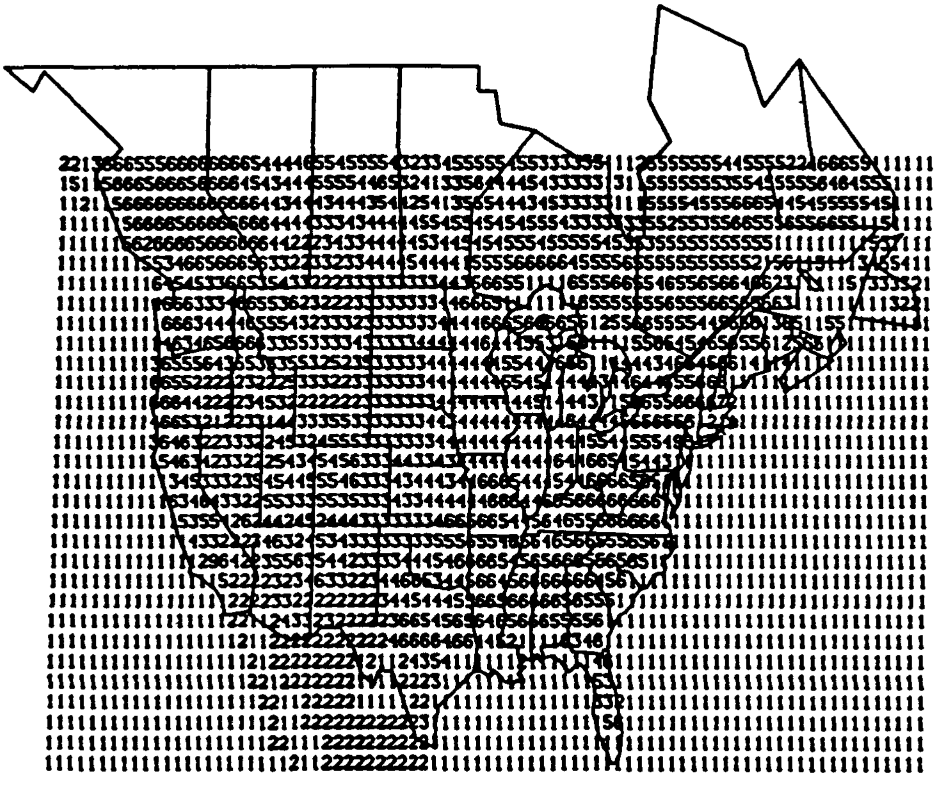

Figure 2. *A dry deposition velocity map of nitric acid vapor. The integers (0, 1, ---, and 9) in the map represent deposition velocities with intervals of 0.596 cm s^{-1}; e.g., 0 and 1 represent the ranges of deposition velocities 0 to 0.596 and 0.596 to 1.192 cm s^{-1}, respectively.*

Conclusions

The dry deposition module provides a means of computing surface dry deposition velocities of major chemical compounds for numerical modeling of acid deposition. The subroutine will produce deposition velocities for SO_2, $SO_4^=$, O_3, NO plus NO_x, and HNO_3 at each grid cell with dimension of 1/4 degree longitude by 1/6 degree latitude, for the continental United States and surrounding regions. It should be noted that insufficient information on surface resistances necessarily limits the accuracy of the computed deposition velocities. Current knowledge of the resistances is good for SO_2, HNO_3 and O_3, fair for $SO_4^=$, and poor for NO and NO_2. However, the subroutine can be easily updated to include new results of research or modified to include additional chemical species.

The dry deposition module is quite easy to apply as provided. The multiple factors that control surface resistances for a given chemical substance over a specified type of surface are taken into account, but not explicitly, so that calculations of deposition velocity can be made very efficiently. A drawback of this approach is that considerable work, often of a research nature, is necessary to modify the module to include additional chemical species. Other deficiencies of the module include ignoring such factors as rapid in-air chemical reactions, which can change the deposition velocity with height, and the effects

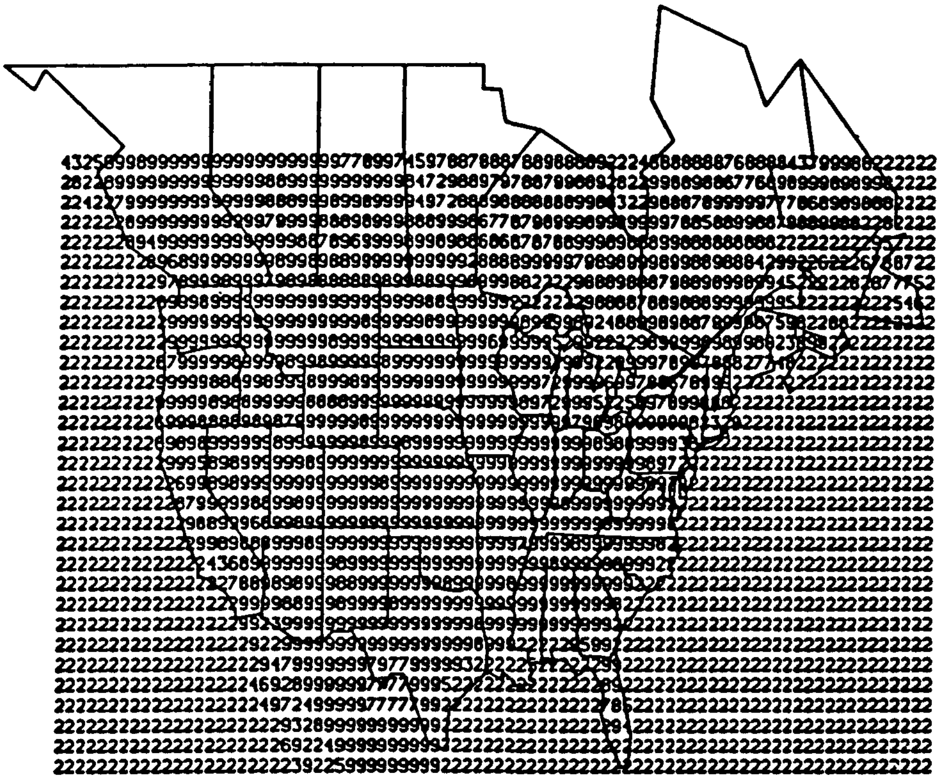

Figure 3. A dry deposition velocity map of particulate sulfur with deposition velocity intervals of 0.0412 cm s^{-1}

of nonuniform and hilly terrain. Also, the temporal variations of surface resistance caused by the surface being wetted by dew or rain are not addressed explicitly in the module, and thus must be taken into account by other components of the controlling numerical model.

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The complete report, entitled "A Dry Deposition Module for Regional Acid Deposition," (Order No. PB 86-218 104/AS; Cost: $11.95, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
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