SIMULATED DRY DEPOSITION OF NITRIC ACID NEAR FOREST EDGES

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Abstract—Dry deposition is simulated to understand and generalize observations of enhanced deposition of air pollution near forest edges. Nitric acid is taken as an example as its deposition velocity is often assumed to be determined by turbulent transport only. The simulations are based on the micro-meteorological model of Klaassen (1992). The multi-layer representation of vegetation accounts explicitly for inflow of air at wind exposed forest edges. Simulated dry deposition near a forest edge appears sensitive to the surface resistance. A small but non-zero surface resistance seems most realistic. Edges of coniferous forest may receive more deposition than deciduous forests due to the small resistance of needles. The enhancement of deposition is caused by advection and inflow. Advection influences deposition over large distances, whereas the local edge effect is mainly caused by inflow. Deposition at a forest edge increases with length of the upwind grassland. On the other hand, deposition is decreased behind a forest. The model is used to scale up local observations into landscape averages. The modelled landscape average deposition is used to evaluate three methods which could be applied as boundary condition in large-scale deposition models. Good results are found when average dry deposition is calculated from the average surface roughness.

Key word index: Dry deposition, nitric acid, aggregation, advection, inflow.

1. INTRODUCTION

Deposition of oxidized and reduced nitrogen compounds causes acidification and fertilization of water and soil (Jaffe, 1992). This has serious consequences: the most important threat to Dutch forests is acidification by SO₂, NH₃ and NOₓ together with the eutrophication as the result of the high N inputs (Hey and Schneider, 1991). The acidifying load arises from wet and dry deposition. Wet deposition from a single shower is extremely variable in space, but on a longer time scale these variations average out as long as orography and sea-breeze are insignificant. Dry deposition, on the other hand, is very variable as it strongly depends on surface roughness, surface conditions and component characteristics. Furthermore, dry deposition is systematically affected by landscape heterogeneity, with enhanced deposition at wind-exposed forest edges (Hasselroth and Grennfelt, 1987; Beier and Gundersun, 1989; Draaijers et al., 1994). This "edge effect" is caused by two processes. The first process is the wind blowing into the edge and thus bringing the pollutants in almost direct contact with the vegetation. This effect is called inflow. The second process is enhanced turbulence behind the edge, resulting in more exchange between vegetation and the atmospheric surface layer. This effect is called advection (Draaijers et al., 1994).

The assessment of deposition into ecosystems is simulated using Inferential Models and Long-Range Transport Models. These models calculate deposition on the basis of a grid with a size of kilometers (Erisman, 1993; Duyzer and Fowler, 1994). On this scale the landscape is generally heterogeneous. Various methods can be used to deal with the sub-grid variations in vegetation:

1. Calculate deposition for the main surface cover. This method neglects all surface variability.
2. Calculate deposition for individual, homogeneous patches and adding these patches to a landscape average. This is the so-called mosaic approach (Avisssar and Pielke, 1989) and used in e.g. the RADM deposition model (Chang, 1986). The method neglects inflow and advection between neighbouring patches.
3. Calculate deposition using the grid-averaged surface roughness. Several methods are available to calculate grid averaged roughness. Here, the method given by Van Dop (1983) will be used. This method accounts for local advection but neglects inflow.
It is expected that the first method is least realistic and the third method is most realistic. However, due to the small size of forests, Draaijer et al. (1994) estimate from measurements of deposition near forest edges that even the last method would result in an underestimation of 5–10% of acid dry deposition in The Netherlands. The present study aims to yield a more accurate estimate of dry deposition in the presence of subgrid variability in vegetation.

The study is executed with a high-resolution model that explicitly simulates the processes of inflow and local advection. A modelling approach is chosen as it enables to generalize existing observations near forest edges into landscape averages. For instance, measurements have preferably been carried out inside forests near wind-exposed edges. Using a model it is possible to analyse whether the observed enhancement of deposition near such a transition is compensated at the leeward side of the forest.

Nitric acid (HNO$_3$) is used as an example as it was mentioned as one of the major uncertainties in the calculation of acid deposition in complex terrain (Duyzer and Fowler, 1994). The uncertainty arises as nitric acid is highly reactive and deposits quickly after entering a forest canopy (Meyers et al., 1989; Sievering et al., 1994). A second advantage of the high reactivity might be the relative ease of simulating deposition for a gas with negligible surface resistance (e.g. Huebert and Robert, 1985). However, a small surface resistance is often included to prevent unrealistically high deposition rates to aerodynamically rough surfaces (Wesely, 1989). Therefore, it was decided to compare simulations with and without a surface resistance for deposition of nitric acid.

2. THEORY

2.1. Dry deposition onto a homogeneous surface

Dry deposition is the mass flux density $F_d$ (mg m$^{-2}$ s$^{-1}$), which is calculated from the deposition velocity using

$$ F_d = - V_d C $$

where $C$ is concentration (mg m$^{-3}$) of the depositing compound at some reference height above the surface.

For heavy particles, the deposition velocity may be approximated by the fall velocity. For gases, like nitric acid, the deposition velocity depends among others on atmospheric turbulence and is calculated with a resistance analogy:

$$ V_d = \frac{1}{R_a + R_b + R_c} $$

where $R_a$ is atmospheric resistance, $R_b$ is laminar leaf boundary resistance and $R_c$ is canopy resistance (all resistances are in s m$^{-1}$). Note that sometimes conductances ($G$) are given, related to resistances by $G = 1/R$.

The atmospheric resistance above a homogeneous surface is given by the Monin–Obukhov similarity theory. For neutral atmospheric stability, it is described by

$$ R_a(z) = \frac{1}{k u^*} \ln \left( \frac{z - d}{z_0} \right) $$

where $z$ is height above the surface (m), $d$ is zero-plane displacement (m), $z_0$ is roughness length (m), $k$ is von Karman’s constant, taken as 0.4, and $u^*$ is friction velocity (m s$^{-1}$).

The leaf boundary resistance $R_b$ accounts for the difference between transport of momentum and transport of heat or gases. Momentum is absorbed by turbulence as well as by air pressure gradients. The latter process does not influence heat or gas transport. Absence of a transport mechanism is described by adding a resistance $R_c$, that is related to the laminar layer around the leaves. We use the formulation of Wesely and Hicks (1977):

$$ R_b = \frac{2}{k u^*} \left( \frac{S_c}{P_r} \right)^{2/3} $$

As nitric acid is highly reactive, one might assume that the canopy resistance is negligible. However, Wesely (1989) proposed a value near 10 s m$^{-1}$ to avoid unrealistic high deposition velocities in high-turbulence situations and Erisman et al. (1994) recommend $R_c = 1$ s m$^{-1}$. The value $R_c = 10$ s m$^{-1}$ is used in this study.

2.2. Three methods accounting for surface heterogeneity

The land surface is seldom homogeneous at the grid size of atmospheric deposition models. Cultivated landscapes can mostly be described as being ‘patchy’, i.e. composed of relatively homogeneous patches with pronounced boundaries between these patches. For simplicity, we assume only two types of patches to be present within the grid: forest and grassland. The size of the patches with forest and grassland will be varied. Three methods to calculate deposition onto a patchy forest–grassland landscape are compared:

(1) Heterogeneity is completely neglected. The grid cell is assumed to be completely covered by the dominant vegetation type.

(2) The deposition velocity is calculated as the area-weighed average of the deposition velocities of forest ($V_{df}$) and grassland ($V_{dg}$):

$$ V_d = (1 - f) V_{df} + f V_{dg} $$

where $f$ is the forested fraction of the landscape. Equation (5) does not take into account inflow and local advection near the boundaries of the patches. As a result, equation (5) should represent the situation that only one boundary between patches is present within the grid.
The deposition velocity is calculated from the landscape-averaged surface roughness. Several methods exist to calculate a landscape-averaged surface roughness, as reviewed by Klaassen and Claussen (1995). Here we will follow the method used in the Dutch Empiric Acid Deposition Model (DEADM; Erisman, 1993) to average local drag coefficients. The drag coefficient is defined as \( C_d = (u^*/u)^2 \), with \( u \) the wind velocity at the reference height \( z \). For neutral stability

\[
C_d = \left[ \frac{0.4}{\ln(z/z_0)} \right]^2
\]

(6)

The area-weighted drag coefficient of a heterogeneous landscape is then calculated according to

\[
C_d = (1 - f)C_{d_g} + fC_{d_f}.
\]

Following Van Dop (1983) we use a reference height \( z = 10 \text{ m} \). Method 3 takes advection implicitly into account by using a homogeneous, fully advected atmospheric boundary layer above the reference height and a surface layer without advection completely adjusted to the patchy surface below that height. The amount of advection thus depends on the reference height. Inflow of air into wind exposed forest edges is still neglected in this method.

2.3. The micro-meteorological model

The micro-meteorological model is based on a model by Klaassen (1992) for heat and momentum fluxes in heterogeneous, vegetated landscapes. It is a two-dimensional model with a horizontal x-axis in the wind direction and a vertical z-axis. Landscape heterogeneity is described in the x direction by alternating homogeneous patches of grassland and forest. The vertical grid interval ranges from 1.5 m near the surface to 40 m near the upper boundary \( h_s = 200 \text{ m} \) height. Forest vegetation is represented in a layer of vegetation is given by

\[
C(z) = \text{leaf area at height} \ z \ (\text{m}^2 \ \text{m}^{-2}) \text{ and } \ r_b(z) \text{ is leaf boundary resistance at the leaf scale. Note that equation (4) is meant for the canopy scale (with resistances in capitals) and equation (11) applies for the leaf scale (with lower case). The boundary resistance at the leaf scale is given by (Pearman et al., 1972):
\]

\[
r_s(z) = 90 \left( \frac{Sc}{Pr} \right)^{0.5/3} \sqrt{l_w/u(z)}
\]

(12)

where \( l_w \) is leaf width, taken as \( l_w = 0.05 \text{ m} \). For \( u = 1 \text{ m s}^{-1} \) in the crown, equation (12) results in \( r_s = 29 \text{ s m}^{-1} \).

The value of \( r_s(z) \) was varied until the calculated deposition on the multi-layer vegetation was equal to the deposition on a single layer vegetation with \( R_s = 10 \) (Wesely, 1989). This resulted in \( r_s = 26 \text{ s m}^{-1} \). So, total resistance to the leaves \( r_b + r_c = 55 \text{ s m}^{-1} \), equivalent to a conductance \( g = 19 \text{ mm s}^{-1} \). Simulated conductance agrees well with the range 6–34 mm s\(^{-1}\) found for coniferous leaves by Hanson.
and Garten (1992) but it is an order of magnitude above the observed range of 0.9–3.4 mm s⁻¹ for hardwoods. Meyers et al. (1989) found a similar total resistance although they used a zero surface resistance in combination with a larger leaf boundary resistance. Given the uncertainty in the exact value of $r_b$ and $r_e$, it was decided to analyze the significance by adding a few simulations with $r_e = 0$.

Using the model

The model is initialized with an atmospheric profile which is completely adjusted to grassland. This boundary condition is not appropriate for complex landscapes where the air cannot adjust to a single patch. A more suitable boundary condition is obtained in the following way: A heterogeneous landscape is defined as a patch of grassland followed by a patch of forest. Then a large number of identical grassland-forest landscapes are joined into a region. The air is simulated to move over the successive landscapes until the atmospheric profile is adjusted. Assuming a common fetch-height ratio of 100, it would take 20 km before the atmosphere up to the upper boundary of 200 m would be adjusted. Observations of deposition near wind-exposed forest edges are generally carried out in the first 100 m downwind of a forest edge. As a result, it is not possible to validate the simulations for fetches exceeding 100 m.

The deposition in the first 100 m from the edge is enhanced by a factor of 2. This agrees with observations of deposition of reactive compounds of air pollution (Hasselroth and Grennfeld, 1987; Beier and Gunderson, 1989). A slightly more quantitative comparison has been made by throughfall observations of Draaijers et al. (1994). The enhancement factor $e$ is defined as the ratio of average enhancement of deposition in the first 100 m compared to the deposition at 150 m from the edge. Note that Fig. 1 shows that deposition might still be enhanced, relative to the deposition to homogeneous forest, at 150 m from the edge. The present definition is just meant to enable comparison of simulations with observations. For a preceding grassland of 500 m the simulations result in $e = 48\%$. For comparison, Draaijers et al. (1994) measured on average for eight forest edges $e = 64\%$ for Na, 54% for Mg, 23% for SO₄ and 18% for NO₃ and NH₄. Deposition of HNO₃ alone could not be measured with the throughfall method, as several compounds add to the total deposition of nitrate (NO₃). The measurements of Draaijers et al. (1994) are used to give an upper and lower limit of enhancement of deposition of nitric acid at a forest edge in the following way: As most nitrates are less reactive than nitric acid, the observed enhancement of NO₃ is a lower limit for deposition of HNO₃. Salt (represented by Na) is taken as an upper limit as aerosol should deposit with even more enhancement at the edge than the gas HNO₃. At first glance, the simulated enhancement ($e = 48\%$) seems near the upper limit of the

### Table 1. Input data of the simulation model

<table>
<thead>
<tr>
<th>Grid layer</th>
<th>Height (m)</th>
<th>Leaf area (in case of forest)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.3</td>
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<td>3</td>
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<tr>
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<td>18</td>
<td>200</td>
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</table>
Deposition of nitric acid 3685

expected range between nitrate ($e = 18\%$) and salt ($e = 64\%$).

When comparing observations and simulations, it should be noted that simulations show the distance from the edge in the direction of the wind and measurements are taken for various wind directions. For instance, wind from the forest to the grass does not lead to enhanced deposition at the edge. Observations were made near forest edges which are exposed to the prevailing wind direction. For these edges, a 45° angle of attack seems to be a reasonable estimate. This would decrease the distance perpendicular to the edge by a factor $0.7$ and reduce the simulated enhancement from $48\%$ to $37\%$, in good agreement with the range of confidence, estimated from the observations ($18\% < e < 64\%$).

The sensitivity of deposition to the canopy resistance $R_c$ is shown in Fig. 2. The normalized flux at the forest edge increases strongly when $R_c = 0$; the enhancement at the first 100 m is increased by a factor of $2$ to $e = 95\%$, well above the estimated upper limit. The comparison of the results with and without canopy resistance suggests strongly that a non-zero canopy resistance, or alternatively a high leaf boundary resistance, is most appropriate to simulate spatial variability of dry deposition of nitric acid.

The enhancement of deposition is caused by two processes: advection (Fig. 3) and inflow (Fig. 4). Advection is caused by an unadjusted atmosphere and is calculated as the difference between total deposition flux and advection. Advection results in a decrease of deposition in the first few meters after the forest edge, followed by an increase. The initial decrease results from the deposition at canopy height being still related to the lower deposition to the upwind grassland. Advection in the first few meters is also reduced as the air slows down in the forest canopy, resulting in an upward wind at the canopy top because of mass conservation and a decrease of downward deposition flux. For larger fetches, wind speed inside forest has become low, so wind shear, friction velocity and deposition above forest increase. With even further increase of fetch advection decreases as equilibrium is slowly approached. Figure 3 shows that it is advection that causes the deviation from equilibrium over relatively large distances. In contrast, inflow is mainly restricted to the first 100 m (Fig. 4).

3.2. Patch averaged deposition

The enhancement of deposition near a forest edge influences average deposition on a forest. With a preceding grassland of 5000 m length, average deposition on a forest of 500 m is enhanced by 68%, relative to the deposition to a homogeneous forest, see Fig. 5. On the other hand, deposition on grassland is decreased by a preceding forest. For instance, deposition on a 500 m long grassland is decreased by 43% when it is surrounded by 100 m forest. The decrease of deposition in the wake behind forest is explained by two processes: (1) at low levels, wind velocity and friction velocity are decreased behind forest due to the high
amount of momentum, absorbed by the forest, and (2) concentrations of polluting compounds are decreased due to the relatively high deposition to forest. So, nature conservation of patches with low vegetation may benefit from surrounding forest as air pollution is partly caught. The percentage decrease of wind velocity by a wind break (Heisler and Dewalle, 1988; Wang and Tackle, 1995), however, is stronger than the decrease of dry deposition after a narrow forested patch. The relative stronger influence of obstacles to wind velocity results from the additional slowing down of wind velocity by pressure gradients, as explained just before equation (4). So a narrow tree line is already useful to decrease wind velocity, but for a significant decrease of dry deposition, a forested patch of at least several tens of meters width is required.
3.3. Landscape-averaged deposition

Figure 5 shows that the relative increase of deposition onto a forest is counteracted by a relative decrease onto grassland. This does not mean that the local effects average out in the landscape, because the amount of deposition on homogeneous forest ($F_d(\text{forest}) = 0.058 \, \mu g \, m^{-2} \, s^{-1}$) exceeds the deposition on homogeneous grassland ($F_d(\text{grass}) = 0.024 \, \mu g \, m^{-2} \, s^{-1}$). These numbers were calculated using the input data of Table 1.

The average deposition on a landscape with alternating patches of grassland and forest is shown in
Fig. 6 as a function of the fraction of forest \( f \) and the density of wind-exposed forest edges \( d \) (edges \( \text{km}^{-1} \)) in the direction of the wind. Note again that it is assumed that the alternation of forest and grassland is present in a long upwind direction, leading to an atmosphere which is fully adjusted to the patchy landscape. Figure 6 shows that (1) deposition increases steadily with the fraction of forest \( f \) and (2) deposition increases with the density of wind exposed forest edges \( d \).

(1) The increase of \( F_d \) with \( f \) is caused by the higher deposition to forest. However, a steady increase was not expected as the same model results in a maximum momentum flux for a landscape with 90% forest cover, followed by a small decrease for a completely forested landscape (Klaassen, 1992, his Fig. 10). The maximum in the momentum flux for incompletely forested landscapes is explained by the absorption of momentum flux by pressure gradients at the wind exposed forest edges (Klaassen and Claussen, 1995). The difference between momentum and scalar quantity fluxes is understandable as pressure gradients do not influence scalar flux.

(2) The density of wind-exposed forest edges \( d \) is a measure of the scale of the landscape. A small-scale landscape (high \( d \)) implies many small forests and clearings. The increase of \( F_d \) when \( d \) increases from 0.1 edge \( \text{km}^{-1} \) to 10 edges \( \text{km}^{-1} \) is roughly equivalent to a 10% increase in forested fraction \( f \). Average deposition hardly increases when \( d > 3 \) edges \( \text{km}^{-1} \). With increasing edge density, the landscape approaches a sparse canopy forest. In that situation, \( F_d \) depends on the canopy density and spacing becomes less important. The edge density still influences the simulated deposition on large-scale landscapes with \( d < 0.3 \) edges \( \text{km}^{-1} \). This sensitivity of deposition to heterogeneity in almost homogeneous landscapes is explained by the large-scale influence of advection, see Fig. 3.

The simulated average deposition has been compared with results of the three methods, presented in Section 2.2 (Fig. 7). Using just the main vegetation cover (method 1) poorly agrees with the present model estimate. The area-weighted average (method 2) results in an underestimation of deposition, especially for small-scale landscapes. Heterogeneity increases the deposition due to advection and inflow by an amount, roughly equivalent to an increase of 20% in forested fraction. Averaged over all forested fractions, method 2 underestimates the deposition by 8% as compared to the model with 1 edge \( \text{km}^{-1} \). Method 3 accurately follows the simulations for 1 edge \( \text{km}^{-1} \) with maximum 9% overestimation for \( f = 0.1 \) and only 0.2%, overestimation on average.

4. DISCUSSION

Enhancement of dry deposition near wind-exposed forest edges is caused by two processes: inflow and advection. Figure 4 shows that inflow dominates deposition at small distances from the edge, where most observations have been carried out. As advection stretches out over larger distances (Fig. 3) the
Deposition of nitric acid

Fig. 7. As Fig. 6, but included are the results of the three calculation methods used in large-scale deposition models.

simulation of advection cannot be evaluated with throughfall measurements. Yet, even the simulations of inflow could hardly be evaluated as measurements cannot be used to separate between nitric acid and other nitrates. For a quantitative validation it is also necessary that the distribution of wind directions is known. Moreover, Fig. 1 shows that the length of the upwind low vegetation must be specified for a quantitative validation. It is concluded that existing observations can only be used to give an indication of the accuracy of the simulations. Therefore, the simulated results should be regarded with some reservations.

The simulations were executed to generalize local measurements to landscape averages. However, it should be noted that the simulations are restricted to only one special case: the atmosphere is taken neutral and a two-dimensional landscape is considered with alternating patches of grassland and forest. Vegetation characteristics were prescribed (i.e. forest height is 18 m) and forest edges were assumed to be a sudden change from grass to forest.

The simulated edge effect is sensitive to the canopy resistance $R_c$ (Figs 1 and 2). In the simulations $R_c$ has been given an arbitrary value, probably most appropriate for coniferous forest. Most measurements have also been made on edges of coniferous forest, so the results might not be transferable to deciduous forest edges. The simulations suggest that due to a larger leaf boundary or canopy resistance, the edge effect might be less important for deciduous forest. Moreover, deposition to deciduous forest might be further decreased in winter due to leaf fall.

Patch deposition is shown to be sensitive to the upwind landscape. Not only is deposition enhanced at wind-exposed forest edges, but dry deposition is also decreased in the lee of a forest. Small nature areas with low vegetation should be better protected against air pollution when situated behind a coniferous barrier.

According to the simulations, landscape-averaged deposition is dependent on the amount of forest edges. Venema (1995) estimated a forest edge density $d = 1.2$ edges km$^{-1}$ for the Netherlands, mainly caused by tree lines. For a 4 x 6 km grid at Sherwood forest area in England $d = 1.04$ edges km$^{-1}$ for western winds and $d = 1.09$ edges km$^{-1}$ for southern winds, suggesting that $d = 1$ edge km$^{-1}$ often is a reasonable estimate and that random distribution of edge orientation is quickly approximated. Landscape deposition is shown to be only slightly dependent on the density of forest edges. As a result, a fair estimate of the amount of landscape heterogeneity should suffice to calculate average deposition.

Landscape deposition is poorly described by method 1 which uses only the main surface cover to calculate deposition. A fair agreement is already obtained in using method 2 which neglects the enhancement due to advection and inflow. Method 3 results in a good agreement with the micro-meteorologically simulated deposition. The good agreement was not expected as method 3 still neglects inflow, and inflow was simulated to be the main cause of the enhanced deposition near the edge (Fig. 4). Method 3 calculates the deposition from the aggregated roughness.
Roughness was shown to be more sensitive to landscape heterogeneity than deposition, due to the supplementary leaf boundary and canopy resistances for deposition. As a result, the neglect of inflow in method 3 is compensated by an overestimation of the influence of advection. Given the restricted theoretical base, method 3 is considered to be an empirical method. Unless the empiricism, method 3 seems to be an adequate boundary condition for large-scale deposition modelling.

5. CONCLUSIONS AND RECOMMENDATIONS

The simulated enhancement of deposition near forest edges is well within the expected range. Accurate quantitative evaluation is not yet possible and so the present results are indicative only. In future studies, it is recommended to improve the confidence level of the simulation by extending the simulation to atmospheric compounds which are more easy to analyse from throughfall observations. Observations should benefit from a careful description of wind climate and upwind terrain.

It is concluded that the observed enhancement of deposition in the first 100 m is mainly caused by streamwise inflow of polluted air into the forest edge. Advection is also shown to increase deposition but its influence is simulated to stretch over larger distances.

Enhancement of deposition near wind-exposed forest edges is partly compensated by decreased deposition in the lee of forest. So, deposition load is decreased when small nature areas with low vegetation are situated behind a forested area. Only a few tens of meters of forest already significantly decrease simulated deposition over a few hundreds of meters behind the forest.

The absolute enhancement of deposition near a forest edge is stronger than the decrease behind the forest. As a result, the landscape-averaged deposition increases due to heterogeneity. Three methods representing landscape heterogeneity in large-scale deposition models have been tested. Using only the main vegetation cover (method 1) results in a poor approximation of average deposition. Neglecting advection and deposition (method 2) results in a moderate underestimation of deposition. Good agreement with the simulations is obtained with method 3, in which deposition is calculated from the average landscape roughness. As method 3 does not account for inflow, it is concluded that method 3 is empirical. It is recommended to test whether method 3 is generally applicable in large-scale deposition models.

The present study is executed for flat terrain with patches of different vegetation. A large part of the earth surface is hilly or mountainous. It is recommended to extend the simulations to hilly landscapes. Mountains also influence dry deposition, but this influence should be simulated with larger-scale models using an adequate method, like method 3, to incorporate heterogeneity at the landscape scale.

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