ISSN:1047-3289 *J. Air & Waste Manage. Assoc.* **58**:1198–1207
DOI:10.3155/1047-3289.58.9.1198

Modeling Studies of Ammonia Dispersion and Dry Deposition at Some Hog Farms in North Carolina

Kanwardeep S. Bajwa, S. Pal Arya, and Viney P. Aneja
Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC

ABSTRACT

A modeling study was conducted on dispersion and dry deposition of ammonia taking one hog farm as a unit. The ammonia emissions used in this study were measured under our OPEN (Odor, Pathogens, and Emissions of Nitrogen) project over a waste lagoon and from hog barns. Meteorological data were also collected at the farm site. The actual layout of barns and lagoons on the farms was used to simulate dry deposition downwind of the farm. Dry deposition velocity, dispersion, and dry deposition of ammonia were studied over different seasons and under different stability conditions using the short-range dispersion/air quality model, AERMOD. Dry deposition velocities were highest under near-neutral conditions and lowest under stable conditions. The highest deposition at short range occurred under nighttime stable conditions and the lowest occurred during daytime unstable conditions. Significant differences in deposition over crop and grass surfaces were observed under stable conditions.

INTRODUCTION

Atmospheric ammonia has become a very important trace gas in recent years. Studies have shown increasing atmospheric concentration levels of ammonia (NH_3) and ammonium (NH_4^+), especially in regions of concentrated animal feeding operations.[1] Measurements made at National Atmospheric Deposition Program/National Trends Network sites in North Carolina show an increasing trend in the NH_4^+ concentration in precipitation since 1990.[2] This increase has been linked with the increasing number of hogs in North Carolina. On a global basis, the amount of nitrogen that enters the biosphere has nearly doubled when compared with preindustrial times, and a significant component of this increase has been in the form of NH_3-nitrogen.[3] In continents with intensive agriculture, atmospheric inputs of reduced nitrogen as NH_3 and NH_4^+ by dry and wet deposition may represent a substantial contribution to the acidification of seminatural ecosystems.[4,5]

IMPLICATIONS

Our study of dispersion and dry deposition of ammonia from hog farms contributes to the understanding of dispersion and dry deposition pattern of ammonia downwind of a hog farm during different seasons, which can help in understanding local and regional fate of ammonia. It also provides validation data for dry deposition velocity of ammonia in the AERMOD model in different seasons.

Air mass trajectories suggest that wet and dry deposition of NH_3 and NH_4^+ emitted from agricultural operations in eastern North Carolina could potentially affect all river basins in the coastal plain region, as well as sensitive coastal ecosystems and estuaries.[2] High nitrogen-loading can have detrimental effects on terrestrial ecosystems, effects that can result in the greater export of nitrogen to the surface and groundwater.[6] Adverse effects on sensitive ecosystems caused by high nitrogen deposition can be reduced by lowering the emissions and, to a limited extent, also by removing sources close to the ecosystem to be protected.[7]

Wet and dry depositions are two pathways for removal of NH_3 from the atmosphere. Data on wet deposition are available through the National Atmospheric Deposition Program (NADP), but there is lack of data on dry deposition of NH_3. Reliance on wet deposition measurement alone can lead to considerable underestimation (by 40–60%) of the total (wet + dry) atmospheric nitrogen deposition.[8] A modeling study by Asman[9] found that dry deposition contributes approximately 66% to the total NH_x (NH_3 and NH_4^+)deposition to the land area of Denmark. Gaseous NH_3 undergoes dry deposition, with deposition velocities ranging up to 14 cm/sec.[10,11] Because of its high deposition velocity and its reactivity in the atmosphere, gaseous NH_3 has a relatively short atmosphere lifetime, on the order of a few days or less.[12] NH_4^+ aerosols deposit more slowly than gaseous NH_3, with a deposition velocity of approximately 0.2 cm/sec.[12] Therefore NH_4^+ has a longer atmospheric lifetime than gaseous NH_3, on the order of 1–15 days,[1] and a more extensive spatial sphere of influence.

Jansen and Asman[13] suggested that near the source, with low emission height, ground-level concentrations should be higher than average, resulting in faster depletion due to enhanced dry deposition. NH_3 is mainly emitted at ground level and has a relatively large deposition velocity. Different studies have been conducted to estimate NH_3 deposition near the source. According to Asman and Van Jaarsveld,[14] 20% of total NH_3 and NH_4^+ deposition takes place within 1 km of the source (animal houses), with 80–90% returning to the earth within 10 km in the form of wet and dry deposition, and the remainder gets dispersed into the atmosphere for distances of several hundred kilometers. Loubet et al.[15] studied NH_3 deposition over a maize canopy using a controlled line source placed at the top of the canopy. The cumulated deposition between 12 and 162 m from the source was estimated to range between 5 and 30% of the emitted NH_3

using a mass balance technique. Fowler et al.[16] quantified the local fate of livestock NH_3 emissions from a poultry farm using measured NH_3 concentrations and the relationship between canopy resistance and ambient NH_3 concentration from intensive flux measurements. Their results showed that local deposition of NH_3 to woodland within 300 m of the source represents 3–10% of the local emissions. NH_3 flux and deposition measurements have been made on different canopies.[17–19]

Dry deposition measurements made by Walker and Robarge[20] showed that NH_3 dry deposition over the nearest 500 m from the barn/lagoon complex of a hog farm accounted for 11.6% of emissions with 3.5% uncertainty, assuming an emission factor of 6 kg NH_3/animal/yr. Community Multiscale Air Quality (CMAQ) simulations by Dennis et al.[21] showed that 15–30% of the hot spot emissions deposit locally in the 12-km grid cell used in simulations, whereas the rest can travel up to 150–300 km from the source region. Because of local advection effects,[22] it is difficult to measure local deposition rates of NH_3 with the standard micrometeorological techniques such as the gradient method. Many field experiments to study NH_3 deposition on a local scale are based on the measurement of the concentration decrease with distance from the source.[15,19,20]

Some uncertainty on the fate of NH_3 on a local and regional scale still exists because of experimental and modeling limitations. This research was designed to study dry deposition of NH_3 in the vicinity of hog farms using a short-range dispersion model. Asman[7] showed that source height, wind speed, surface resistance, atmospheric stability, surface roughness length, and surface concentration affect dry deposition of NH_3 in different ways. The U.S. Environmental Protection Agency (EPA) short-range air quality model, AERMOD, used in this study takes into account these factors, except for the surface concentration of NH_3. The objectives were to study dispersion and dry deposition patterns of NH_3 downwind of a hog farm using the actual geometry of emission sources at the hog farm. This will help us to further understand how much NH_3 is dry deposited near the farm and how the remaining NH_3 gets transported farther away.

METHODS AND MATERIALS

The EPA's recommended short-range air quality model, AERMOD, is used to study dispersion and dry deposition of NH_3 from hog farms. AERMOD, a steady-state dispersion model, includes the effects on dispersion from vertical variations of winds and turbulence in the planetary boundary layer (PBL). In the stable boundary layer (SBL), the concentration distribution is assumed to be Gaussian, both vertically and horizontally, across the plume from a continuous point source. Gaussian distribution is also assumed in the horizontal (lateral) direction in the convective boundary layer (CBL), whereas the vertical concentration distribution is described with bi-Gaussian probability density functions, as demonstrated by Willis and Deardoff.[23] The buoyant plume mass that penetrates the elevated stable layer is tracked by AERMOD and allowed to reenter the mixed layer at some distance downwind. Cimorelli et al.[24] have given a description of model formulation and boundary layer parameterization in AERMOD. The growth and structure of the PBL is driven by the fluxes of heat and momentum. The PBL depth or height and dispersion of pollutants within it are influenced on a local scale by surface roughness, albedo, and available moisture. AERMOD utilizes surface and mixed-layer scaling to characterize the structure of the PBL.[24] AERMOD's meteorological preprocessor (AERMET) uses surface characteristics, cloud cover, upper-air temperature sounding, and at least one set of near-surface measurements of wind speed, wind direction, and temperature. AERMET computes the friction velocity, Obukhov length, convective velocity scale, temperature scale, mixing height, and surface heat flux. AERMOD uses these scaling parameters to construct vertical profiles of wind speed, lateral and vertical turbulence, potential temperature gradient, and potential temperature. Evaluations of the overall model have shown that these parameterizations lead to estimates of plume concentration that compare well with a wide variety of field observations.[24]

Dry deposition refers to the transfer of airborne material to the earth surface, including soil, vegetation, and water, where it is removed.[25] The dry deposition flux, F_d, is calculated in AERMOD as the product of the concentration, C, and a deposition velocity, V_d, computed at a reference height, z_r, as

$$F_d = C \times V_d \tag{1}$$

Dry deposition velocity is calculated using the commonly used resistance method in most land-surface models.[26,27]

$$V_d = (R_a + R_b + R_c)^{-1} \tag{2}$$

where R_a is the aerodynamic resistance (sec/m), R_b is the quasi-laminar sublayer resistance (sec/m), and R_c is the bulk surface or canopy resistance (sec/m).

Measurements

As a part of the Odor, Pathogens, and Emissions of Nitrogen (OPEN) project, NH_3 flux measurements were made at several hog farms in eastern North Carolina. Barham farm (35.70 N, 78.31 W) was sampled during spring and fall of 2002, and Moores (35.14 N, 77.47 W) farm was sampled during winter of 2002 and summer of 2003, but limited to a sampling period of about 2 weeks in each season. NH_3 flux measurements were made over waste lagoons using a dynamic flow-through chamber system, whereas barn emissions were measured using open-path Fourier transform infrared (OP-FTIR) spectroscopy. Meteorological data on ambient temperature, relative humidity (RH), wind speed, and wind direction were also collected during each sampling period. These emission and meteorological data were used in modeling NH_3 dispersion and dry deposition from the two farms. AERMOD also needs upper-air sounding and cloud-cover data for its meteorological input file. Upper-air sounding data were used from National Weather Service stations and cloud-cover data were taken from the nearest North Carolina State Climate Office's weather stations.

Philips et al.[11] used a micrometeorological method in conjunction with Monin–Obukhov similarity theory to estimate the vertical flux and dry deposition velocity of NH_3 over a natural grass surface near an animal farm site, over a wide range of meteorological conditions encountered between fall 2001 and summer 2002. Data on NH_3 concentration, wind speed, wind direction, RH, and ambient temperature were also collected at two different heights (2 and 6 m). The measured meteorological data and concentration data from Philips et al.[11] were used to calculate model dry deposition velocities of NH_3 using AERMOD. These modeled dry deposition velocities were then used for comparison with observed values by Philips et al.[11] under the same meteorological conditions to validate the modeled deposition velocities.

The emissions data from Barham and Moores farms were collected at different periods and different locations than the dry deposition velocity data by Philips et al.[11] and should not be confused with each other. NH_3 concentrations were measured using Thermo Environmental Instruments Inc. (TEI), Model 17C chemiluminescence ambient NH_3 analyzer.[28] These NH_3 analyzers can measure NH_3 concentrations with uncertainty level of $\pm$10%[28] and dry deposition velocities can be resolved with an uncertainty of $\pm$20%.[11]

Model Runs

In this study, grass and crop were used as surrogate ground covers to study dry deposition on these surfaces separately. Separate AERMET files were created for both surfaces giving respective surface characteristics. Different stability conditions are predicted by AERMET for grass and crop surfaces. The information on surface characteristics can be found in the AERMET manual.[29] AERMOD calculations were made for both grass and crop surfaces in each season. Crop and grass dry deposition calculations were made for the same date and hour with the same wind speed at a height of 10 m to compare the differences between deposition under the same wind speed and emission conditions. The deposition along the wind direction given as orientation 1 (Figure 1) was studied in detail and later compared with orientation 2. All other meteorological parameters were kept the same while changing wind direction only to study dispersion and dry deposition along these orientations.

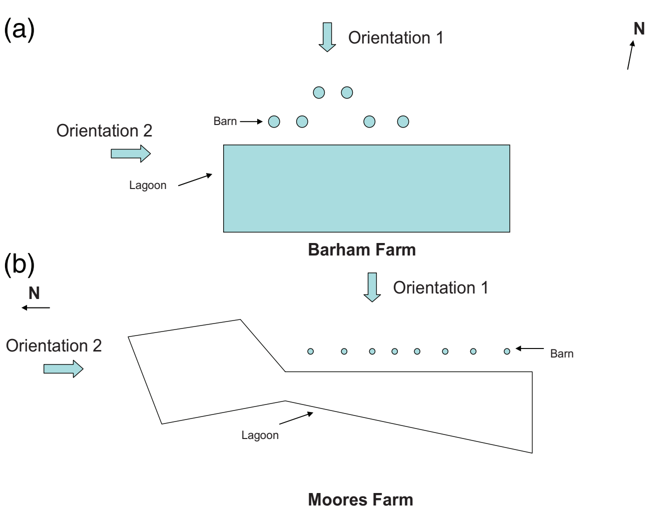

Figure 1. Orientations of (a) Barham farm and (b) Moores farm with respect to wind direction.

RESULTS AND DISCUSSION

Dry Deposition Velocity

Considerable uncertainty is involved in modeling deposition of NH_3, because deposited NH_3 can also be emitted back to the atmosphere. Farquhar et al.[30] explained this in the terms of a "compensation point," which is the air concentration at which no net influx occurs through a stomata. A compensation point is expected to occur because of the presence of NH_x in plant metabolism and in soil and its equilibrium with gaseous NH_3. Deposition of NH_3 occurs when ambient NH_3 concentration is higher than the compensation point, otherwise there would be net emission. In some cases, NH_3 emission may also occur from recently fertilized soils, decomposing leaves, or decomposing urine from grazing animals.

Determination of compensation point requires the knowledge of soil and plant leaf chemistry. Appropriate use of compensation point in relation to NH_3 exchange has been made in resistance models developed by Sutton et al.[31] However, AERMOD assumes the surface concentration of NH_3 to be zero to calculate NH_3 deposition flux. An important parameter in the calculation of NH_3 deposition velocity is the cuticular resistance to NH_3 on the leaf surface. However, a satisfactory parameterization of cuticular resistance is not available under North American conditions because no measurements of this resistance have been made. A simple parameterization of cuticular resistance was proposed by Sutton et al.[31] as a function of RH. This estimation of cuticular resistance was used for this study, but model-predicted deposition velocities were too low when RH was low. To obtain a deposition velocity in a comparable range to measured values, a minimum cuticular resistance value was used as an input to this model.

Philips et al.[11] measured NH_3 deposition velocity at a relatively flat, uniform, and smooth site with grass or short vegetation. This site was located near a small experimental hog farm with a lagoon. Dry deposition velocity was modeled using AERMOD, the meteorological data from Philips et al.,[11] and using grass surface. Table 1 gives a comparison between measured and modeled NH_3 deposition velocities in different seasons. Deposition velocities are divided into daytime and nighttime on the basis of sunrise and sunset times in each season. The model underpredicted deposition velocities in all seasons and at both daytimes and nighttimes. Daytime deposition velocities were lower by a factor of about 2 in spring and 3–5 in other seasons. Nighttime dry deposition velocities were consistently very low (0.06 to 0.09 cm/sec) in all seasons. The reason for such a low calculated deposition velocity was that the aerodynamic resistance calculated by AERMOD was very high and was the dominant resistance at night. The highest deposition velocities calculated by the model were during unstable and near-neutral conditions and lowest during stable conditions. This is consistent with stability dependence of observed deposition

Table 1. Comparison of modeled vs. measured dry deposition velocities for different seasons and times of day.

	Spring		Summer		Fall		Winter	
Dry Deposition Velocity	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
Modeled (cm/sec)	1.74	0.09	1.04	0.09	0.80	0.06	0.51	0.08
Measured (cm/sec)	2.85	0.62	3.94	0.76	2.82	0.07	2.41	0.19

velocities by Philips et al.[11] Lower model-calculated deposition velocities were also reported by Dennis et al.[21] using the CMAQ regional model. They proposed that deposition velocities of NH_3 should be adjusted higher in the models so that these are comparable to observed deposition velocities of sulfur dioxide.

Dispersion of NH_3

Perry et al.[32] provide an overview of the AERMOD model's performance against the concentration observations taken from 17 field-study databases. The studies include sites with flat and complex terrain, urban and rural conditions, elevated and surface releases, and with and without building wake effects. The evaluation measures were restricted to those that are relevant to regulatory applications, with an emphasis on the ability of the model to simulate the upper end of the concentration distribution. Among these databases, Project Prairie Grass represented surface releases over a flat terrain rural site, similar to our modeling scenario. AERMOD shows a tendency to underpredict the higher concentrations over this flat terrain rural site. It showed a concentration distribution that matched observations well, suggesting that the model is capable of simulating near-field dispersion from the surface releases. The robust high concentration (RHC) ratio of predicted-to-observed concentration was 0.87, which also shows 13% underprediction. RHC represents a smoothed estimate of highest concentrations on the basis of an exponential fit to the upper end of the concentration distribution and is the preferred statistic because it mitigates the undue influence of the individual unusual events.

Our study represents surface releases of NH_3 from several point sources (exhaust fans in barns) and a finite area source (waste lagoon) at the hog farm and its dispersion over a flat rural terrain. The NH_3 dispersion pattern was studied by plotting crosswind-integrated NH_3 concentrations against the downwind distance. Dispersion study was done with data from Barham farm, with wind direction along orientation 1 (Figure 1). Downwind concentrations depended on the barn and lagoon emission rates, wind speed, and stability conditions for the given hour. NH_3 concentration was crosswind-integrated every 50 m to study the decrease in concentration at a height of 1 m or at ground level.

NH_3 Dispersion under Different Stability Conditions. Crosswind-integrated concentrations were normalized using the surface-layer similarity theory to study the downwind dispersion pattern. Dry deposition was not considered in the first part of this dispersion study, which means that dry deposition was assumed to be zero. Crosswind-integrated concentration (C_y) was normalized with friction velocity (U^*), roughness parameter (Z_0), and emission rate (Q). Dimensionless ground-level concentration, C_0^*, is given by Van Ulden [33] as

$$C_0^* = C_{Y0}\, U \times Z_0/Q \tag{3}$$

where the subscript 0 indicates surface-layer scaling.

Downwind distance is made nondimensional as X/Z_0, where X is downwind distance, and C_0^* is plotted against X/Z_0 for different values of stability parameter Z_0/L (Figure 2), where L is the Obukhov length. Negative values of Z_0/L represent unstable conditions, positive values represent stable conditions, and near-zero values indicate near-neutral conditions. Figure 2 shows normalized ground-level concentrations at X/Z_0 values from 1000 to 50,000 under different stability conditions. Concentrations were high in the immediate vicinity of the farm but decreased very rapidly as we moved away from the farm. Further downwind concentrations were smaller and the decrease in concentration is also small. The decrease in downwind concentration was slowest under the most stable conditions because of low vertical mixing. Under very stable conditions ($Z_0/L = 0.031$), concentration first remained almost constant with distance and then started decreasing. Under near-neutral and unstable conditions, the decrease in concentration with distance was faster than in stable conditions. Ground-level concentration showed a different pattern under unstable conditions when compared with other stability conditions. Slopes of C_0^* versus X/Z_0 curves show that downwind concentration decreased more rapidly under unstable condition as compared with stable and near-neutral conditions but further downwind, ground-level concentrations decreased very slowly and concentrations became even higher than those in near-neutral conditions. This pattern is a result of the way the vertical distribution is treated in AERMOD under convective conditions. The vertical and lateral velocities in each element are assumed to be random variables and characterized by their probability density functions (PDF). In the CBL, the PDF of the vertical velocity (w) is positively skewed and results in a non-Gaussian vertical concentration distribution.[34] This positive skewness is consistent with the higher frequency of occurrences of downdrafts than updrafts under convective conditions. NH_3 that mixes up in the CBL keeps moving slowly toward the ground in more frequent downdrafts than updrafts. The sudden change in slope of concentration distribution under unstable conditions is because of the assumed bi-Gaussian distribution. This pattern is consistent with the results of numerical simulations and field observations.[34,35] This plot also shows that concentrations at ground level in the vicinity of a hog farm would be higher under stable conditions and lower

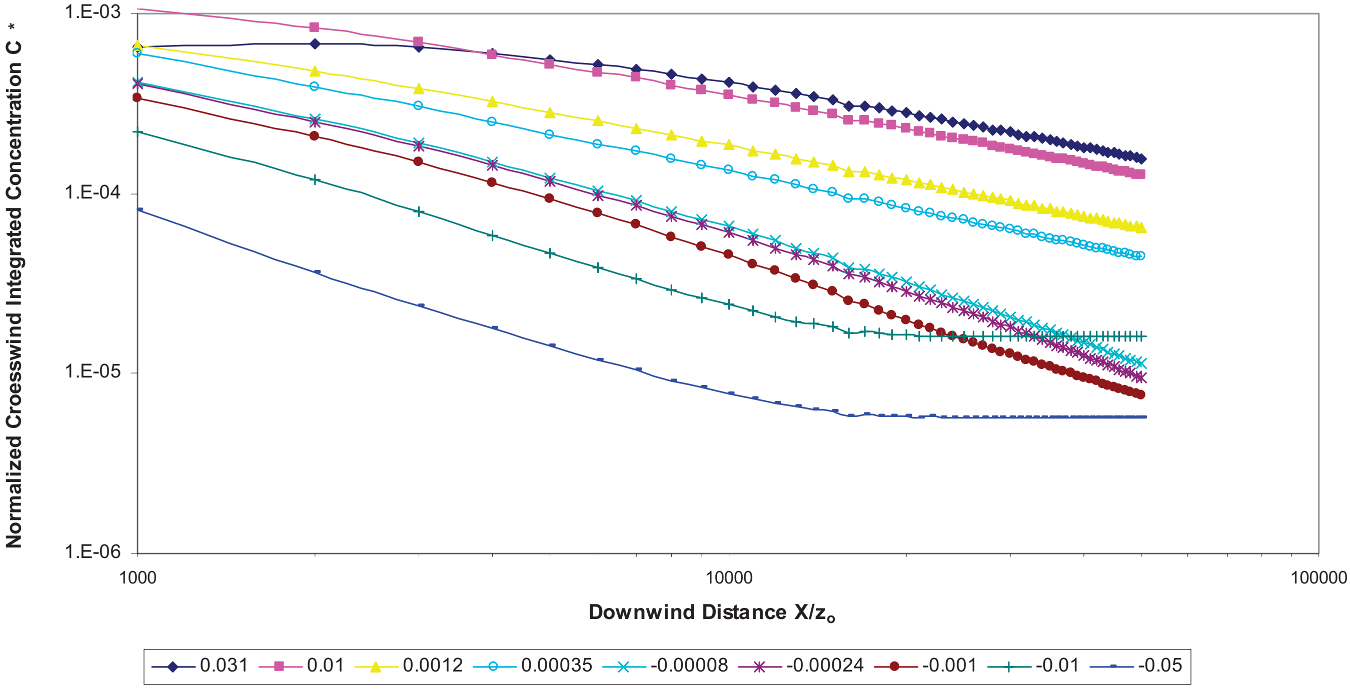

Figure 2. Change in dimensionless ground-level concentration with dimensionless distance for several stability conditions based on Z_o/L at Barham farm with direction along the orientation 1.

under unstable conditions for a given emission rate and wind speed conditions. But further downwind, ground-level concentrations under unstable conditions might become higher than those in near-neutral conditions.

NH_3 Dispersion in Highly Convective Conditions. For highly convective conditions, the mixed layer similarity theory was used to study dispersion pattern. The convective velocity scale (W^*) and mixed layer depth (H) along with wind speed (U) and emission rate (Q) are used to normalize downwind crosswind-integrated concentration (C_y) and downwind distance (X), as given in Arya.[36] Normalized concentration is given by

$$C_y^* = C_y UH/Q \quad (4)$$

and downwind distance is normalized as

$$X^* = W \times X/UH \quad (5)$$

In the CBL, C_y^* is plotted as a function of X^* for different stability conditions on the basis of H/L, and is shown in Figure 3. This graph shows that under convective conditions, concentration distribution does not change much with the change in H/L. Arya[36] has discussed that normalized crosswind-integrated ground-level concentration initially decreases as $X^{*-3/2}$, as predicted by local free convection and mixed-layer similarity theories. It attains a minimum value of less than 1 and then increases and becomes constant at value of one. A similar decrease in C_y^* with X^* can be seen in Figure 3, where it flattens out at a large distance. This could be the minimum value attained by C_y^* before it increases and becomes constant. The slopes of C_y^* versus X^* are -1.55 and -1.72 for H/L values of -550 and -620, respectively, which are higher than the expected value of 1.5 discussed above. Nieuwstadt[37] also discussed the dependence of C_y^* on X^* using the measured data from Project Prairie Grass. Van Ulden[33] and Briggs[38] predicted that under convective conditions C_y^* decreases as a function of X^{*-2}. However, Nieuwstadt[37] showed that within the convective matching region, the $X^{*-3/2}$ power law is superior to X^{*-2} dependence, where the convective matching region has been defined by the $-L < z < 0.1\ H$ condition. Venkatram[39] discussed the behavior of crosswind-integrated ground-level concentrations under neutral, stable, and unstable conditions. He found that under unstable conditions, the normalized concentration falls off as X^{*-2} rather than $X^{*-3/2}$ predicted by the local free convection similarity theory, where $X^* = X/L$.

The vertical profile of concentration in the plume in the CBL from a near-surface continuous point source was studied by Willis and Deardorff[40] using laboratory simulation in a convection tank. They found that the height of maximum C^*, or the plume centerline, coincides with the release height only up to a dimensionless distance $X^* \sim 0.5$, after which it lifts off rapidly, attains a maximum around $Z^* = 0.8$, and then gradually comes down to the surface. This implies a highly non-Gaussian vertical distribution of concentration for $X^* > 0.5$.

Vertical Profiles in Convective Conditions. We also studied the vertical profiles of concentration under convective conditions for $H/L = -550$. This vertical profile was studied for Barham farm using the wind direction orientation 1 and downwind distance was measured from the boundary of the farm. Here, C_y^* is plotted against $Z^* = z/H$ for

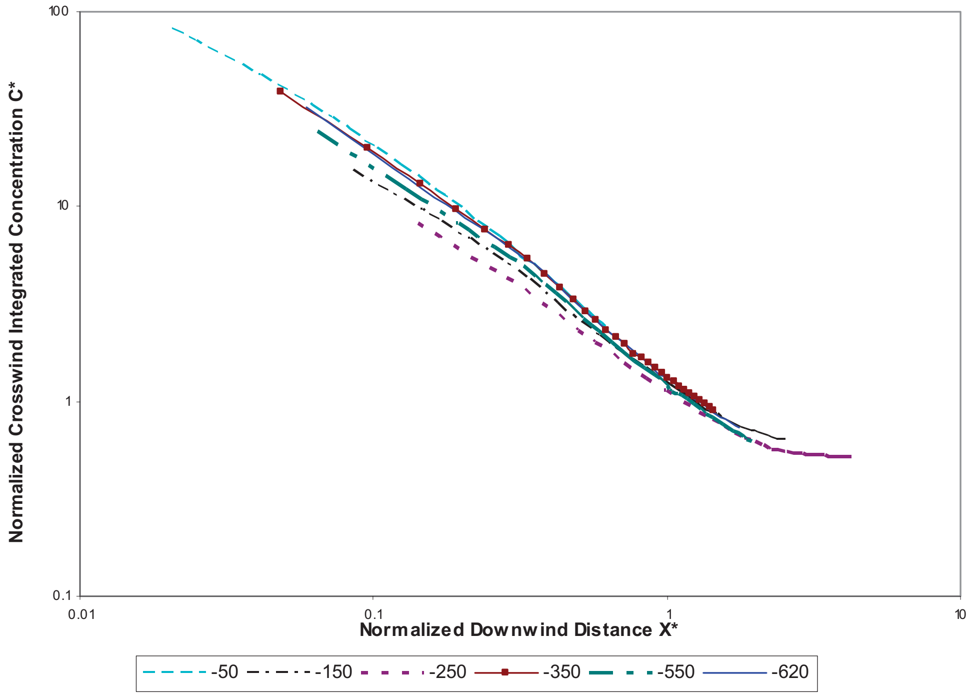

Figure 3. Normalized crosswind intergrated ground-level concentration as function of normalized downwind distance, for convective conditions based on *H*/*L* at Barham farm with direction along the orientation 1.

different values of X^* (Figure 4). Vertical profiles show nearly exponential distribution up to $X^* \sim 0.5$, but without a clear lifting of plume at $X^* > 0.5$. A slight bend in slope is visible at $X^* = 0.97$, but maximum concentration is still at the surface. Nearly uniform concentration distribution throughout the PBL was reached at higher value of $X^* \sim 3.2$, as a consequence of plume trapping between the surface and the capping

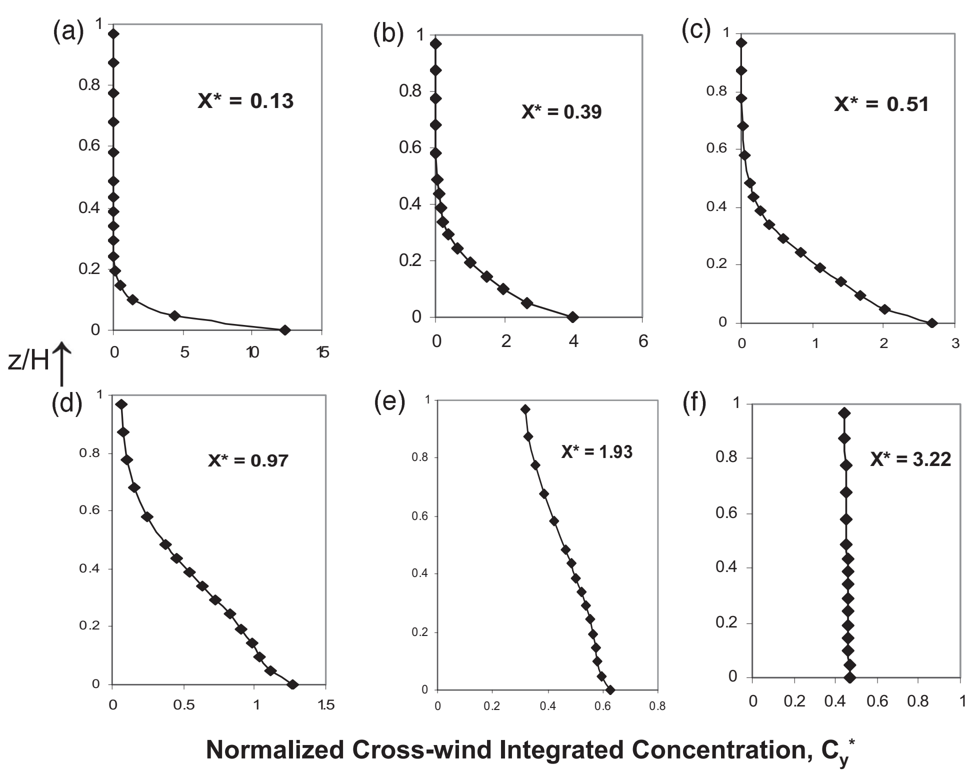

Figure 4. Vertical profile of normalized crosswind-integrated concentration (C_y^*) at (a) $X^* = 0.13$, (b) $X^* = 0.39$, (c) $X^* = 0.51$, (d) $X^* = 0.97$, (e) $X^* = 1.93$, and (f) $X^* = 3.22$.

inversion. Some differences between our model simulations and Willis and Deardorff's[40] laboratory experiment might be expected because of different source geometry and configuration (an area source and multiple sources) used in our model study.

NH_3 Deposition

NH_3 deposition was studied downwind at two hog farms, Barham farm and Moores farm using AERMOD. Barham farm has two types of sources, a wastewater lagoon and six barns where hogs are housed. Moores farm has a wastewater lagoon and eight barns. Barns at both farms are forced ventilated using large fans. Barn fans were treated as point sources and the lagoon was treated as an area source in this study. Meteorological data from Barham farm represent spring and fall seasons, whereas Moores farm data represent summer and winter periods.

Deposition of NH_3 is influenced by the stability conditions, wind speed, dry deposition velocity, and emission rate of NH_3 for that particular hour. Three particular hours were selected to represent a set of conditions under which deposition was studied and compared. Three hours represent different times of the day with different stability conditions and emission rates. An unstable condition with a low, negative value of the Obhukhov length was chosen to also represent high emission rate. A nighttime stable condition was selected with a low, positive value of the Obukhov length and low emission rate. Evening time near-neutral conditions were chosen with large magnitude of the Obukhov length. Deposition of NH_3 downwind of the farm boundary was studied on grass and crop surfaces separately.

For comparison of grass and agricultural/crop surfaces, wind speed was assumed to be the same at a height of 10 m on both surfaces. Because roughness length is different for grass and crop, the wind speed profile would also be different over both surfaces. Bowen ratio and albedo values for grass are different from crop surface in each season, which would affect sensible heat flux. Thus, the values of the Obukhov length and friction velocity were different over both surfaces. These factors affected the dry deposition velocity calculations and deposition patterns. The Bowen ratio was higher over the crop surface when compared with the grass surface in all seasons, although the difference between the two values was small in spring, which is the sowing season for crops in North Carolina, and so the crop height and leaf area index were low. In winter, Bowen ratios for the crop and grass surfaces were comparable under conditions of frost or snow. The Bowen ratio was higher over the crop surface in summer, assuming high leaf density, because crops are green and at full bloom in summer. This high Bowen ratio over the crop surface led to a lower sensible heat flux as compared with that over the grass surface. Roughness length, which affects friction velocity, was higher for crops as compared with grass surface, except in spring when crop height was small. These combinations of different sensible heat fluxes and friction velocities led to different stability parameter values over grass and crop surfaces under similar meteorological conditions. Thus, deposition velocity and deposition pattern are expected to be different over the two surfaces.

Table 2, a and b, gives deposition of NH_3 emitted from Barham farm in spring and fall, respectively, over

Table 2a. Dry deposition of NH_3 (in grams and percentage) from Barham farm during the spring measurement period.

	Grass			Crop		
	Stable	Near Neutral	Unstable	Stable	Near Neutral	Unstable
Monin–Obukhov length (m)	7	−610	−21.1	6.1	−489	−18.7
Wind speed (m/sec)	2.1	5.1	3.1	2.1	5.1	3.1
Emission (g/hr)	4765	6973	6484	4765	6973	6484
Deposition velocity (cm/sec)	0.09	1.71	1.49	0.09	1.68	1.42
Up to 500-m deposition	282 (5.9)	421 (6.5)	408 (5.8)	316 (6.6)	448 (6.9)	426 (6.1)
500- to 2500-m deposition	354	259	181	398	266	187
Total deposition	636 (13.3)	680 (10.5)	589 (8.4)	714 (15)	715 (11)	612 (8.8)

Table 2b. Dry deposition of NH_3 (in grams and percentage) from Barham farm during the fall measurement period.

	Grass			Crop		
	Stable	Near Neutral	Unstable	Stable	Near Neutral	Unstable
Monin–Obukhov length (m)	5.8	−54.9	−5	8.6	−132	−12
Wind speed (m/sec)	2.6	4.2	2.6	2.6	4.2	2.6
Emission (g/hr)	3748	4406	5476	3748	4406	5476
Deposition velocity (cm/sec)	0.09	1.10	0.92	0.09	1.10	0.95
Up to 500-m deposition	225 (6.0)	191 (4.3)	159 (2.9)	157 (4.2)	160 (3.6)	160 (2.9)
500- to 2500-m deposition	303	109	75	208	96	80
Total deposition	528 (14.1)	300 (6.8)	234 (4.3)	365 (9.8)	256 (5.8)	240 (4.4)

Table 3a. Dry deposition of NH_3 (in grams and percentage) from Moores farm during the summer measurement period.

	Grass			Crop		
	Stable	**Near Neutral**	**Unstable**	**Stable**	**Near Neutral**	**Unstable**
Monin–Obukhov length (m)	7.1	−88.8	−6.6	11.1	−280	−18.7
Wind speed (m/sec)	2.1	4.6	2.6	2.1	4.6	2.6
Emission (g/hr)	4392	5796	5040	4392	5796	5040
Deposition velocity (cm/sec)	0.09	1.14	1.06	0.09	1.94	1.76
Up to 500-m deposition	242 (5.5)	245 (4.2)	154 (3.0)	164 (3.7)	327 (5.6)	248 (4.9)
500- to 2500-m deposition	285	119	54	190	173	98
Total deposition	527 (12.0)	364 (6.3)	208 (4.1)	354 (8.0)	500 (8.6)	346 (6.9)

Table 3b. Dry deposition of NH_3 (in grams and percentage) from Moores farm during the winter measurement period.

	Grass			Crop		
	Stable	**Near Neutral**	**Unstable**	**Stable**	**Near Neutral**	**Unstable**
Monin–Obukhov length (m)	3.7	−59.4	−3.7	5.7	−135.4	−8.5
Wind speed (m/sec)	2.6	5.1	2.6	2.6	5.1	2.6
Emission (g/hr)	756	936	936	576	936	936
Deposition velocity (cm/sec)	0.09	0.62	0.48	0.09	0.92	0.74
Up to 500-m deposition	52 (7.0)	32 (3.4)	23 (2.5)	42 (5.5)	38 (4.1)	31 (3.3)
500- to 2500-m deposition	73	16	20	61	20	23
Total deposition	125 (16.6)	48 (5.1)	43 (4.6)	93 (12.2)	58 (6.2)	54 (5.8)

the grass and crop surfaces. Table 3, a and b, gives deposition of NH_3 from Moores farm in summer and winter, respectively, over the grass and crop surface. These tables give NH_3 depositions up to 500 m from the farm, between 500 and 2500 m, and total deposition up to 2500 m. In parentheses are the depositions as a percentage of total NH_3 emitted for that hour. Tables 2 and 3 also show that Obukhov length was higher over the crop surface than the grass surface, except in spring when it was comparable for the two surfaces. In other seasons, conditions were more stable at night for crop area and unstable during the daytime hour selected for this study. Deposition velocity was high in near-neutral and unstable conditions but low in stable conditions and this trend was seen in all seasons for both crop and grassy surfaces. This trend was also observed in measurements and was discussed earlier in this paper. Difference between deposition velocities over crop and grass surfaces was very small in spring and fall. In summer and fall, however, deposition velocities over crops were higher than those over the grass surface. As shown in Figure 2, NH_3 ground-level concentrations were large in the immediate vicinity of the farm. NH_3 deposition was also high in the first few hundred meters downwind of the farm. Deposition up to the first 500 m is compared with that between 500 and 2500 m in Tables 2 and 3.

Deposition Pattern in Spring. At Barham farm in spring, 8.4 and 10.5% of NH_3 emitted from the farm gets deposited on the grass surface up to 2500 m from the farm, under unstable and near-neutral conditions, respectively (Table 2). Out of this percentage, more than half gets deposited within 500 m of the farm. NH_3 deposition was highest under stable conditions, in which 13.3% deposition occurred within 2500 m of the farm. This value was high compared with unstable and near-neutral conditions, even though deposition velocity was much lower, because ground-level concentrations of NH_3 are higher under stable conditions due to less turbulent mixing. Also, the wind speed was lower than in unstable and near-neutral conditions and this lower wind speed also contributed to higher deposition. Deposition under near-neutral conditions could be higher because wind speed was high when compared with other stability conditions. Over the crop surface, deposition was slightly higher than that over the grass surface. Difference in total deposition up to 2500 m under unstable and near-neutral conditions was very small (~0.5%), but under stable conditions, deposition was 1.5% higher over crop area than the grass surface.

Deposition Pattern in Fall. In fall, total deposition (up to 2500 m) on grass surface was higher (14.1%) under stable conditions as compared with 4.3% under unstable conditions for the same wind speed (Table 2b). Here the difference was larger than for spring, although the Obukhov length was also lower in fall than in spring. Deposition under near-neutral conditions was 6.8%, which falls between stable and unstable conditions. Deposition velocity was high under near-neutral conditions, because wind speed was also higher in comparison to other stability conditions. The deposition velocities over crop and grass surfaces were not much different, except for the nighttime stable conditions. The same pattern was predicted for spring, when a major portion of deposition occurred in the first 500 m, except under stable conditions in which this contribution was lower.

Deposition Pattern in Summer. Deposition study under summer conditions was done with the data from Moores farm (Table 3a). As in spring and fall seasons, deposition during summer was higher under stable, and lowest under unstable conditions, with a major portion of the deposition being within 500 m. NH_3 deposition was higher by 4% under stable conditions over the grass surface, whereas it was higher over crop surface under unstable and near-neutral conditions. This could be because deposition velocity was higher over crop surface under unstable and near-neutral conditions, whereas it was comparable to the grass surface under stable conditions. The difference in deposition in unstable and near-neutral conditions was also higher in fall season (2.3–2.8%).

Deposition Pattern in Winter. In winter, NH_3 deposition downwind of Moores farm showed the highest deposition of 16.6% under stable conditions over the grass surface. This could be due to smaller Obukhov length when compared with other seasons. Depositions under unstable and near-neutral conditions were 4.6 and 5.1%, respectively. Under stable conditions, deposition was higher over grass surface by 4.4%, whereas it was slightly higher over crop surface under unstable (1.2%) and near-neutral (1.1%) conditions.

Wind Orientation. NH_3 deposition modeling results as discussed above, are for along the wind direction orientation 1 as shown in Figure 1. NH_3 deposition calculations were also done along the orientation 2 as shown in Figure 1, for both Barham and Moores farms. Comparison of results shows that the change of orientation can make a difference of up to 2.3% in NH_3 deposition. This difference was more on the Barham farm than on Moores farm. Orientation 1 gave higher deposition on both of the farms and in all the seasons and stability conditions. The reason for this difference could be the difference in geometry of the farms, with different wind directions and the area over which NH_3 disperses being different under different orientations.

CONCLUSIONS

This study was done to investigate how NH_3 emitted from a hog farm disperses and gets deposited downwind of the farm using EPA's air quality/dispersion model AERMOD. Data on meteorological parameters and emission rates collected at two hog farms (Barham and Moores farms) were used for this study. Dry deposition velocity and related meteorological data from Philips et al.[11] were used to compare dry deposition velocity calculations by AERMOD. Modeled dry deposition velocities were lower than the observed values, by a factor of 2–4 during daytime and up to 8 during nighttime. These lower values are attributed to the lack of understanding of the NH_3 deposition and emission from grass and crop surfaces. Observations show both deposition and emission occurring, depending on the compensation point at the vegetation surface. AERMOD cannot simulate this pattern because deposition parameterization in the model does not account for compensation point. An NH_3 dispersion study showed that NH_3 ground-level concentrations are very high near the farm and decrease rapidly as we move away from the farm. This decrease in concentration with distance is small when we move further downwind of the farm. The decrease of concentration is faster under unstable conditions and slowest under stable conditions. The rate of decrease in concentration with distance for near-neutral conditions lies somewhere between stable and unstable conditions. Ground-level concentrations are lower under unstable conditions for a given emission rate, but become higher than those under near-neutral conditions at certain distance downwind because of bi-Gaussian distribution of vertical distribution under unstable conditions. Dry deposition of NH_3 up to 2500 m downwind of the farm was studied under different stability conditions and over crop and grass surfaces. The majority of deposition as a percentage of total emission occurs within 500 m of the farm because ground-level concentrations are much higher there. Deposition was highest under stable conditions and lowest under unstable conditions. Under stable conditions, more deposition occurred over the grass surface than over the crop surface with the exception of spring, in which it was higher over the crop surface. Under unstable and near-neutral conditions, deposition was higher over the crop surface for winter, summer, and spring; these differences between crop and grass surfaces were higher under stable conditions. The underprediction of dry deposition velocity of NH_3 by AERMOD suggests that the actual amount of dry deposition of NH_3 in the vicinity of the farm could be higher than predicted. Higher deposition of NH_3 near the farm would lead to lower ground-level concentrations of NH_3 further downwind from the farm because less NH_3 will be available for dispersion. Wind orientation could also make a difference on the downwind deposition depending on the layout of the sources on the farm. Further studies should be done by taking into account the effect of soil emissions and farm buildings. Study on the dry deposition of NH_3 in the forest canopy downwind, if present, should also be studied. Better understanding of deposition parameterization and soil and leaf chemistry is also needed to reduce the uncertainties involved in this study.

ACKNOWLEDGMENTS

This research was supported by Grant 2003-05360 from the U.S. Department of Agriculture's National Research Initiative.

REFERENCES

1. Aneja, V.P.; Murray, G.C.; Southerland, J. Atmospheric Nitrogen Compounds: Emissions, Transformation, Deposition and Assessment; *EM*, **1998**, *April*, 22-25.
2. Walker, J.T.; Aneja, V.P.; Dickey, D.A. Atmospheric Transport and Wet Deposition of Ammonium in North Carolina; *Atmos. Environ.* **2000**, *34,* 3407-3418.
3. Galloway, J.; Cowling, E.; Erisman, J.W.; Wisniewski, J.; Jordan, C. Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection. In *Proceedings of the Second International Nitrogen Conference,* A.A. Balkema: Potomac, MD, 2001.
4. Fowler, D.; Cape, J.N.; Unsworth, M.H. Deposition of Atmospheric Pollutants on Forests; *Phil. Trans. Roy. Soc. B* **1989**, *324,* 247-265.
5. Grennfelt, P.; Thornelof, E., Eds.; *Critical Loads for Nitrogen: a Workshop Report*; Nord 19912:41; Nordic Council of Ministers: Copenhagen, 1992.
6. Paerl, H.W. Coastal Eutrophication in Relation to Atmospheric Nitrogen Deposition: Current Perspectives; *Ophelia* **1995**, *41,* 237-259.
7. Asman, W.A.H. Factors Influencing Local Dry Deposition of Gases with Special Reference to Ammonia; *Atmos. Environ.* **1998**, *32,* 415-421.

8. Krupa, S.V.; Moncrief, J.F. An Integrative Analysis of the Role of Atmospheric Deposition and Land Management Practices on Nitrogen in U.S. Agricultural Sector; *Environ. Pollut.* **2002**, *118,* 273-283.
9. Asman, W.A.H. Modeling the Atmospheric Transport and Deposition of Ammonia and Ammonium: an Overview with Special Reference to Denmark; *Atmos. Environ.* **2001**, *35,* 1969-1983.
10. Hanson, P.J.; Lindberg, S.E. Dry Deposition of Reactive Nitrogen Compounds: a Review of Leaf, Canopy and Non-Foliar Measurements; *Atmos. Environ.* **1991**, *25A*, 1615-1634.
11. Philips, S.B.; Arya, S.P.; Aneja, V.P. Ammonia Flux and Dry Deposition Velocity from Near-Surface Concentration Gradient Measurements over a Grass Surface in North Carolina; *Atmos. Environ.* **2004**, *38,* 3469-3480.
12. Warneck, P. *Chemistry of the Natural Atmosphere*; International Geophysical Series 71. Academic Press: San Diego, CA, 1999.
13. Jansen, A.J.; Asman, W.A.H. Effective Removal Parameters in Long Range Air Pollution Transport Models; *Atmos. Environ.* **1988**, *22,* 359-367.
14. Asman, W.A.H.; Van Jaarsveld, H.A. In *Ammoniak in der Umwelt*; Hartung, J., Paduch, M., Schirz, S., Dobler, H., van der Weghe, H., Eds.; Vol. 2.; Landwirtschaftsverlag GmbH, Munster, Germany 1990, 1-35.
15. Loubet, B.; Pierre, C.; Genermont, S.; Laville, P.; Flura, D. Measurement of Short-Range Dispersion and Deposition of Ammonia over a Maize Canopy; *Agri. Forest Meteorol.* **2003**, *114,* 175-196.
16. Fowler, D.; Pitcairn, C.E.R.; Sutton, M.A.; Flechard, C.; Loubet, B.; Coyle, M.; Munro, R.C. The Mass Budget of Atmospheric Ammonia within 1 km of Livestock Buildings and Deposition Pattern within Adjacent Woodland; *Environ. Pollut.* **1998**, *102,* 343-348.
17. Sutton, M.A.; Nemitz, E.; Milford, C.; Fowler, D.; Moreno, J.; San Jose, R.; Wyers, G.P.; Otjes, R.P.; Harrison, R.; Husted, S.; Schjoerring, J.K. Micrometeorological Measurements of Net Ammonia Fluxes over Oilseed Rape during Two Vegetation Periods; *Ag. Forest. Meteorol.* **2000**, *105,* 351-369.
18. Wyers, G.P.; Erisman, J.W. Ammonia Exchange over Coniferous Forest; *Atmos. Environ.* **1998**, *32,* 441-451.
19. Duygers, J.H.; Verhagen, H.L.M.; Weststrate, J.H. The Dry Deposition of Ammonia onto a Douglas Fir Forest in the Netherlands; *Atmos. Environ.* **1994**, *28,* 1241-1253.
20. Walker, J.T.; Robarge, W. Dry Deposition of Ammonia in the Vicinity of a Swine Production Facility. In *Proceedings of Workshop on Agricultural Air Quality: State of the Science*; Potomac, MD, 2006.
21. Dennis, R.L.; Mathur, R.; Donna, S.; Walker, J.T.; Robarge, W. The Fate and Transport of Ammonia at the Local and Regional Level. In *Proceedings of Workshop on Agricultural Air Quality: State of the Science,* Potomac, MD, 2006.
22. Loubet, B.; Celia, M.; Mark, A.S.; Cellier, P. Investigation of the Interaction between Sources and Sink of Atmospheric Ammonia in an Upland Landscape Using Simplified Dispersion-Exchange Model; *J. Geophys. Res.* **2001**, *106,* 24183-24196.
23. Willis, G.E.; Deardoff, J.W. A Laboratory Study of Dispersion in the Middle of the Convectively Mixed Layer; *Atmos. Environ.* **1981**, *15,* 109-117.
24. Cimorelli, A.J.; Perry, S.G.; Venktaram, A.; Weil, J.C.; Paine, R.J.; Wilson, R.B.; Lee, R.F.; Peters, W.D.; Brode, R.W. AERMOD. A Dispersion Model for Industrial Source Applications Part 1: General Model Formulation and Boundary Layer Characterization. *J. Appl. Meteorol.* **2005**, *44,* 682-693.
25. Seinfeld, J.H. *Atmospheric Chemistry and Physics of Air Pollution*; Wiley-Interscience: New York, 1986.
26. Walcek, C.J. A Theoretical Estimate of O_3 and H_2O Dry Deposition over Northeast United States; *Atmos. Environ.* **1987**, *21,* 2649-2659.
27. Wesely, M.L.; Doskey, P.V.; Shannon, J.D. *Deposition Parameterizations for the Industrial Source Complex (ISC3) Model*; Draft ANL report ANL/ER/TR-01/003; Argonne National Laboratory: Argonne, IL, 2002.
28. Thermo Environmental Instruments Inc. *Instruction's Manual Model 17 C: Chemiluminescence NH_3 Analyzer*; 2000; available at *http://www.thermoei.com/* (accessed 2008).
29. *User's Guide for the AERMOD Meteorological Preprocessor (AERMET)*; U.S. Environmental Protection Agency: Research Triangle Park, NC, 1998.
30. Furquhar, G.D.; Firth, P.M.; Wetselaar, R.; Weir, B. On the Gaseous Exchange of Ammonia between Leaves and the Environment: Determination of the Ammonia Compensation Point; *Plant Physiol.* **1980**, *66,* 710-714.
31. Sutton, M.A.; Burkhardt, D.G.; Nimitz, E.; Fowler, D. Development of Resistance Models to Describe Measurements of Bi-Directional Ammonia Surface-Atmosphere Exchange; *Atmos. Environ.* **1998**, *32*, 473-480.
32. Perry, S.G.; Cimorelli, A.J.; Paine, R.J.; Brode, R.W.; Weil, J.C.; Venktaram, A.; Wilson, R.B.; Lee, R.F.; Peters, W.D. AERMOD: a Dispersion Model for Industrial Source Applications. Part 2: Model Performance against 17 Field Study Databases; *J. Appl. Meteorol.* **2005**, *44*, 694-708.
33. Van Ulden, A.P. Simple Estimates for Vertical Diffusion from Sources near the Ground; *Atmos. Environ.* **1978**, *12,* 2125-2129.
34. Lamb, R.G. *Diffusion in Convective Boundary Layer. Atmospheric Turbulence and Air Pollution Modeling*; Nieuwstadt, F.T.M., van Dop, H., Eds.; Reidel: Dordrecht, the Netherlands, 1982; 159-229.
35. Weil, J.C. In *Lectures on Air Pollution Modeling*; Venkatram, A., Wyngaard, J.C., Eds.; American Meteorological Society: Boston, MA, 1988; 167-227.
36. Arya, S.P. *Air Pollution Meteorology and Dispersion*; Oxford University: New York, 1999.
37. Nieuwstadt, F.T.M. Application of the Mixed-Layer Similarity to the Observed Dispersion from a Ground-Level Source; *J. Appl. Meteorol.* **1980**, *19,* 157-162.
38. Briggs, G.A. Prairie Grass Revisited: Optimum Indicators of Vertical Spread. In *Proceedings of 9th NATO-CCMS International Technical Symposium on Air Pollution Modeling and Its Application*; Toronto, Ontario, Canada, 1978.
39. Venkatram, A. Vertical Dispersion of Ground Level Releases in the Surface Boundary Layer; *Atmos. Environ.* **1992**, *26*, 947-949.
40. Willis, G.E.; Deardoff, J.W. A Laboratory Model of Diffusion into the Convective Planetary Boundary Layer; *Quart. J. Roy. Meteorol. Soc.* **1976**, *102,* 427-445.

About the Authors

Kanwardeep S. Bajwa was a graduate research assistant, S. Pal Arya is a professor, and Dr. Viney P. Aneja is a professor with North Carolina State University. Please address correspondence to: Dr. Viney P. Aneja, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695; phone: +1-919-515-7808; fax: +1-919-515-7802; e-mail: viney_aneja@ncsu.edu.