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TECHNICAL REPORTS

Atmospheric Dispersion of Ammonia During Application of Anhydrous Ammonia Fertilizer[1]

O. T. DENMEAD, J. R. FRENEY, AND J. R. SIMPSON[2]

ABSTRACT

There is a need to develop techniques for the prediction of the aerial spread of hazardous chemicals released in agricultural operations. The dispersion of ammonia (NH_3) gas during soil injection of anhydrous NH_3 is one such example. In previous work we established that after injection NH_3 escaped from the soil to the atmosphere at a rate that decreased exponentially with time; in our study the whole process took about 2 h. In this paper we combine the dynamics of the emission process with existing micrometeorological theory for atmospheric dispersion from line sources, to predict NH_3 concentrations in the air at the downwind edge of the field. The predictions are compared with concentrations measured during an injection operation.

Although the total NH_3 emission during the operation was only 1.2 kg/ha, NH_3 concentrations up to 213 $\mu g/m^3$ were recorded at the downwind edge in the early stages of injection. Wind speed and atmospheric stability had large influences on NH_3 dispersion. In light winds and stable conditions NH_3 concentrations >100 $\mu g/m^3$ were recorded when the applicator was >200 m upwind, and some NH_3 enrichment still occurred when it was 600 m upwind.

The model underestimates NH_3 concentrations when the treated width is <30 m, but predicts them very well at greater distances in both stable and unstable conditions. The model is used to predict NH_3 concentrations downwind of the applicator for a range of wind speeds and emission strengths.

The approach should prove useful not only for estimating NH_3 pollution hazards but also for predicting dispersion in related agricultural operations where a time-dependent decay and/or a line-source analogy are appropriate.

Additional Index Words: atmospheric diffusion, atmospheric pollution, aerial spread, nitrogen loss.

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There is often a need to predict the aerial spread of hazardous chemicals released during applications of pesticides, herbicides, or fertilizers. In many cases the material is applied in rows or bands by continuous-applicator traverses. One such operation is the injection

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into the soil of anhydrous ammonia (NH_3) fertilizer, which results in the liberation of NH_3 gas to the atmosphere. Besides constituting a direct health hazard, NH_3 is involved in the formation of aerosols affecting health, visibility, corrosion, and precipitation processes and may contribute to N enrichment of water bodies (Hutchinson and Viets, 1969). In this paper, we report on the atmospheric dispersion of NH_3 gas during the injection of anhydrous NH_3 when the operation was proceeding at various distances up to 600 m away from the measuring point, and present a model for predicting NH_3 concentrations in the air at the downwind edge of the field. The model combines the dynamics of the emission process with existing micrometeorological theory for diffusion from line sources.

In usual practice, anhydrous NH_3 is injected in bands in the soil at a depth of 10–15 cm. The liquid boils and some NH_3 gas escapes to the atmosphere through the injection slits and soil cracks. This emission continues at a decreasing rate for some time after the initial injection (Denmead et al., 1977).

The emission pattern can thus be expected to have characteristics of both a moving, ground-level point-source, and a continuous, ground-level line-source, the former model accounting for crosswind dispersion associated with the initial NH_3 release and the latter for the downwind diffusion from the continuous line sources. The line-source releases will have an increasing influence on the concentrations at the downwind edge as the treated area grows; we have therefore chosen to examine the dispersion of NH_3 in terms of the simpler line-source solutions, bearing in mind that the analysis is likely to be less appropriate for the early stages of the injection operation.

METHODS

Experimental

The experimental layout, procedures, and methods of measurement during the first stages of the study have been described previously (Denmead et al., 1977). Briefly, anhydrous NH_3 was injected at a rate of 130 kg/ha into a bare, moist, clay soil (pH 8.2, total N 0.07%), 12 bands at a time (0.5 m apart), during each pass of an applicator that traversed the field across the wind, gradually working upwind. The mean injection depth was 0.12 m. Wind speeds, air temperatures, and NH_3 concentrations were measured at heights of 0.31, 0.74, 1.24, and 2.24 m at a point on the downwind edge of the field, midway along the track of the applicator. Wind directions were also recorded.

Sampling periods during the first stages of injection extended from the time the applicator passed directly upwind of the measuring point until just before it returned from the end of the field, 500 m away. The average time for one such traverse was 17 min. During the later stages of the experiment, the sampling periods were lengthened to embrace two, and then four, traverses.

Theoretical

The equation describing steady-state atmospheric diffusion in two dimensions is

$$\bar{u}(z)\,\frac{\partial \bar{c}}{\partial x} = \frac{\partial}{\partial z}\left[K(z)\,\frac{\partial \bar{c}}{\partial z}\right], \qquad [1]$$

where $\bar{u}$ is the mean horizontal wind speed at height, z; $\bar{c}$ the mean atmospheric NH_3 concentration in excess of the background level, a function of both height and distance from the source, x; and K the eddy diffusivity for vertical transfer (Sutton, 1953). Calder (1949) and Sutton (1953) have considered the diffusion from a single, crosswind line-source of infinite extent, emitting continuously at a steady rate. Both have based their analyses on power-law profiles for the variation of wind speed and eddy diffusivity with height, viz.,

$$\bar{u}(z) = u_1\,(z/z_1)^m \quad \text{and} \qquad [2]$$

$$K(z) = K_1\,(z/z_1)^n, \qquad [3]$$

where u_1 and K_1 are the values of $\bar{u}$ and K at a reference height, z_1. For convenience, z_1 may be set at unit height above the ground; in our case, at 1 cm. The empirical constants m and n are related to the aerodynamic roughness of the surface and the thermal stability of the atmosphere (Calder, 1949).

Throughout the paper we frequently refer to atmospheric stability, which we have specified by the Richardson number, Ri:

$$\mathrm{Ri} = g/\bar{T}\,(\partial\bar{T}/\partial z + \gamma)/(\partial\bar{u}/\partial z)^2,$$

where g is the acceleration due to gravity, $\bar{T}$ is the mean absolute temperature, and γ the adiabatic lapse rate. Sutton (1953) gives a description of the theoretical basis of the Richardson number, but in short, it provides a means for specifying the relative effects of buoyancy and wind shear on vertical diffusion. A negative Ri denotes an unstable atmosphere, which usually occurs in daytime when the mechanical turbulence of the wind is augmented by buoyancy forces. A positive Ri, denoting a stable atmosphere, is characteristic of the nighttime, when the temperature inversion suppresses mechanical turbulence. Conditions are usually defined as near-neutral when $|\mathrm{Ri}| <$ about 0.03.

As will be shown later, Eq. [2] can provide a very good description of the wind profile near the ground. Furthermore, if the experimental area is large and uniform, the wind profile will be well-established and the shearing stress will be constant with height (Calder, 1949), which lead to the simplification that $n = 1\text{-}m$, $0 < m < 1$; hence,

$$K = K_1\,(z/z_1)^{1-m}. \qquad [4]$$

Calder's and Sutton's solution for the concentration distribution from a single line-source of strength, Q, along $x = z = 0$ has the form

$$\bar{c}(x,z) = \frac{Q}{u_1\,\Gamma(s)}\left[\frac{u_1}{(2m+1)^2K_1x}\right]^s \exp\left[-\frac{u_1z^{2m+1}}{(2m+1)^2K_1x}\right], \qquad [5]$$

where $s = (m+1)/(2m+1)$ and Γ denotes the gamma function.

Analytical

In order to apply Eq. [5] to the experimental data, it was first necessary to estimate the parameters m, u_1, and K_1. The first of these was estimated from twenty wind profiles measured at the site in periods of strong winds and near-neutral conditions by comparing wind speeds at the higher levels with those at 0.31 m. From Eq. [2],

$$m = \log\,(\bar{u}_z/\bar{u}_{0.31})/\log(z/0.31).$$

The mean of all such determinations of m was 0.225, with a standard deviation of 0.016. The reference wind speed, u_1, was calculated for each sampling period directly from Eq. [2] using this value of m and the $\bar{u}$ at 0.31 and 2.24 m. The excellent fit of Eq. [2] to all the wind-speed data collected at the site, which included periods of light winds and strong inversions, is shown in Fig. 1.

To calculate K_1, a low-level drag coefficient, C_z, was estimated from the 20 near-neutral wind profiles following the procedure of Deacon and Swinbank (1958). This coefficient was then used in conjunction with the wind speed at 0.31 m to calculate K_1 for each sampling period from the relationship

$$K_1 = C_{0.31}\,z_1\,\bar{u}_{0.31}{}^2/m\,u_1.$$

For this site, $C_{0.31}$ had an average value of 0.0127.

As noted in the introduction, NH_3 emission continues at a decreasing rate for some time after injection (Denmead et al., 1977). An analysis of the early stages of the experiment indicated that emission continued for about 2 h. The total emission was equivalent to 1.2 kg

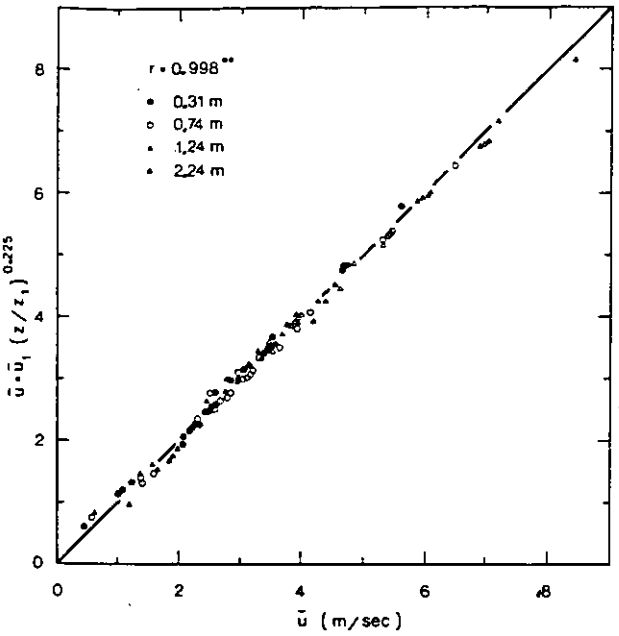

Fig. 1—Fit of power-law profile, Eq. [2], to wind-speed data.

NH_3/ha and the instantaneous emission rate, q, was described by the equation

$$q(t) = q_o \exp(-\lambda t), \qquad [6]$$

where t is time (s), q_o is the initial rate (= 37.0 μg NH_3 m^{-1} s^{-1}), and λ is a rate constant (= 6.3 × 10^{-4} s^{-1}). The time constant of the decay was 26 min. Particular values of q_o and λ depend on how strongly NH_3 is absorbed by the soil and the nature of the escape path from the site of injection to the soil surface. They can thus be expected to vary from soil to soil and with the method of injection.

Since one traverse of the applicator required 1" min, the average concentrations measured at the downwind edge of the field during each sampling period were influenced by emissions from several upwind sources located at different distances from the edge and emitting at various rates, depending on their times of injection. To analyze the data, we therefore added the separate solutions given by Eq. [5] for each injected band with Q set equal to the appropriate average rate for that band during the sampling period. From Eq. [6],

$$Q = q_o\{\exp[-\lambda(t_1 - t_*)] - \exp[-\lambda(t_2 - t_*)]\}/\lambda(t_2 - t_1), \quad t_* \le t_1 \le t_2,$$

where t_* is the time (from the start of the operation) at which the band was injected, t_1 is the start of the sampling period, and t_2 is the end of the sampling period. In effect, we approximated the experimental situation by a series of steady line-sources at different distances upwind.

In applying Eq. [5], it was necessary to account for wind directions other than those normal to the edge of the field, since deviations from normality increased the effective upwind distance of the sources. This adjustment was made for each sampling period by dividing the nominal upwind distance of each source by the cosine of the deviation in wind direction.

RESULTS

Meteorological parameters and NH_3 concentrations during the experiment are listed in Table 1. Most of the observations were made in slightly unstable atmospheric conditions, but the last three sampling periods were in stable conditions.

The data in Table 1 illustrate the main features of the dispersion process. Concentrations were highest close to the ground, where they increased rapidly during the first three traverses. As more of the field was treated and the emitting sources became more remote, NH_3 diffused to greater heights in the atmosphere and concentration gradients lessened; concentrations at lower levels fell while those at higher levels increased. These features are evident in the NH_3 concentrations measured while the treated width was extended to 120 m. During this period, winds were steady at 3–4 m/s.

The effect of wind speed on the concentrations at the downwind edge is evident in sampling periods 14, 15, and 16. In period 15 the wind speed dropped to about one-half that in period 14 and this resulted in a doubling of NH_3 concentrations. In period 16 wind speed had dropped to about one-third that in period 14, and the concentrations were almost four times as high, despite the fact that by then most of the effective sources were twice as remote from the measuring point. However, an additional influence during this period was the develop-

Table 1—Meteorological data and atmospheric NH_3 concentrations during injection of anhydrous NH_3.

Sampling period†	Width injected	Wind direction‡	$\bar{u}$ at 2.24 m	u_1	K_1	Ri at 1.67 m	Mean NH_3 concentration§ 0.31 m	0.74 m	1.24 m	2.24 m
	m	degrees	m/s		m^2/s		μg·m^3			
1	0–6	6	3.80	1.15	0.0032	−0.038	169	37	7	0
2	6–12	12	3.45	1.03	0.0027	−0.034	195	101	66	8
3	12–18	24	3.16	0.95	0.0026	−0.044	213	157	94	17
4	18–24	43	3.49	1.05	0.0029	−0.056	119	104	62	13
8	30–36	30	3.88	1.15	0.0031	−0.047	59	47	24	21
9	36–42	20	3.39	1.01	0.0027	−0.054	63	54	33	22
10	42–48	40	3.96	1.19	0.0032	−0.038	49	43	31	17
11	48–60	31	3.97	1.19	0.0032	−0.044	45	40	26	28
12	60–72	25	3.82	1.14	0.0030	−0.039	50	38	21	22
13	72–96	47	3.95	1.17	0.0031	−0.019	39	26	25	14
14	96–120	41	3.94	1.15	0.0030	−0.003	28	29	24	17
15	120–144	48	1.90	0.56	0.0010	0.094	41	33	35	36
16	210–234	26	1.19	0.35	0.0004	1.814	104	114	100	60
17	600–600¶	30	0.70	0.21	0.0001	2.538	10	14	12	8

† Some data for sampling periods 1, 2, 3, 4 are cited in Denmead et al. (1977). The numbering here is consistent with that paper, but concentrations there are for NH_3-N. Injection was stopped during sampling periods 5, 6, and 7. Some data for these periods are given in Denmead et al. (1977).
‡ Deviation from a direction normal to edge of field.
§ The background concentration (during the experiment) of 3 μg/m^3 has been subtracted from these values.
¶ Injection ceased at 600 m ½ h before sampling commenced. The sampling period was 1 h.

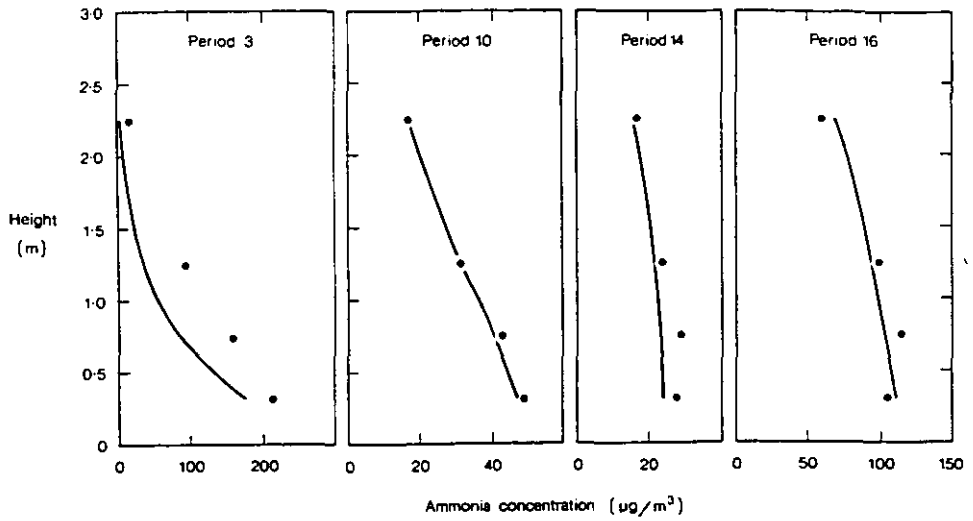

Fig. 2—Observed and calculated profiles of atmospheric NH_3 concentrations. Symbols for measurements; lines for calculations.

ment of a strong inversion and the consequent suppression of vertical diffusion (compare Ri and K_z values for periods 16 and 14).

The extent to which these observed features are reproduced by the model is shown in Fig. 2–4. In Fig. 2 the calculated NH_3 concentrations at the downwind edge are compared with those measured during sampling periods 3, 10, 14, and 16.

As expected, agreement between prediction and observation was not good for short treated widths where the line-source analogy is less appropriate. This is evident in the comparison for period 3 when 18 m had been treated. In fact, the model underestimated the concentrations at all heights when the treated width was <30 m. For greater widths, however, agreement improved markedly, as the comparisons for periods 10, 14, and 16 show. The effects of source remoteness, wind speed, and atmospheric stability on the concentrations downwind were predicted very well. The same good agreement for treated widths >30 m can be seen in Fig. 3 and 4, which compare predictions and observations of NH_3 concentrations for all the sampling periods.

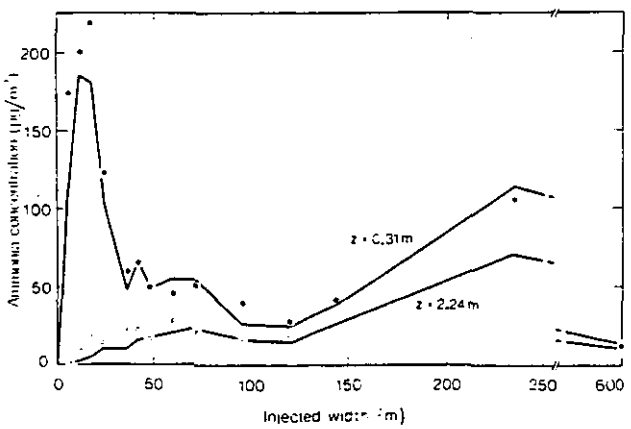

Fig. 3—Variation of NH_3 concentrations at two heights at downwind edge of field with distance from applicator. Symbols for measurements; lines for calculations.

DISCUSSION

The comparisons presented here show that the dispersion of NH_3 following anhydrous NH_3 injection can be predicted satisfactorily by existing diffusion theory at distances of 30 m or more from the source. The theory should then be useful for estimating the extent of NH_3 pollution in other field situations.

Efficiencies of particular applications of anhydrous NH_3, and the dynamics of emission, can be expected to vary with soil conditions and the method and amount of application. In this experiment the total emission of NH_3 was 1.2 kg/ha. Other published estimates of NH_3 loss during the injection operation range from ≪1

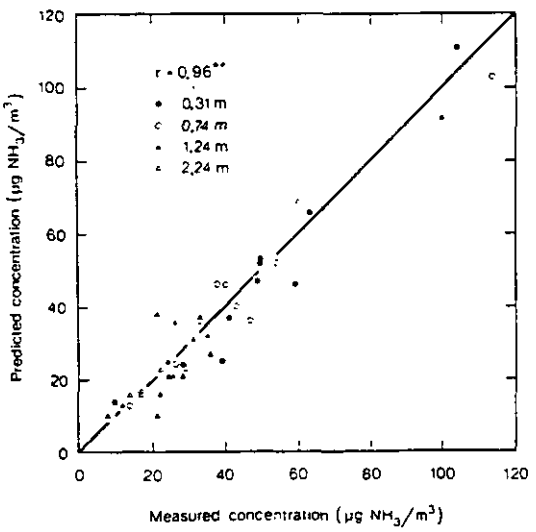

Fig. 4—Comparison of observed and predicted NH_3 concentrations for injected widths > 30 m.

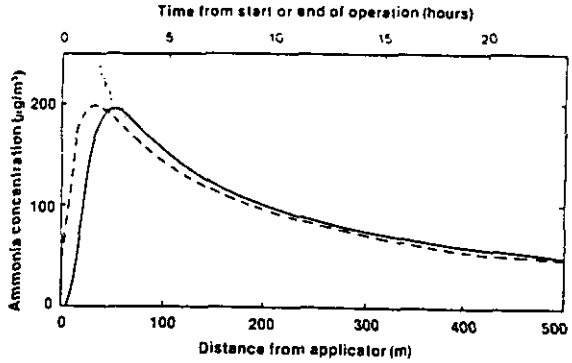

Fig. 5—Predicted NH_3 concentrations at downwind edge of field at height of 1.5 m. Solid line for applicator working away from edge; dashed line for applicator working towards it. See text for parameters used.

kg/ha (Baker et al., 1959) to as much as 45 kg/ha (Blue and Eno, 1954).

Equation [5] indicates that the concentrations at particular heights and distances downwind are directly proportional to the strength of the emitting source and inversely proportional to the wind speed. Assuming the same dynamics for NH_3 emission as we measured (as embodied in Eq. [6] and our value for λ), the same traverse time, and the same roughness characteristics and atmospheric stability (implying the same value for m and the same ratio between u_* and K_*), it is a simple matter to calculate NH_3 concentrations for other source strengths and other wind speeds. Figure 5, for instance, shows expected concentrations on the downwind edge at a height of 1.5 m for a wind speed at 2 m of 4 m/s, a source strength of 5 kg NH_3/ha, a value of 0.225 for m, and the same ratio between u_* and K_* as in sampling period 1. (A height of 1.5 m was selected as a reasonable head height.) Two curves are shown in Fig. 5: one for injection starting at the downwind edge with the applicator traversing crosswind and gradually working upwind, the other for injection starting at the upwind edge with the applicator again traversing crosswind and gradually working downwind. The concentrations close to the downwind edge in the latter case are higher because of the greater extent of the upwind sources.

In both cases the concentrations can be scaled directly for different source strengths or wind speeds. For instance, an emission of 10 kg/ha would result in twice the concentrations shown in Fig. 5 at the same wind speed, or eight times, if the wind speed at 2 m was only 1 m/s. To take an extreme case: if the emission was as high as the 45 kg/ha reported by Blue and Eno (1954), the dynamics were the same as used here, and the wind speed at 2 m was 1 m/s, concentrations at the downwind edge would exceed 7,000 $\mu g/m^3$ in the early stages of injection and would still be > 1,000 $\mu g/m^3$ when the applicator was 500 m upwind.

Air quality standards for NH_3 are listed by Stern (1968) and discussed by the National Research Council (NRC, 1979). Of these, the most stringent is the USSR permissible standard, which is a concentration of 200 $\mu g/m^3$ persisting for 20 min. Conservative as the standard may be, it is evident from Fig. 5 that it would be breached during the injection operation in light to moderate winds if the NH_3 emission rate was 5 kg/ha or more. Other factors, such as temperature inversions that suppress vertical diffusion, as in sampling period 16, or reduced lateral dimensions of the treated field, which would make for a quicker injection operation and a more rapid concentration increase, could lead to concentrations in excess of the standard for even lower emission rates.

As discussed by the NRC (1979), there is a wide range in standards for different environments and between countries, so that the above examples can be no more than illustrative of potential health hazards. The underlying dispersion theory, however, should prove useful in related problems in agriculture where a time-dependent decay and/or a line-source analogy are appropriate; for instance, in estimating the atmospheric concentrations of pesticides or herbicides released from row applications.

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