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WORKSHOP ON LONG-RANGE TRAJECTORY-PUFF AND PLUME MODELING OF CONTINUOUS POINT SOURCE EMISSIONS

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Abstract. Differences in thought exist concerning the computer modeling of long-range transport and diffusion of pollutants from continuous point sources. The differences pertain to the treatment of plumes as continuous or as a series of discrete diffusing puffs. For example, the physics governing the spread of a plume and a puff are different and it is not clear that one can use the mathematics of one process to simulate the physics of the other. Puff modelers argue that the use of puffs expedites the parameterization of removal processes and affords instantaneous realizations of the plume geometry. Furthermore, the use of the integrated plume equation fails to show the meandering of the plume by the large eddies, and since these eddies constitute the primary diffusion mechanism on the regional and synoptic scale, their simulation is quite important. Critics of this approach argue that tracking of many puffs throughout a region is computationally inefficient and unnecessary.

In an attempt to clarify these and other questions, resolve some of the misunderstandings, and provide an opportunity for a free exchange of ideas and opinions, a small workshop was held on 26-27 January 1977 at the Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, Tennessee. This report summarizes the speaker's presentations and the open discussion periods of the workshop.

1. INTRODUCTION

A workshop on the use of puffs and plumes in modeling long-range transport and diffusion of pollutants from point sources was held at NOAA's Air Resources Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, Tennessee on 26-27 January 1977. The purpose of the workshop was to identify the problems and resolve some of the misunderstandings surrounding the modeling of emissions from point sources out to mesoscale distances using either continuous plumes or a series of discrete diffusing puffs.

Invited participants[1] included modelers, model users and theoreticians. Government and private research laboratories as well as regulatory agencies were represented. The workshop format consisted of brief presentations followed by open and informal discussions. In this report, summaries of both the speaker's presentations and the discussion periods are presented.

2. SUMMARY OF THE TALK BY G. E. START

Fundamental aspects of the modeling problem that must be addressed by any kind of model used are:

(1) A description of the magnitude of exposure due to the airborne material including ground deposition.

(2) A correct prediction of the area of coverage.

(3) An accurate prediction of where the material goes.

(4) The correct prediction of the duration of exposure.

In making judgments of the accuracy for model prediction, one must consider the air analysis techniques used in obtaining verification data. For example, if the uncertainty in the observations is as great as the variance among model predictions, one should use the cheapest or simplest model. In many cases, one is not interested in predicting the exposure to individual people but rather the impact on a large area or population. These predictions are often in the form of statistical inferences on exposure, i.e., what percent of the population will be exposed to so much radiation which may result in such a percent of cancer tumors. Such predictions do not require high details in the model. Hence, one must keep in mind the details of a model and how it achieves its effects and the problem to be solved which is usually determined by other people besides the modelers.

The types of problems that face modelers extend from the long term or chronic exposure to the very short term or episodic impact of air pollution. The nature of the problem will determine which type of model (plume, puff, windrose) to use. One approach to the long range problem is the use of long term climatological models which have time scales

[1]Attendees were A. Bass, F. A. Gifford, J. L. Heffter, R. A. Kornasiewicz, R. Lange, R. A. Lott, F. J. Ludwig, E. H. Markee Jr., B. D. Murphy, C. J. Nappo Jr., D. W. Pepper, D. C. Powell, C-M Sheih, G. Start, A. D. Taylor, and V. Sharma.

from week to years and distances extending from 25 ~ 50 miles to 500 ~ 1000 miles from the point of release. The premise of these simple models is that random errors or deviations will cancel out as averaging times increase or for long dispersion times. Unfortunately, if the errors are not truly random, then there will be a systematic bias in the answers such as in the case of a preferred wind direction. These considerations have lead to the analysis of windrose models and trajectory-rose models using the MESODIF model (Start & Wendell 1974). In the real world, stability category and dilution rate can change with travel time and if these changes are not allowed in a model, one ends up with a biased result. If initial wind speeds and directions are held constant, as in the simple model, one ends up neglecting the situation where stagnation or curved effluent plumes can occur.

It was felt in the early work that attempting to account for plume dispersion by applying statistical adjustments to a plume axis was not desirable and there was little justification for doing so. Instead, it was decided to break the plume down into a number of chunks or plume segments. When using these plume segments a question concerning time step size must be answered. For example, if a plume segment does not completely pass over a receptor, how does one calculate the dose at the receptor? One way is to apply to the receptor all the dose in the segment. One may, however, wish to partition the dose according to what percent of the segment passed over the receptor. Another way is to eject from the source small pulses of mass as puffs. These puffs would contain the same mass as a plume segment; however, they would be instantly created.

When facing a modeling situation, one must first determine what is going to be calculated and the time scale of the calculation. If the time scales are sufficiently large so that certain effects will cancel out, one can use a simple model. However, if one is faced with a short time scale the simple model cannot be used.

The discussion is concluded by illustrating the difference between a plume axis which is a streak line and the path of a plume element which is the trajectory of the elements center. Streak lines and trajectories are identical only in a steady-state wind field.

3. SUMMARY OF THE TALK BY C-M SHEIH

The central issues concerning the use of puffs for modeling long-range transport and diffusion are:

(1) Why use a puff model?

(2) The theoretical bases for the puff models.

(3) The need for partitioning of diffusion.

(4) Models which might offer some of the solutions.

(1) It is obvious that puff models provide much more flexibility than plume models. For example, a plume model cannot handle the situation where there is a sharp curve or kink in the wind field. In such a case, the use of puffs is more likely to generate the correct concentration distribution. Another reason for using puffs is that they offer the best way of treating plume rise, multiple inversion layers and time dependent mixing heights. Another advantage of using puffs over plumes is the treatment of the calm wind case. In such cases, along-wind diffusion may be greater than advection and the plume formula will be incorrect. The criterion concerning the relative importance of along-wind diffusion is

$$U \frac{\partial C}{\partial X} \leq \frac{\partial}{\partial X} (K \frac{\partial C}{\partial X})$$

where U is the wind speed, C is a pollutant concentration, X the along-wind direction, and K is the eddy diffusion coefficient. Now making use of mass continuity and assuming an incompressible flow, the above can be written as

$$\frac{\partial}{\partial X} (U- \frac{K}{C} \frac{\partial C}{\partial X}) C \leq 0.$$

In this form, $\frac{K}{C} \frac{\partial C}{\partial X}$ is usually defined as a diffusion velocity while U is called the advection velocity. We see that alongwind diffusion must be accounted for whenever the diffusion velocity is greater than the advection velocity.

(2) The theoretical basis for the puff model is that the puff model can be integrated into the plume model. Because plume models have been accepted as correct, one should calibrate a puff model against the plume model. An example of this calibration is found in the case of determining the proper spacing between puffs so as to achieve the most economically smooth distribution of material. By selecting a case with near-uniform and near-steady winds, one runs the puff model with increasing spacings between puffs until a distribution similar to the plume model is achieved.

(3) The motion of a puff center is produced by the action of the measured mean wind field. The growth of the puff size is due to diffusion of the turbulence with scales smaller than the puff. This is usually done in terms of the puff spreading parameters σ_y and σ_z. The

partitioning of the atmospheric kinetic energy into turbulence spreading and puff or plume meandering is justified as a consequence of the spectral gap. However, the correct parameterization of this partitioning must be yet determined for regional scale problems.

(4) For regional-scale long-term problems, the statistical trajectory models may be best (e.g., Sheih, 1977). For the short-term problem, the puff-trajectory model is good (e.g., Start and Wendell, 1974). Note that the puff-trajectory model is to the statistical trajectory model as a signel puff is to a plume, i.e. the statistical trajectory model is obtained from the ensemble averaging of many puff trajections.

4. SUMMARY OF THE TALK BY D. C. POWELL

In using σ_y values in puff models which are measured from plume dispersion experiments, the meandering of the plume is included in the measurements, if the sampling time is long enough. Therefore, if these values are used in conjunction with a puff or plume model which includes the effects of meandering, the effects of meandering may be included twice. If this is the case, the σ_y values now in use may be too large.

As has been mentioned before, meandering and spreading are often viewed as independent processes. An important question regarding this assumption is when does the meandering of the wind, or mesoscale turbulence, dominate over local turbulence diffusion which affects the spreading of a puff? It was shown that predicting concentrations over a sampling grid with a cell size of about (34 km) using 3-dimensional Gaussian puffs with $\sigma_x = \sigma_y$ is equivalent to doing the calculations with a moving element of fixed horizontal spread if enough time is allowed. This is because the transport motions of the puffs have a greater impact on the long time average concentration patterns than the local spreading of each puff. This effect is especially true on a large or regional scale. In this case, use of a segmented plume model with running times of one month or more will distribute material such that errors in σ_y will cancel, if the sampling interval is on the order of an hour. Another statement of the same idea is that the running time should be roughly three orders of magnitude greater than the sampling time if errors in σ_y may be expected to cancel. However, a bias in σ_y would bias the calculated average concentrations of a long time assessment if the probability density function of wind direction in the data is quasi-discontinuous. Such discontinuity will be a true reflection of nature if the wind is channeled into some preferred direction by local terrain features. It will occur in the data without occurring in nature if the wind directions are arbitrarily discretized to certain points on the compass and the location of sampling points is likewise discretized. However, in the basic model we are developing, we are assuming that over most of the northeastern multistate region neither of these effects is important. Rather, we believe it is more pertinent to focus on the likelihood that the predicted average concentrations may be biased due to over-simplification or inaccurate parameterization in modeling one of the following:

(1) mixed layer depth behavior

(2) transformation rate of SO_2 to sulfate

(3) dry and wet deposition of SO_2 and of sulfate

5. OPEN DISCUSSIONS (MORNING, 26 JANUARY)

In a discussion on chemical reactions, especially $SO_2 \rightarrow SO_4$, F. A. Gifford pointed out the importance of knowing the physical volume or space through which reactions are taking place and the relative speed of reaction and diffusion. What the meteorology should be able to tell is how big is the space within which chemical reactions are taking place. In this regard, the plume approach should be most successful since it gives the volume in a straightforward way.

An observation made by F. A. Gifford is that there appears to be several kinds of models which have their own utility, and which model is to be used depends upon the problem.

G. Start makes the observation that when considering a problem such as chemistry, rainout, etc., always choose the most simple meteorological model that will do the job. One does not want a complicated meteorological model competing for CPU time with the real problem which may be chemistry. One must then choose the simplest model that will do the job needed for the problem.

6. SUMMARY OF TALK BY F. A. GIFFORD

This discussion presents some very elementary aspects of plume modeling. Pasquill shows that there are three ways of predicting the concentrations at a point, K-theory, statistical theory and similarity theory. Excluded in this discussion are second and higher order closure schemes.

Statistical theory tells us that for single particle diffusion

$$\sigma_y \sim \begin{cases} t & t \ll t_\ell \\ t^{\frac{1}{2}} & t \gg \tau_\ell \end{cases}$$

where τ_ℓ is the Lagrangian time scale. These results follow from Taylor's theory for the case of homogeneous turbulence for long sampling times. For relative or two-particle diffusion we have

$$\sigma_y \sim \begin{cases} t \\ t^{3/2} \\ t^{1/2} \end{cases}$$

The asymptotic state for long times is the result that the two particles will have drifted so far apart that they can be considered as individual particles.

In K-theory for very large times, K is constant. By very large times is meant $t \gg \tau_\ell$. When this isn't true, the behavior of K is a very complex function of space and time. In general it is not known how to specify K. K is Eulerian, e.g. it is related to space attached quantities and can be related reasonably to the turbulent structure of the boundary layer.

The problem in statistical theory is to find the dependence of mean concentration distributions on various planetary boundary layer flow parameters when these parameters are set together with the spatial variables and summarized in terms of the Monin-Obukhov length L. In this method, however, one gets more dimensionless ratios then one knows how to deal with. A very precise theory is obtained but it is very inflexible as to the type of sources. As a result, for example, there is no solution from similarity theory for the single point source. Similarity solutions are also very difficult to extend upward into the PBL because specific forces such as Coriolis forces are not explicitly contained in the theory. Such forces enter the theory by way of dimensionless parameters such as the surface Rossby number. Similarity theory can, on the other hand, reproduce the standard type of diffusion observed fairly well out to distances of hundreds of meters.

The question that brought this meeting together is, how does one model diffusion from isolated sources? Frankiel (1957) envisioned air pollution in Los Angeles by modeling using curved trajectories and assumed typical Gaussian puff elements using the argument that along-wind advection outweights along-wind diffusion. These plume elements were generated by assuming a spreading disk or bologna slice model.

In order to handle the distinction between meandering and spreading, the fluctuating plume model was developed. In this model, the plume is deformed in the usual way and the disk elements are allowed to fluctuate. The statistics of the sum of the actions of spreading and meandering were investigated under the assumption of homogeneous turbulence and Gaussian distributions of turbulence statistics. This is a perfectly acceptable way to proceed in this analysis. The net result of this type of spreading and meandering under these conditions can be shown to be equal to precisely the Taylor term for single particle dispersions. Another fact is that a gap in the spectrum is not necessary to produce a meandering plume type formula. One can still develop a model for the statistical description of meandering plus spreading. What modelers are attempting to do is calculate the meandering of plume elements and supply, through some theory or a combination of theory and observations, a spreading factor. This situation is much more complicated than that involved in the meandering plume formulation. This is because it is difficult to determine what is the mean and instantaneous winds when one only has a single measurement. We only can know the plume path as determined by wind observations to a resolution as fine as that of the wind resolution. Whatever is the physical situation, there are definite limits to the details of the resolution.

Some concerns about the puff models are:

(1) If one is calculating using instantaneous puffs then one must use instantaneous σ's (although this is not a very strong factor).

(2) People are saying that a puff model is necessary because plume paths accelerate and a puff model is necessary to describe this.

(3) If one is going to use a puff model on theoretical considerations one ought to be prepared to deal with the situation in which puffs are not going to look nice and circular but rather quite peculiar. This is especially true when looking at the near field. However, many modelers use puffs because the calculations are quite efficient if one assumes $\sigma_y = \sigma_x$ and this gives symmetrical puffs in which case it is easy to simulate right angle turns in the flow. It appears that this does not have to be assumed and that a segmented plume model will work just as well.

7. SUMMARY OF TALK BY F. L. LUDWIG

When using a puff model, one must generate puffs, move them around, change their dimensions, calculate concentrations and get rid of them. In generating puffs, attention must be paid to the spacing of the puffs so that in the case of uniform winds, the plume equation results. Experimental results show that puffs should be generated on an equal-space rather than on equal-time spacing, with a maximum spacing of $\Delta X \simeq 2\sigma_H$ where ΔX is the sampling grid cell size and σ_H is the horizontal standard deviations of the puff.

The use of puffs over plumes is required when considering nonsteady conditions. The use of spherical puffs over segmented plumes comes as an expedient. It seems to be the most straightforward approach to the problem at hand. The use of puffs enables one to model any situation whereas the plume formula or segmented plume model requires some special conditions. In short, it's easier to move puffs around rather than segmented plumes.

Regarding the time resolution of the wind field, it is shown that when one has a source oriented problem and has certain specific things to look for, such as areas of maximum concentration, constant winds of 15-minute duration are adequate. These times are related in some way to the box size.

8. SUMMARY OF TALK BY R. LANGE

A review was given of some of the transport modeling being done at L.L.L. as well as a description of the ADPIC model and a few examples of its application. In ADPIC whether a puff or plume formalism is used depends upon the length of the release time. For release times shorter than 1 hour, a puff is assumed, and for longer release times a plume is assumed. The great advantage of the PIC method is that each particle is tagged and has a memory, and deposition, chemistry, etc. become easy to handle.

Because advection rates are hourly in ADPIC, the description of a plume is correct if σ values are taken from the Pasquill-Gifford curves. However, after the hour a new plume axis is defined and it is assumed that this is the proper way to handle the meandering problem.

9. OPEN DISCUSSION (AFTERNOON, 26 JANUARY)

In answer to a question on the justification of breaking down the distribution of continuous particle releases (plume) into discrete puffs or elements of material, it was pointed out by Albion Taylor that in the case of linear partial differential equations, Green's functions can be used to model a continuous distribution by using discrete elements.

Frank Gifford pointed out that many people use puffs and advance these puff models as cases of applications of Taylor's statistical theory. In about all cases of models, it appears that use is made of the statistical predictions for homogeneous turbulence since these are easily used and represent the only judgments that have thus far been made concerning diffusion in the atmosphere. Modelers taking the puff form of this theory and advecting puffs out along streak lines, assume they are generating an equivalent plume. This can be done, but one must be aware that the Gaussian puff model as conceived by Sutton and Frenkiel does not refer to an instantaneous release of marked particles. What it does refer to is the ensemble average of many such releases with respect to some fixed coordinate axis. One can use these statistical treatments in another sense, but one must then justify this use. So far this justification has not appeared, and the Green's function approach does not stand as a justification.

Brian Murphy pointed out that a puff has a σ_y and the puff follows the instantaneous wind vector while a plume follow the mean wind. The whole problem is that part of the atmosphere must be defined as a mean transport wind and part must be defined as turbulence. The problem is how to make these definitions in the proper physical way.

Another problem is deciding how to use the sigmas. For a long range problem, the sigmas, which are defined from observations less than an hour and more like 3 minutes, must be applied to plume or puff diffusion on time scales small when compared to the transport times. This diffusion process can be thought of as a kind of subgrid scale parameterization - subgrid in time.

A problem that Frank Gifford sees is the proper specification of σ_x. It is not obvious that one can assume $\sigma_x = \sigma_y$ and physical observations of σ_x do not appear to have been made. It may be argued that since in the limit of many puffs the true plume is approached, the along-wind diffusion cancels out and hence the specification of σ_x is not important. However, when the limiting number of puffs necessary for this to be true is not reached, i.e. when there are not many puffs - what can be said about the non-importance of σ_x. In these cases, the specification of σ_x may be extremely important.

Frank Gifford asked the question, at what distance can diffusion be neglected and only the trajectory need be considered? It is assumed that when material is uniformly distributed throughout the boundary layer, the material can be identified with an air mass and the path of this air mass is what needs to be determined. Nick Heffter answered this question by describing the results of a single long-range verification experiment. It was found that if one allows a puff (or plume) to continue to expand, eventually everything smears out and one has real problems in growth and over estimations of the concentration. At some point, something goes on and this point is estimated to be around 4 or 5 days. Beyond these times, one gets utter nonsense by letting the material still expand.

Frank Gifford points out that at some distance downwind, the motions of a plume across a receptor as a result of the hourly variation of the wind field will be much stronger than the plume diffusion. C-M Shieh points out that the sampling time at the receptor determines the magnitude of this effect.

Gene Start spoke of a study to compare the results of a MESODIF type model against weekly air samples taken in the area. While the data was not all good, one result was that with say on the order of 168 trajectories or so, it didn't matter too much what kind of day or night conditions these trajectories were initiated under, the single best correlation of the variations of the environmental sampling was "yes" or "no". That is whether or not a trajectory passed over a receptor.

Obviously, if such a distance or travel time existed where and when advection dominates over diffusion, the necessary calculation will be much simpler. The time resolution of the wind field must somehow restrict how the diffusion is used.

These arguments lead again to the question of how one separates diffusion from the transport or meandering. Gene Start discussed the results from a study by Sagendorff (1974) which dealt with diffusion under low windspeed conditions out to about 400 M over flat terrains in Idaho. Under low wind speed inversion conditions, one can imagine the plume would go in any number of directions so that after a time of about 1 hour one would achieve a total integration at a number of samplers set out in an array. About a dozen tests were made. The simplest approach taken was that

$$\sigma^2_{total} = \sigma^2_M + \sigma^2_T$$

where σ^2_M = mean variance based over all end to end 2-minute time periods within that hour time period, and σ^2_T = variance of the 2-minute mean wind distribution. A substantial amount of bivane data was collected and sampled and one of the things looked at was σ_M. The results of this study were that one could probably describe a short term dispersion of the chunk of plume by σ_T spreading and the meandering of the plume by σ_M and if these were close to a Gaussian function one could get a good estimate of the total σ_y. This is the main part of the paper.

Dividing σ_{total} into σ_M and σ_T enables one to describe these in terms of local and mean conditions. For example, σ_T is felt to be due to stability, surface roughness, etc. while σ_M is (or may be) a function of terrain, windspeed or synoptic situation. σ_T controls plume spreading about the plume axis while σ_M controls plume meandering.

10. OPEN DISCUSSION (MORNING, 27 JANUARY)

Art Bass opened the discussion period by bringing up the subject of nonlinear chemistry. An important application is the study of sulfate on inter-state scales. It is not obvious that non-linear chemistry can be done in the context of a puff model where the concentration at a given point is the result of the linear superposition of several puffs. In this case, the concentration is due to the simple sum of the contributions of many puffs. Frank Gifford suggests that the shape or form of a plume element is not important, as regards chemistry, but the volume of the element is important. One must get at the essential physical facts of the problem; one must ask if there is a volume that can be characterized by a state of the turbulence and diffusion length as a function of space and time.

Brian Murphy pointed out that the complicated models are quite difficult to work with when the need for quick answers arises. This is almost always the case in the private sector or for regulatory studies. Perhaps these complicated models should be run and the results parameterized into simpler models.

Frank Gifford pointed out that the thing to remember in all chemistry models is the difference between the time scales governing diffusion and the time scales of the chemical reactions. In these cases, the physical scales of the problem are going to be governed by the time scale. For example if chemical changes are occurring on a time scale of 0.1 sec and one is interested in these reactions, then one must have an extremely small grid in order to keep track of the material and its changes. On the other hand, one can choose to parameterize these fairly rapid reactions. It is hoped that some kind of lumped reaction scheme will turn up and can be parameterized by some kind of fairly slow time scale say characterized by the turbulence diffusion.

Sumnar Barr makes what he calls a minority report. In trying to sum up it seems to him as though the conversation went like, "one can construct plume-like behavior out of sequences of puffs in an asymptotic approximation, but the asymptote seems to be made up of a few puffs so that one can get plume-like behavior from collections of from 6 to 10 puffs." The question that comes to mind is, is there something that puffs do that plumes cannot do? It appears that in the non-steady case, the puff formulation is best in defining the plume. There are times when 180° wind shifts occur on the synoptic scale and one also sees 180° wind shifts in the West on a diurnal cycle. Therefore, these extreme cases are not unusual and cannot be ignored. For example, at Four Corners it is a daily occurrence. These conditions must be able to be accounted for in any application work. So there may be a role when the expense of running a puff or trajectory model is necessary.

11. SUMMARY OF TALK BY J. L. HEFFTER

This discussion is concerned with the use of puffs and plumes in a regional to continental scale trajectory model. In such an effort, many practical problems are present concerning the use of puffs and plumes and limited resolution of the wind field. The regional-continental scale transport and dispersion model under study has been described by Heffter et. al. (1975). Portions of the model were later revised (Heffter and Ferber, 1977) to include:

(1) Vertical temperature profiles along a trajectory to determine a mixing layer in which average transport winds are calculated.

(2) Time interpolation of the winds to provide additional data at the four daily observation times.

(3) A better estimate of long-term average concentrations based on the equation where the effluent plume is represented by a series of diffusing puffs rather than the continuous plume equation.

Effluent transport and dispersion are calculated in the following way.

A trajectory, composed of 3-hour segments, is computed assuming time centered persistence of winds. The winds are averaged in a transport layer determined from vertical temperature profiles. After the trajectories have been determined, diffusion calculations are made. It is assumed that there is one puff for each trajectory and that a puff diffuses as it is transported along the trajectory path.

Concentrations can be calculated over a regional area using either puff or plume concepts. The equations are:

$$C_{puff} = \frac{Q}{2\pi\ Z_m\ \sigma_h^{\ 2}}\ e^{-R^2/2\sigma_h^{\ 2}} \qquad (1)$$

$$C_{plume} = \frac{Q'}{(2\pi)^{\frac{1}{2}}\ Z_m\ \sigma_y\ \bar{u}}\ e^{-y^2/2\sigma_y^{\ 2}} \qquad (2)$$

C = air concentration in the mixed layer

Q = emission amount per puff

Q' = emission rate

Z_m = height of the mixed layer

σ_h = horizontal standard deviation

σ_y = lateral standard deviation

$\bar{u}$ = mean wind speed

R = distance from puff center

y = lateral distance from trajectory

The plume equation (Eq. 2) is derived from the puff equation (Eq. 1) and is applicable, ideally, in a non-variant wind field (where a representative mean wind $\bar{u}$ exists). In reality, especially over regional scales, representative winds that can be used in the plume equation become difficult to define. It is, therefore, assumed that the better estimate of concentration is made using the puff equation, where $\bar{u}$ does not appear, so an assumption about its value is not required.

Heffter described some initial results of a study to compare the differences in using puff and plume formulations. Average surface air concentrations were calculated over the eastern U.S. for January 1977 with a hypothetical source at the Savannah River Plant, South Carolina. In the plume equation, $\bar{u}$ was determined at the source (for the first 3-hour trajectory segment) and held constant for the remainder of segments that comprise a 5-day trajectory. With $\bar{u}$ so defined, the plume equation gave concentrations 5 to 10 times greater than the puff equation at large distances from the source, i.e. New York and the New England states. If, however, $\bar{u}$ was defined for each 3-hour trajectory segment along the trajectory, the results at large distances were greatly improved relative to the puff equation, but close to the source the plume equation concentrations were about twice as great as the puff equation concentrations. Of course, these results apply to the very limited case presented here. A more extensive climatological study is necessary to make general statements about the choice of $\bar{u}$.

Heffter concludes by pointing out that in his judgment, the puff formula is preferable for the regional scale. On the mesoscale, the choice of equations may not be as clear-cut. The puff equation still should be preferable but the differences between puff and plume concepts are probably more subtle and certainly need further investigation similar to that presented here.

12. REFERENCES

Frenkiel, F. N. (1957): Atmospheric Pollution in Growing Communities, Smithsonian Report for 1956, pp. 269-299.

Heffter, J. L., A. D. Taylor, and G. J. Ferber (1975): A Regional-Continental Scale Transport, Diffusion, and Deposition Model, NOAA Technical Memo. ERL ARL-50, Air Resources Laboratories, Silver Spring, MD, 29 pp.

Heffter, J. L., and G. J. Ferber (1977): Development and Verification of the ARL Regional-Continental Transport and Dispersion Model, Preprint - Joint Conference on Applications of Air Pollution Meteorology, Salt Lake City, Utah, pp. 400-407.

Holzworth, G. C. (1972): Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous U.S., Environmental Protection Agency, Research Triangle Park, NC, pp. 31-35.

Sagendorff, J. F., and C. R. Dickson (1974): Diffusion under low wind speed inversion conditions. NOAA Tech. Memo. ERL ARL-52, U.S Dept. of Commerce.

Sheih, C. M. (1977): Application of a statistical trajectory model to the simulation of sulfur pollution over Northeastern United States. Atmos. Environ., 11, pp. 173-178.

Start, G. E., and L. L. Wendell (1974): Regional effluent dispersion calculations considering spatial and temporal meteorological variations. NOAA Tech. Memo. ERL ARL-44, U.S. Dept. of Commerce.