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Project Summary

Research on Diffusion in Atmospheric Boundary Layers: A Position Paper on Status and Needs

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The introduction of a new understanding of atmospheric boundary layers (ABLs) has caused a major change in the view of the diffusion of pollutants. The turbulence parameters now standard in ABL work, have provided a method for systematically organizing diffusion parameters. Concurrently with these advances, alternatives to the operational models have emerged, but existing experimental data sets are inadequate for model comparisons and evaluations. The most important knowledge gap is the lack of an adequate specification of the relevant meteorology both at the point of release and downwind. A second major inadequacy is experimental measurements of plume characteristics up to 100 km from the release point. There is also a great need for formulating new operational models based upon this newly acquired experimental data and the new alternative approaches. Finally, it is recognized that a modest but steady effort is necessary.

This Project Summary was developed by EPA's Atmospheric Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The purpose of this study is to review the current state of science concerning diffusion within the atmospheric boundary layer (ABL) and to identify major issues and research needs. The study is limited to considering only the diffusion of non-buoyant, conservative substances over homogeneous and level or moderately hilly terrain. Thus, chemical transformation, wet and dry deposition, buoyancy effects, and diffusion in complex terrain are all topics which are excluded. Certainly these are very important topics both from the point of view of the research scientist and from that of a regulator; however, each of these topics deserve a review study of the same scope as attempted here. The topics that will be included here are: a review of diffusion experiments and models, and a discussion of research needs. We begin, however, with a highly simplified description of the major meteorological factors affecting diffusion. The main report contains the necessary details and references.

Meteorological Factors Controlling Diffusion

Material released from the ground or from a stack is mixed and transported by air motion. This process dilutes the material and carries it horizontally away from the source. This mixing process is called turbulent diffusion, or simply diffusion. The turbulence responsible for this mixing may result from the wind blowing over the ground, generating turbulent eddies, or it may result from heated parcels of air or thermals that are generated in air heated by contact with ground which has been warmed by the sun. Thus, we distinguish between "mechanical" and "convective" turbulence, because in addition to having different generative mechanisms, they have considerably different diffusive properties.

The current view of the ABL divides it into three conceptual states, the neutral boundary layer (NBL), the convective boundary layer (CBL), and the stable boundary layer (SBL). The NBL occurs when there is a negligible transfer of heat from the ground surface to the air. This occurs with strong winds and usually when most of the sky is covered with clouds. Only mechanical turbulence is generated in the NBL which extends up to or even into the cloud bases. The SBL occurs when the ground is substantially cooler than the air above it causing a stable profile to develop. This means that an upward moving parcel of air, for example, experiences a downward restoring force because it is colder, therefore denser, than its surroundings. Mechanical turbulence is generated as the wind blows over the ground, but vertical motions are very much restricted by the stability. Vertical diffusion, consequently, is restricted and plumes of effluent dilute slowly during transport downwind. The depth of turbulent mixing is also very restricted in the SBL, being of the order of 100 m or less It is under these conditions that some of the most serious air pollution episodes can occur. The CBL occurs in the daytime, with low to moderate wind speeds and clear to partly cloudy conditions. Then the ground is warmed and thermals rise from the surface to generate convective turbulence. The diffusion process is dominated by the vertical transfer of material in the thermals and downdrafts. The height to which these thermals rise is called the mixing depth. As a result of this efficient type of mixing, the CBL often has a "well mixed" condition in which the vertical profile of a pollutant becomes constant from a few meters above the surface to the mixing depth.

On a day without many clouds, and with neither fronts nor shorelines nearby, the diurnal course of the ABL is as follows: starting about an hour before sunrise, the ground has cooled to its minimum temperature. The temperature profile is stable but there is some vertically restricted mechanical turbulence from the surface to the top of the SBL. Any plumes within this SBL are very well defined. Any plumes above the SBL have virtually no vertical dilution but may be spread horizontally by meanders caused by large scale horizontal eddies. As the sun comes up, thermals begin to rise from the ground but must work against the stable temperature profile until all the air in the developing CBL is warmed and mixed. The CBL, thus formed, grows until the diminished surface heating in the late afternoon can no longer overturn stable air above the CBL. Typically, the maximum mixing depth is of the order of a kilometer. Any plumes beneath this height released into the previously stable air are mixed downward to the ground, a process referred to as fumigation. Late in the afternoon, the strength of the thermals diminishes. Soon a new stable layer is established at the surface and a new SBL forms. The transitional times around sunrise and sunset are as yet poorly understood. Little is known about the structure of the ABL and even less about diffusion during these periods.

In a typical diurnal cycle, the large changes in stability correspond to large changes in diffusion rates. Some method of indicating the ambient stability is necessary and there are several indices of stability currently used. The index most indicative of the physical processes at the surface is the Obukhov length, L. By convention L is defined to be negative with an upward flux of heat at the surface (unstable conditions). In principle, this length is defined such that at height $z = L$ above the ground, the buoyant production (or destruction) and the mechanical production of turbulent kinetic energy are comparable. Hence, above $z = L$, the turbulent state of the ABL is dominated by buoyancy effects and below $z = L$, the turbulent state of the ABL is dominated by the mechanical overturning caused by the wind blowing over the surface. Profiles of mean wind speed and other meteorological quantities are functions of z/L near the surface.

Besides the Obukhov length, other quantities of importance in describing the turbulence in the ABL are the surface heat flux, the surface friction velocity scale u^*, and the mixing depth. A velocity scale analogous to u^* has been developed for the CBL. Called the convective velocity scale, w^*, it is essentially defined by the surface heat (or buoyancy) flux the depth of the CBL; w^* has proven to characterize the turbulent velocities within the CBL very well. The depth of the CBL divided by L serves as a useful indicator of the relative importance of the thermals as a major transfer mechanism; the larger this ratio is, the more important thermals are to the description of diffusion. As fundamental as these variables are to our understanding of ABL processes, u^* and the surface heat flux are not easily measured; both are needed to determine L using its definition. An alternative index related to L, called the Richardson number, Ri, uses a temperature difference and velocity differences between two heights: in another form known as the bulk Richardson number, only one wind measurement is used. There are simple methods to convert from Ri to Obukhov length. An estimate of the site roughness length, z_0, is necessary with the bulk Ri approach, while the velocity differences approach strongly demands wind sensors that are properly calibrated. With the temperature differences, and at least one wind velocity, the same methods that yield the Obukhov length can be used to obtain u^* and the heat flux. The only other essential measurement needed for characterizing ABL turbulence and diffusion is the mixing depth. This can be obtained from good profiles of temperature and humidity. In the case of the SBL, a profile of wind speed is also required. In recent years it has become possible to estimate this depth by using remote sensors such as lidars and acoustic sounders. Lateral diffusion at large distances is enhanced by wind direction changes with height, which are best determined from wind velocity soundings.

Experimental and Theoretical Bases for Our Understanding of Diffusion

The current understanding of diffusion processes is based upon results from field experiments, laboratory experiments, and theoretical models. Field experiments may be conveniently grouped into two classes, those in which the tracer material is released from very near the surface and those in which the release is elevated. The data from previous experiments has been very useful in formulating our current understanding of the diffusion process but there are major inadequacies. First, the tracers used in most early field studies were not conservative. This means that as a cloud or plume of tracer was transported downwind, the material stuck to the ground or deposited, thus reducing the concentration further downwind by an uncertain amount. The theoretical view of diffusion prevalent at the time of the earlier experiments was that the vertical profile of concentration was Gaussian. If this were true and the tracer were conservative, the standard deviation of the concentration, Sigma-z, is easily obtained from ground samples alone. When deposition occurs, however, the

Sigma-z estimate is biased by an unknown amount to be an overestimate. A second difficulty with these data is that with one notable exception, the Prairie Grass experiment done in 1956, the experiments did not take sufficient meteorological data for either interpretation using contemporary concept or for validation of current diffusion models. Two recent experiments, one in Copenhagen, Denmark and one under EPA sponsorship in Boulder, CO, had extensive meteorological data. The Danish experiment used a conservative tracer, while the EPA-sponsored experiment used remote sensing to get concentration profiles at several locations downwind of the source. This experiment, named Convective Diffusion Observed with Remote Sensors (CONDORS), was designed to verify some new insights into CBL diffusion that were gained from numerical experiments and laboratory studies.

Laboratory studies of ABL diffusion are gaining wider acceptance as the scientific community has learned how to simulate ABL processes more faithfully. The major problem faced in a laboratory simulation is to maintain the proper balance of forces and yet attain the required reduction in scale. In strictly neutral conditions, this is not too difficult. One problem is that if the scale reduction factor is very large, viscous effects smooth out turbulent eddies in the laboratory which would not be smoothed in the atmosphere. This is usually overcome by making the bottom of the wind tunnel have a rougher texture than strict scaling would predict. A major difficulty is properly simulating buoyancy effects. Since gravity cannot be easily scaled down on the earth's surface, density differences must be exaggerated. This distorts other aspects of the simulation so that technical trade-offs are necessary. The most effective use of laboratory work then is to examine a particular, but important aspect of the diffusion problem. One such application which illustrates this point is the work done at the EPA Fluid Modeling Facility that showed that a tall slender building required a shorter stack for good plume dilution than would have been predicted by using building height alone.

Experimental work alone is insufficient for an understanding of diffusion. A proper conceptual framework is also necessary. Most current applications of diffusion models are based upon the Gaussian distribution in both vertical and horizontal directions in order to characterize the diffusion. The Gaussian distributions are based upon empirical data collected primarily during near surface releases over relatively flat terrain. Unfortunately, most of the model applications are for situations that were not considered in the experimental situations which provided the empirical data for the formulation of these models. Finally, for diffusion of non-buoyant releases within a CBL, the Gaussian assumption for the vertical distribution of material was recently shown to be incorrect. Current practice has adjusted the necessary parameters so that surface concentrations are nearly correct for the CBL case even though the vertical profile is not. There are, however, several modeling methods that have been demonstrated to be superior for particular applications. In the interest of brevity, only three examples will be mentioned. The first is the statistical method which relates the standard deviations of the concentration distribution directly to the observed turbulent intensities of the wind field. Since the statistics of the wind field tend to be fairly uniform in the horizontal direction, this method has the greatest success in characterizing the horizontal concentration distribution for transport over an area of homogeneous land use. A second approach is to simulate the diffusion as a random walk or "Monte Carlo" process. Recent work in this area has allowed for vertical and horizontal inhomogeneities in the flow field. A disadvantage to this approach is that it generates individual material trajectories and then constructs the distributions directly. For realistic cases, a very large number of trajectories must be calculated. Finally, a third method is numerical simulation of the diffusion process by solution of the relevant governing partial differential equations in an Eulerian framework. There has been great progress made in formulating these models which require a number of simplifying assumptions. For example the laboratory work on surface releases in the CBL inspired a set of numerical simulations that in turn included a prediction about unexpected behavior of an elevated release. The numerical work predicted that the plume centerline for a non-buoyant release would descent to the surface, then rise again. This prediction inspired further laboratory work that verified the finding. The CONDORS experiment was conducted specifically to confirm the numerical and laboratory findings for diffusion in the CBL. Here is an example of how the various methods for studying diffusion interact in the discovery and confirmation of major new findings in diffusion theory. All of the work mentioned in this example was supported by EPA.

Needs for Future Work

Before listing the future needs it is imperative to state at the outset that the human and fiscal resources for these endeavors are not trivial. A modest steady commitment of personnel and funds for an extended period is necessary, as the work described requires a sustained scientific effort.

The first major need is for field data for selected meteorological scenarios for the development, testing, and evaluation of diffusion meteorology models. The characterization of those meteorological variables important to the diffusion process is a major impediment to the implementation of new and emerging approaches to diffusion characterization. To meet these needs requires detailed profiles of the relevant variables within the first kilometer or so of the atmosphere. In addition, sufficient measurements are needed to characterize the surface energy balance, the forcing of the wind fields by the large-scale migratory pressure systems, the horizontal temperature field and the cloud conditions. These studies should be conducted over a variety of terrain types using a minimum of preparation and personnel. This would allow the study of the meteorological events of interest at the locations of interest. A portable instrumented tower, a tethersonde (a tethered balloon carrying an instrument package), and an acoustic sounder would be the basic tools for such studies. The development of such meteorological field studies would greatly facilitate the transfer of theoretical results into practical operational models useful for decision making.

A second major need is for the comparison, evaluation, and construction of new operational models. An interdisciplinary team with skills in meteorology, chemistry, numerical modeling, and statistics is required to meet this need. Such a team would evaluate the models not only with respect to experimental data, but also with respect to the expected uncertainty in the model inputs. These type of comparisons are necessary to make improvements in the operational models.

A third major need is for diffusion experiments, both in the field and in laboratory settings. The laboratory studies are needed to test theoretical results in specific simplified situations that are free of confounding influences. The field data are needed because there is a wide disparity between the flat homogeneous land where the best of the previous field studies have been conducted and the complex woodlands and urban-suburban developments typical of the American landscape. One example of important information to be gained from such field studies is the characterization of the concentration field at 100 km downwind from the source. Current models extrapolate to this distance based upon measurements to only 3 km. Vertical and lateral profiles of concentration even at widely spaced plume transects would improve the current situation considerably. Other examples include the characterization of releases made during the hours of transition, that is near sunrise and sunset, as the behavior of the atmosphere during these periods is very poorly understood. For any of these examples, a good diffusion experiment is of necessity a good meteorological experiment, since a full complement of meteorological measurements is essential to the success of the experiment and to the continued usefulness of the data set.

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The complete report, entitled "Research on Diffusion in Atmospheric Boundary Layers: A Position Paper on Status and Needs," (Order No. PB 86-122 587/AS; Cost: $22.95, subject to change) will be available only from:
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