REVISITING 1992 HARMO1 (RISO) COMMENTS ON LIMITATIONS OF SHORT RANGE ATMOSPHERIC DISPERSION MODELS

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Abstract: During the 1992 HARMO1 (Riso) workshop, I presented an overview of limitations of the state-of-the-art short range atmospheric dispersion models. The topics were: 1) mixing depth, 2) vertical profiles of turbulence, 3) formation of the nocturnal jet, 4) non-steady-state periods, 5) surface constants (albedo, soil moisture and roughness), 6) surface energy balance relations, and 7) Lagrangian time scales. The current paper revisits these seven topics. The most progress has been made in topics that are also of interest to climate change, such as 5) and 6) on surface parameters and surface energy balance relations. Other areas, such as mixing depths and vertical profiles of turbulence and Lagrangian time scales, have seen less progress. Some current difficult topics are added to the list: 8) boundary layer profiling and dispersion in low-wind stable conditions, 9) how to handle steep terrain, building obstacles, and variations in land use, 10) whether newer technology is helping, and 11) how to handle dense plumes and chemical reactions.

Key words: *Dispersion models, Boundary-layer models, Uncertainties*

INTRODUCTION

In my paper in the HARMO1 (Riso) workshop proceedings (Hanna, 1992), I listed some "confessions" regarding limitations of short range atmospheric dispersion models. These comments were generally applicable, although I illustrated my points using examples from the Hybrid Plume Dispersion Model (HPDM) (Hanna and Paine, 1989). At that time there had been a "revolution" in these types of models, which were gradually moving from the existing Pasquill-Gifford stability class approaches to the use of the Monin-Obukhov length, L, and associated vertical profiles of wind speed, temperature, and turbulence. Improved surface energy balance schemes, such as suggested by Holtslag and Van Ulden (1983) were used to calculate the surface sensible heat flux, H_s, and the friction velocity, u*. A few of these new models were described at the HARMO1 conference, such as HPDM (Hanna, 1992; see also Hanna and Paine 1989), ADMS (Carruthers et al., 1992), and OML (Olesen et al. 1992). Other model developers were following the same path; for example, the US EPA organized a working group to develop AERMOD (Cimorelli et al., 2005), which took several years to make its way through the regulatory approval process.

To arrive at a comprehensive new dispersion model that includes a broad range of processes, model developers must work with theoretical advances that are at various stages. Some of these algorithms are more developed and better evaluated than others. The developers privately recognize the uncertainties and limitations, but sometimes are hesitant to point them out in the model users' guides or peer-reviewed publications. Few authors want to include a list of problem areas because they want to put a positive spin on their models. In my 1992 paper, several technical problems and a few possible solutions were described. The current paper revisits these topics and brings up some new difficult issues.

DISCUSSION OF LIST OF 7 TOPICS FROM 1992 PAPER

1. Mixing depth

Estimation of the mixing depth, z_i, continues to be a problem area, despite advances in the theory and in remote measuring systems. The main reason is that the real atmosphere does not recognize the need to provide the well-defined mixing depth expected by the model. Analyses of lengthy data sets from, for example, tall meteorological towers, remote sounders, and slow rise balloons show that too often (say about ¼ to ½ of the time) the mixing depth is fuzzy or poorly-determined. During the daytime, there is sometimes no clear capping inversion and often there are multiple weak inversions. During the night time, there is ambiguity since the actual mixing depth is defined by the level where the turbulence decreases to some empirical minimum value, and this level might be quite small (less than 10 m) during light winds.

Remote sounders have promise for improving our knowledge of the mixed layer. However they work best when there is a clearly-defined mixed layer at an intermediate level that can be "seen" by the sounder. Most sounders have low limits caused by surface interference and high limits caused by signal attenuation. Also, because many of the sounders automate the mixing depth output, they report a value even though it may be weak or there may be other weak inversions above and below.

With earlier models such as ISC, a plume that has risen to a certain level was either above or below the mixing depth, z_i. If the plume centreline was above z_i, then it did not contribute to ground level concentrations. Current dispersion models, though, allow for partial plume penetration of capping inversions. Thus z_i is a porous lid that allows plume material to pass through it in both directions. But these state-of-the-art models depend on accurate knowledge of the height of the mixing depth and the magnitude and thickness of the capping inversion.

2. Vertical profiles of turbulence

Over 50 years ago, Pasquill, Richardson, Taylor, and other founders of our field stated that it is best to estimate σ_y and σ_z from the turbulent speeds σ_v and σ_w and the turbulent Lagrangian time scales T_{Ly} and T_{Lz}. See topic 7 for a discussion of Lagrangian time scales. Since the turbulence observations were hardly ever available, Pasquill developed an empirical method (known to us as the "Pasquill curves") to estimate σ_y and σ_z from observations of wind speed and parameterizations of stability class, combined with data from extensive field experiments where σ_y and σ_z were observed. Our state-of-the-art short range dispersion models have adopted the original recommendations and use estimates of σ_v and σ_w to calculate dispersion. This has worked out fairly well for convective boundary layers at heights below z_i, where turbulent speeds are well-determined by z_i and w*. But the turbulence-based models have run into problems at the top of the neutral mixed layer, where the turbulent speeds do not drop off as fast as the simplified theory says, and in the stable boundary layer, where profiles of turbulent speeds are often uncertain. In the stable case, the Monin-Obukov similarity theory (MOST) formulas for boundary layer profiles are valid only below about 5L, which can easily be only a few meters (Arya, 2001). Thus the turbulent speeds are indeterminate above 5L (i.e., through most of the range of heights where an industrial plume is located).

In the absence of a good theoretical methodology, operational dispersion models often specify a "minimum σ_v and σ_w" based on field observations. The averaging time for these minimum values is usually one-hour. However, these minimum values often differ quite a bit from model to model. For example, AERMOD assumes a minimum σ_v of 0.2 m/s while SCIPUFF assumes a minimum of 0.5 m/s, and AERMOD assumes a minimum σ_w of 0.02 m/s while SCIPUFF assumes 0.10 m/s. These minimum values will be used during light wind periods and/or at heights near and above the mixing depth.

3. Formation of the nocturnal jet

This issue has been put on the "back-burner" for the past several years. It mainly comes up when discussing mesoscale or long-range transport, which occurs when pollutants in the nocturnal jet layer (about $100 \text{ m} < z < 500 \text{ m}$) can be transported at the nocturnal jet speeds of as high as 20 or 30 m/s, thus moving as much as 72 to 108 km in an hour. Research over the past 20 years has looked at the pulsating nocturnal boundary layer. As stability increases in the evening, the nocturnal jet builds at the top of the inversion. As a result, the wind shear increases and may drop the Richardson number enough that there is enhanced vertical mixing, which can disperse an elevated plume to the ground. Periods of enhanced vertical mixing have been observed at intervals of 2 or 3 hours during stable nights. This effect was empirically included in HPDM in order to fit night-time observations of concentrations during the EPRI Indianapolis field study (Hanna and Chang, 1992). However, in the absence of remote sounders to observe this phenomenon, it is difficult to forecast it directly.

4. Non-steady-state periods

The operational short-range dispersion models still do not directly address the non-steady-state problem, which can cause actual plumes to vary in growth rate and transport speed and direction. This is related to discussions about the downwind distance limits of the hourly-averaged straight line models. That is, the plume can be expected to remain in roughly a straight line for an hour only out to distances of u times 3600 s. For u of 2 m/s, the distance limit is 7.2 km. Many regulatory models (such as AERMOD) allow the straight line assumption to extend out to 50 miles (80 km). We could change the regulatory guidance so that the model can only be used out to a distance of u times 3600 s, but this would result in confusion in interpretation.

Another way around this problem is to adopt Lagrangian puff and particle models instead of straight line models and apply them at all distances and times. The Lagrangian models could make use of time and space varying outputs of mesoscale meteorological models such as WRF or outputs of observation-based mass-consistent wind models such as CALMET. This would require another round of public hearings, plus efforts to make sure the Lagrangian models agree with the straight-line models in the limit of constant winds and stabilities.

5. Surface constants (e.g., albedo, soil moisture and roughness)

Meteorologists have made great progress in this area because of the need for these land-use parameters in climate models. Also, extensive studies of urban areas over the past 15 years have resulted in better methods for estimating roughness lengths and displacement lengths as a function of building mean height, density and frontal areas. However, it is important to transfer this into the default input tables for short-range dispersion models. I notice that, although some dispersion models like SCIPUFF are using the new methods, others are still using numbers for surface roughness, albedo etc. that were in the original documentation from many years ago.

6. Surface energy balance relations

Here too our field has benefited from the many advances made by the climate research community, who recognize that slight changes in, say, the surface sensible or latent heat flux can have a significant effect on estimates of global temperature change. Some of these advances are making their way into the meteorological preprocessors for dispersion models, such as the overwater COARE surface flux methods (Fairall et al., 2003) being incorporated in beta versions of AERMOD, but a more comprehensive effort is needed.

Another example of a problem area is the estimation of surface momentum and sensible heat fluxes as wind speeds drop towards zero, especially during stable conditions. See Topic 8 for more details.

7. Lagrangian time scales

Most short-range dispersion models include explicit or implicit assumptions about Lagrangian time scales for the lateral T_{Ly} and vertical T_{Lz} directions. When the dispersion parameters σ_y and σ_z are calculated, T_{Ly} and T_{Lz} describe how long the linear growth region lasts. Lagrangian particle dispersion models directly use T_{Ly} and T_{Lz} in the basic equation for turbulent motion of the particle. The Briggs formulas, the Draxler formulas, and other operational formulas for σ_y and σ_z contain implicit assumptions about $T_{L.}$ However, Gifford and others showed in the 1990s that lateral dispersion σ_y is maintained at close to a linear relation out to travel times of many hours, because of the presence of mesoscale and regional horizontal eddies. Further difficulties are found in estimating T_L and dispersion very near the ground, since T_{Lz} was assumed to be proportional to height z and therefore approached zero near the ground. AERMOD resolves this by using K-theory for near-ground sources.

QUIC-URB (Brown et al., 2009) avoids the problem of having minimal dispersion near the ground and near building walls by setting a "minimum T_L" proportional to the street canyon width in urban areas, thus maintaining linear growth (which is observed in field studies) in σ_y and σ_z while the plume is in the street canyon.

Some short-range dispersion models used the suggestions by Hanna et al. (1982) for calculating T_{Ly} and T_{Lz}. However, as recently found by the developers of the IIBR Israel Lagrangian particle model (Kaplan and Dinar, 1996), these formulas can sometimes lead to too small T_{Ly} and T_{Lz} at the top of the mixed layer.

It can be concluded that, although much new work has been carried out on how best to parameterize T_{Ly} and T_{Lz} and other turbulence variables in dispersion models (e.g., Wyngaard, 2010), this information needs to be more consistently adopted by the widely-used short-range dispersion models.

DISCUSSION OF NEW ADDITIONS TO LIST

8. Boundary-layer profiling and dispersion in low-wind stable conditions

By definition, as the mean wind speed decreases, the usual governing forces (such as regional pressure gradients) have become weak. The common phrase "light and variable winds" is applicable. Local terrain effects (e.g., downslope winds at night) and thermal effects (e.g., sea and land breezes) can dominate the mean flow.

Operational short-range dispersion models such as AERMOD, OML, SCIPUFF, and ADMS have meteorological preprocessors that are similar. They are based on the assumption that there will be limited availability of observations. In most operational regulatory runs, the only observations available are hourly surface data at a nearby airport and twice-daily upper air soundings at the closest official site. Sometimes prognostic meteorological models can provide inputs. The dispersion models also ask for land use information (they have internal default tables for, e.g., z_o and albedo). The meteorological preprocessors use the above inputs to calculate u* and H_s, using surface energy balance assumptions and MOST. This system breaks down when the wind measurement height is above the stable mixed layer, which is about 2L to 5L. The meteorological preprocessors then use subjective assumptions about u* and the temperature scale θ* and how they vary with wind speed at very low wind speeds (less than about 0.5 or 1 m/s). Thus with very low winds, the boundary layer profile modelling system breaks down and is replaced by some empirical relations. The intent is to have the dispersion model agree with the meagre available tracer observations during low-wind stable conditions. Recent studies suggest that u* and minimum σ_v could be increased, but much more study is needed.

Since the stable mixed layer may be only 5 or 10 m deep, the standard MOST profile formulas do not apply above that height. Yet the dispersion models require knowledge of profiles at plume heights of 20, 50, and 100 m or more. This is one of the major current challenges.

9. How to handle steep terrain, building obstacles, and variations in land-use
Much progress has been made since HARMO1 in the ability of some short-term dispersion models to account for the presence of obstacles such as terrain and buildings. For example, ADMS can use FLOWSTAR to simulate the flow around specific terrain obstacles, SCIPUFF allows input of detailed 3-D building geometry in an urban neighbourhood, and AERMOD uses the PRIME building downwash algorithms. However there is often a delay in the transfer of research results to operational models used for regulatory purposes. This is sometimes caused by a decrease in robustness discovered when new technology is tested. When running the model for five years of hourly data, sometimes the new model may give an unrealistic result during a few of the hours. This is one reason why detailed variations in land use across the domain are not included in operational models, even though we have developed research-grade models for how internal boundary layers develop.

Another example of a theoretical advance with robustness problems is the module that can estimate interactions of elevated plumes with the Thermal Internal Boundary Layer (TIBL), which forms on summer days in coastal areas with onshore flow. The plume from a coastal power plant may intercept the TIBL and be fumigated downwards, with resulting excessively high concentrations simulated by the model due to the relatively low TIBL height.

10. Has new technology helped (e.g., CFD models, faster computers, links between meteorological and dispersion models, using 3-D regional models at ever-shrinking scales)?
Since the time of HARMO1 in 1992, computer speed and storage have increased by many orders of magnitude. Have the accuracies and capabilities of short-range dispersion models increased that much? Not quite. Perhaps we can say that accuracies have improved by a factor of two and this applies to a wider range of scenarios than in 1992. We are now able to complete five years of hourly AERMOD runs on a PC in a few minutes for simple scenarios. We can now run CALPUFF for hourly emissions over a year in less than a day. We can now run prognostic meteorological models (MM5 or WRF) for a few days and use the outputs as inputs to AERMOD or similar models.

In principle, we might expect Computational Fluid Dynamics (CFD) models to perform better than models such as AERMOD, ADMS, or OML. However, this too has not resulted in statistically-significant improvements when compared with observations. Part of the reason for the lack of improvement is the natural variability of the atmosphere. Often CFD models are marketed as being "very accurate". I usually respond that they are very precise, but are not necessarily very accurate. Also, CFD models are currently limited to a few runs because of the large amounts of storage computer time needed. This has led to some modelers to creative methods such as "prerunning" the wind fields for a set of expected scenarios (as done by Patnaik and Boris (2010) with their FAST3D-CT model), or to simplifying the solution methods (as done by Gexcon with their FLACS model, see Hanna et al. 2004). Still others have developed diagnostic mass consistent wind field models for complex scenarios (such as a set of buildings in an urban domain) and then apply Lagrangian particle models. The most widely-used examples of this type are described by Kaplan and Dinar (1996) and Brown et al. (2009). The resulting outputs "look" like CFD outputs and are often mistaken as such.

Research versions of WRF have been developed that can be run at small grid size (1 m) and can simulate flows near vertical cliffs and around 3-D buildings (Lundquist et al., 2012). Probably in ten or twenty years, models like this version of WRF will be run routinely in a few minutes on a smart-phone.

11. How to handle dense plumes, aerosols and in-plume chemical reactions in short-range dispersion models
The short-range models available in 1992 were generally best for inert neutral or positively-buoyant pollutants or for chemicals with slow linear chemistry (such as for SO_2 in the near field). Interest in dense gases has grown since HARMO1 due to some high-profile chemical accidents and the threat of terrorist attacks on chemical facilities. Advances in models for chemical reactions in plumes and in formation of $PM_{2.5}$ have also occurred recently, mostly due to more stringent regulations on $PM_{2.5}$ and its components (e.g., nitrates and sulphates), O_3, SO_2, and NO_2. The latter topic is important not only for modelling industrial plumes, but also for modelling the dispersion of emissions from traffic and other low-level sources.

Several good dense gas dispersions models have been developed and evaluated in the past 20 years, but have not been widely incorporated in the short-term regulatory models because the dense gas issues are mostly related to emergency response rather than to regulations. A major need is for improved emissions estimates for various hazardous release scenarios. None of the widely-used dense gas models can address complex terrain, although research-grade CFD models can include a wide range of terrain types.

In most countries, the development of short-range dispersion models and regional dispersion models are on separate tracks. In the US, the bulk of current dispersion model research concerns regional models, including comprehensive sets of chemical reactions (some non-linear). The short-range models such as AERMOD include only rudimentary linear reactions for SO_2 and NOx. But for some applications, a "plume-in-grid" model is needed within the regional grid model to simulate the small-scale plume dispersion and chemical reactions, until the plume is "handed over" to the regional model when the plume size approaches the grid size. In the US, the SCICHEM model (a version of SCIPUFF with non-linear plume chemistry) is being considered for this purpose. However, as pointed out earlier, as the grid sizes of the regional models steadily decrease due to improvements in computer technology, the grid models may eventually "take over" the short-range dispersion.

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