Dispersion Models

ATM 515: Earth Systems

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Dispersion models have been created for a number of uses ranging from research on pollution and air chemistry to creating information for emergency responses. They come in a wide range of complexities from simple parameterizations plugged into other models to stand-alone high-resolution gridded models. They all share the goal of showing how the concentration of airborne material becomes diluted over time. In this paper I will cover the reasons why we have dispersion models, I'll give a description of the process being modeled, I'll go over the various types of dispersion models, and I'll explain some of the benefits and drawbacks of various models. At the end I will give specific examples of dispersion models.

Uses of Dispersion Models

One of the more widely known uses of dispersion models is the monitoring of pollution levels to assess compliance with pollution regulations. This is partly because a model must be thoroughly studied with a number of case studies before it will be considered for regulatory decisions. The models used can be complicated as decisions on regulations don't require rapid solutions. They do require accurate solutions though since some emissions are only permitted in small concentrations. The goal of a model being used for pollution modeling is to make sure that the concentration of a pollutant doesn't exceed the limits set by regulations. The models currently recommended by the Environmental Protection Agency are AERMOD and CALPUFF, but they also accept BLP, CALINE3, CAL3QHC, CTDMPLUS, and OCD (EPA, 2007).

Another use of dispersion models is creating information for responses to hazardous releases. This is similar to pollution modeling, except the event is unplanned and the model must provide output quickly. The model output is needed to determine what concentrations people have been exposed to and what areas need to be evacuated. The models can also be adapted to account for special conditions that occur with the hazards such as dense gasses or confined spaces. One example of such a hazard that can prove especially dangerous is a tunnel fire. The model for smoke from a tunnel fire is a dispersion model that is enclosed on the sides (Neophytou and Brittier, 2005). In such a case the smoke plume can only disperse in one direction.

Some models include components that use dispersion to move material in the model. Air chemistry models can use dispersion to move chemicals around as they react with each other. Models studying plumes with particulate matter in them such as smoke or tephra plumes also use dispersion models. The dispersion models account for the spread of the material while it is suspended and the material is removed with time based on its size (Byrne, Laing, and Connor, 2006). This allows predictions of exposure to particulate matter or accumulation of material on the ground.

The Dispersion Process

Dispersion is the process by which a volume of air containing a material becomes diluted with the surrounding air. At its simplest, dispersion is an action of turbulence mixing the air. In the atmosphere the motions are random, but they have a tendency to occur at certain rates in certain directions (UCAR, 2002). The primary control in the rate of dispersion is the amount of turbulence. Other factors include wind speed and stability. When discussing dispersion, the volume being diluted usually takes the form of a plume or puff, such as the emissions from a smoke stack.

The more turbulent the atmosphere is the faster a plume can be diluted. There are three types of turbulence that can affect dispersion. These include mechanical turbulence caused by friction with surfaces such as the ground, shear turbulence caused by differences in wind speed and direction, and buoyancy turbulence caused by explosions or heated air rising (UCAR, 2002). Turbulence only acts to dilute a volume of air, it doesn't cause it to become more concentrated. This means that the concentration of a pollutant in a dispersion model won't increase if there is only one source, multiple sources are needed to increase concentrations.

Wind has a couple of effects on dispersion other then generating turbulence. For starters, it controls the direction a plume will travel. Variable winds can cause a plume to spread out widely in the horizontal. A strong wind will also keep a plume near the ground since it mixes the ambient air into it quickly enough to reduce the buoyancy (UCAR, 2002). In the case of dense gasses though, wind doesn't have much of an effect and the gas flows downhill regardless of wind direction. Most dispersion models assume that the wind is uniform throughout the region and thus they don't handle complex wind scenarios such as different wind directions at different levels.

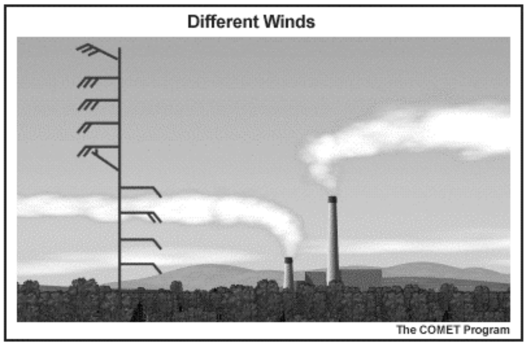
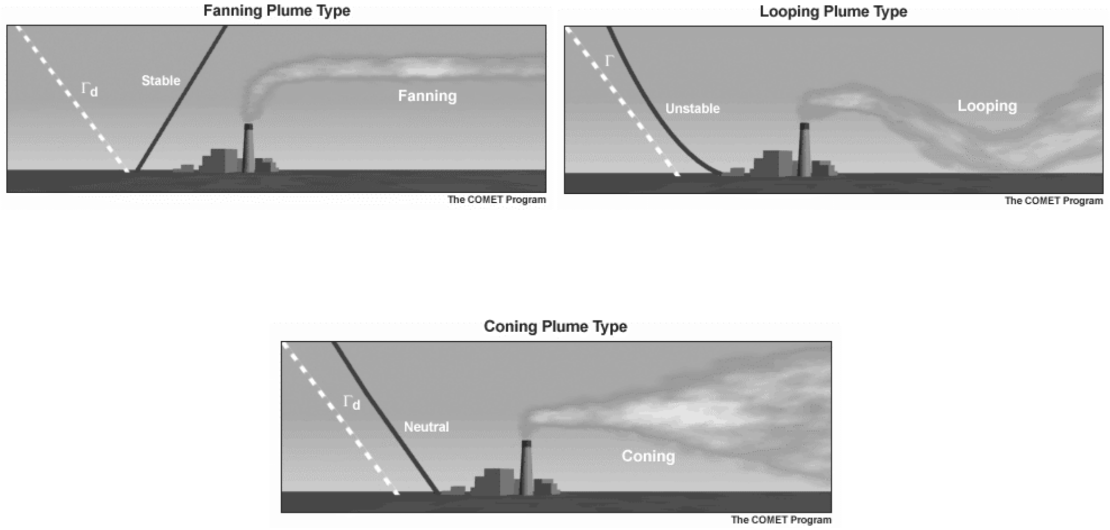


Figure 1 Impact of changing wind direction with height (UCAR, 2002).

Stability affects how turbulence spreads a plume out in the vertical. In stable conditions the plume tends to have little vertical motion and it remains confined to a narrow area. In unstable conditions the plume rises and falls quickly causing it to extend over a wide area. In neutral conditions the plume spreads out gradually the same way it does horizontally. The effects of stability are often approximated using available meteorological conditions and looking up the stability class from a table. (See Table 1) Some models will create their own stability approximations as part of their calculations.



Fanning Plume Type

Looping Plume Type

Coning Plume Type

The COMET Program

Figure 2 Primary stability types: Stable, Unstable, and Neutral (UCAR, 2002).

One process often found in dispersion models is plume rise. While technically not a factor in dispersion, it does impact the height at which a plume is dispersing at. The dispersion itself is not affected by the plume rise. When a plume is first emitted into the ambient air it normally has buoyancy and initial speed factors that drive the plume upward before it attains the same buoyancy as the surrounding air. This can have an impact on concentrations seen at ground level.

$$\text{Plume Rise} \cong \frac{\text{Ejection Velocity, Plume Buoyancy}}{\underset{(u) \qquad\quad \partial\theta/\partial z}{\text{Wind Speed, Stability}}}$$

Equation 1 Plume rise (UCAR, 2002).

Types of Dispersion Models

The box model is one of the simpler types of dispersion modals. It is a simple grid cell that has all of the pollutants put into it. The pollutants are instantly distributed evenly throughout the cell (Ministry for the Environment, 2004). This makes it usable only in certain situations that involve small areas and simple, dispersed sources. When it can be used, the simplicity means that the calculations are quickly and easily calculated.

The Gaussian model is one of the more widely used dispersion models (UCAR, 2002). It takes advantage of the fact that dispersion is a random process that tends to occur in certain directions at certain rates. This causes the concentration of pollutants in a plume to assume a Gaussian distribution. This can be easily calculated with an equation that adds the factors that account for the rate the plume disperses in each direction. The equation can also be further modified to account for other effects such as reflection from the ground and plume rise. Gaussian models are steady-state so they don't represent a single moment in time but the result over the entire time the plume is formed (Ministry for the Environment, 2004). This means they can't tell you anything about the timing involved with seeing pollution concentrations at a given point. The meteorological conditions are the same throughout the modal so you can't modal plumes in complex or changing conditions. A primary reason for the wide use of Gaussian models is the ease in which they can be used. The calculations are simple and are easily performed by programs or even solved in spreadsheets. It takes little training to learn how to use a Gaussian model.

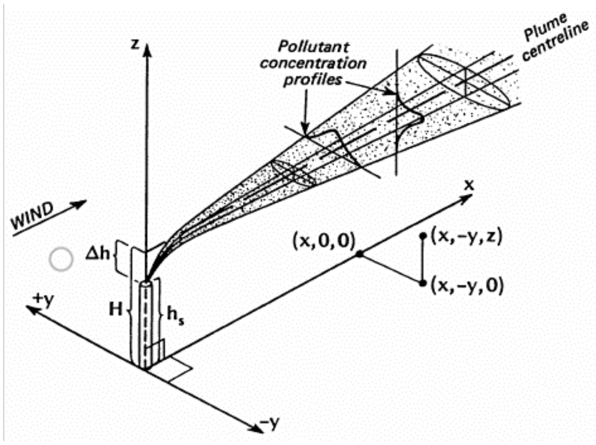


Figure 3 Typical Gaussian plume model (Ministry of the Environment, 2004).

$$C = \frac{Q}{2\pi\sigma_y\sigma_z u}\ \exp\left[\frac{-y^2}{2\sigma_y^2}\right]\left[\exp\left\{\frac{-(Z-H)^2}{2\sigma_z^2}\right\} + \exp\left\{\frac{-(Z+H)^2}{2\sigma_z^2}\right\}\right]$$

Equation 2 Gaussian model concentration (UCAR, 2002).

Puff models are used for cases when a gas is released in one burst. The dispersion is calculated with respect to the puff instead of the surroundings, making puff models Lagrangian models. The dispersion in a puff model tends to be independent of the wind and more a function of turbulent eddies. If an eddy is smaller than the puff it will act to disperse the puff, but larger eddies just move the puff through (UCAR, 2002). Puff models can provide better results then Gaussian models in conditions of low winds, and they are still relatively cheap for computations.

A better picture of the meteorological conditions is needed to run puff models though so more data is required to start them.

$$C = \left[\frac{Qp}{(2\pi)^{3/2}\sigma^3}\right] \exp\left[\frac{-r^2}{2\sigma^2}\right] \quad r = \text{radius of puff}$$

Equation 3 Puff model concentration (UCAR, 2002).

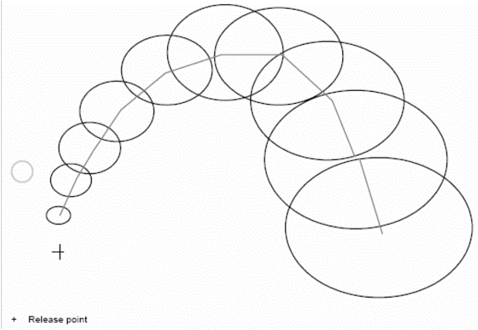


Figure 4 Concept of a puff model. Cross is the release point (Ministry of the Environment, 2004).

Gradient transport models calculate the concentrations of a plume as it changes with time. The dispersion rate depends on the gradient of the concentration and the eddy diffusivity (UCAR, 2002). If the gradient of the concentration is steeper then it is going to disperse faster. The fact that you are calculating the change in concentration over time means you can associate timings with the dispersion of a plume. Further more, a gradient transport model is calculated on a grid so you can account for more complex weather and terrain. This of course comes at a cost. Gradient transport models require a good deal more in the way of computing resources and they are harder to use. They require more configuration than the other models and generally don’t come packaged in graphical interfaces. They can be used with other models though allowing more detailed studies to be conducted.

$$\frac{\partial C}{\partial t} = \frac{K_x \partial^2 C}{\partial x^2} + \frac{K_y \partial^2 C}{\partial y^2} + \frac{K_z \partial^2 C}{\partial z^2}$$

Equation 4 Gradient transport model concentration (UCAR, 2002).

Dispersion Models

In this section I will give specific examples of various dispersion models. I’ll discuss what kind of models they are and how they fit in with the previous model types. I will also, where possible, mention some of the features that stand out in the models. I’ll start with the EPA recommended models and finish with a set of models that haven’t been accepted by the EPA.

AERMOD – The AERMOD model was developed by the American Meteorological Society and the Environmental Protection Agency to replace the ISC3 model. It is a steady-state plume model. In stable conditions it is completely Gaussian and in unstable conditions it is Gaussian in the horizontal and bi-Gaussian in the vertical. The model can allow the plume to contact the ground or follow the terrain. One aspect of the model that sets it apart from other Gaussian models is its attempt to account for changes in meteorology with height. It does this by combining the varying conditions into an average which it then uses for the calculations. AERMOD is designed to run with minimal meteorology input and often only needs the surface temperature, surface wind speed and direction, and cloud cover. (Cimorelli et al., 2004)

CALPUFF – The CALPUFF model was developed by the Atmospheric Studies Group. It is a non-steady-state puff model. The model is intended to be used in cases where the weather is complex or the plume travels farther then 50km. It also allows resolving the timing of concentrations in the model. CALPUFF comes with its own 3D meteorological model called CALMET, but it can also use standalone meteorological models. Each of the programs in the CALPUFF modeling system comes with a graphical user interface. (Atmospheric Studies Group, 2007)

BLP – The BLP model was developed by Environmental Research & Technology, Inc. for the purpose of modeling plumes from aluminum reduction plants. It is a Gaussian plume model that is designed to use multiple point and line sources. It is intended to be used in flat terrain and for short distances. It uses pollutant decay to remove pollutants with time by removing the pollutants as they reach a certain distance from the source, based on a constant wind speed. (Schulman and Scire, 1980)

CALINE3 – The CALINE3 model was developed by the California Department of Transportation. It is a Gaussian model designed to use line sources. The purpose of the model is to model inert pollutants coming from roadway traffic. The model works up to a distance of 150 meters. It can only handle uncomplicated terrain. The model is supposed to be fairly simple to set up and only requires a minimal meteorology dataset and information about the site such as shape. (Benson, 1979)

CAL3QHC/CAL3QHCR – These two models are an update to the CALINE3 model. Since they are based on the CALINE3 model they are still Gaussian models. They add effects caused by traffic patterns that occur at intersections with signals. The specific purpose of these two models is modeling carbon monoxide. The CAL3QHCR model is a refined version that requires local meteorology data. (EPA, 2007)

CTDMPLUS – CTDMPLUS stands for Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations. It was developed under the Environmental Protection Agency. As the name implies it is meant to model dispersion in complex terrain no matter what the stability is. It is still a point source Gaussian dispersion model though. The model contains parameterized hill shapes to determine the effect of terrain on the plume. These hills don't affect the wind patterns, which remain uniform through the model, so once a plume is past a hill it no longer is affected by it. Since the model is trying to account for the effects of complex terrain the configuration and input data for both terrain and meteorology is highly detailed. (Perry et al., 1989)

OCD – The Offshore and Coastal Dispersion model was developed by the Minerals Management Service. It is a Gaussian model that can use points, lines, or areas for sources. It was developed specifically to handle the effects on a plume as it moves from open water to the coast. As such it has the ability to model plumes over water. The model runs on hourly intervals and requires hourly meteorology data from both onshore and offshore stations. (DiCristofaro and Hanna, 1989)

That is the end of the EPA accepted models. As you can see the majority of them were Gaussian type models. Some of the models are also kind of old and were developed during the period when research was being conducted on dispersion. You can expect some of these models to be replaced or new ones added to the list as newer models go through the review process. The following models will provide examples of the other types of models and dispersion models that have unique features.

ADMS-3 – ADMS-3 was developed by the Cambridge Environmental Research Consultants. It is a gradient transport model. It uses a parameterization of the boundary layer instead of using stability categories to describe the vertical environment. It is capable of handling complex situations as well as situations requiring shorter time scales around 15 minutes. The model has a range of 60km. The model also handles more advanced features such as chemistry and plume visibility. (Cambridge Environmental Research Consultants, 2004)

HOTMAC/RAPTAD – HOTMAC is a 3D meteorological model that works with RAPTAD. They were developed by the Yamada Science & Art Corporation. RAPTAD is a puff model. It is primarily designed for smaller scale features that are too complex for normal dispersion models. This means it requires detailed input from a larger-scale meteorology model. While the input can be complicated, the company wants to make money off of their model so they have created a graphical user interface to use with the model. (Yamada Science & Art, 2005)

HYROAD – HYROAD was developed as part of the National Cooperative Highway Research Program. The purpose of the model was to study carbon monoxide emissions occurring at street intersections. It is actually a collection of modular models, each designed to handle a different portion of the emissions problem. The section that handles the dispersion is a puff model. The wind and stability fields are gridded instead of being uniform across the domain. HYROAD can describe concentrations up to 500 meters from the source. (Carr, Johnson, and Ireson, 2002)

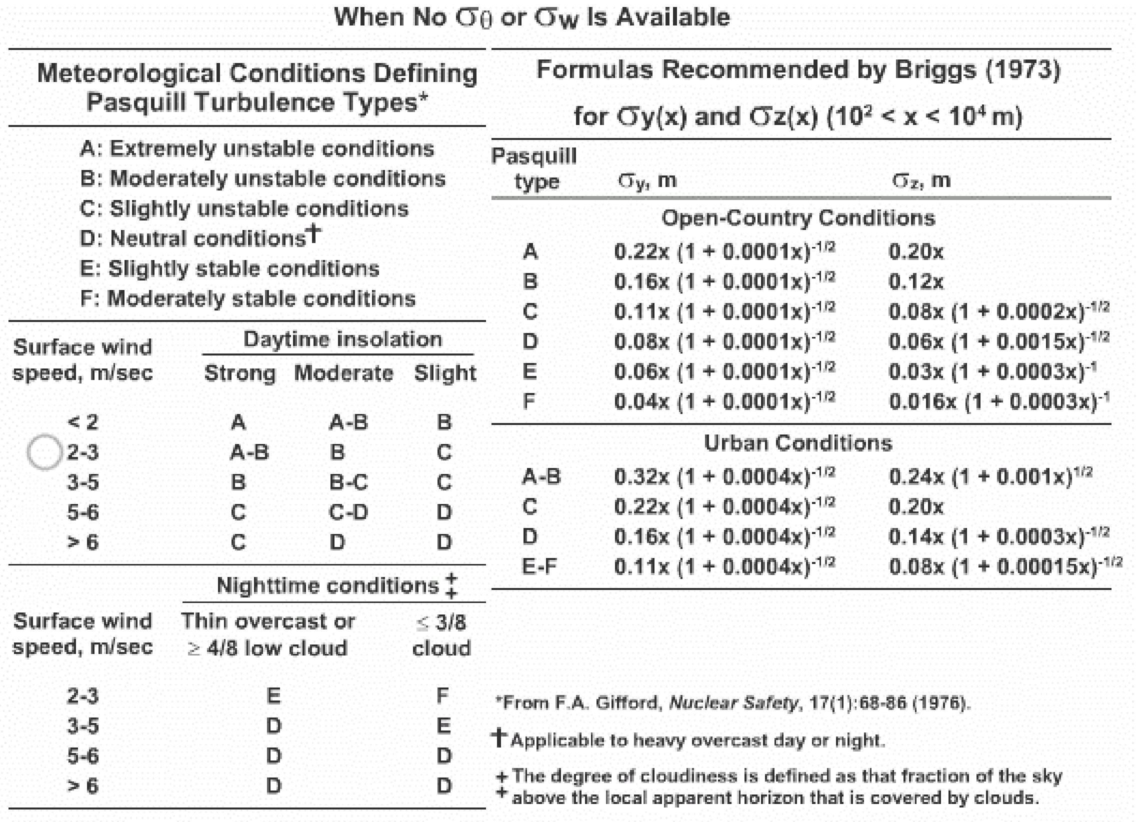
OZIPR – OZIPR was developed by Atmospheric Research Associates, Inc. It is a 1D box model. They created it to study the photochemical reactions that take place in a pollutant plume. The model works by moving a fixed box along a trajectory. Pollutants enter the box as it moves over emission sources. The model is run by calling the input file from a command line. Other then the results of chemical reactions taking place in a plume, this model doesn't give you much more in the way of information. (Gery and Crouse, 2005)

Panache – Panache was developed by fluidyn. It is a hybrid model that uses puff, Gaussian, and gradient transport models. It can run in both simple and complex terrain. It is another set of models working together, which is how it uses a number of dispersion types. Since it is another model for sale it comes with a graphical user interface. It is a highly complex model that requires numerous input datasets. (Fluidyn, 2003)

SCIPUFF – SCIPUFF is a puff model that uses a collection of puffs to represent an entire plume. It was developed by the Titan Corporation. The puffs are kept track of using an adaptive grid and overlapping puffs are merged together. The model will work with a variety of complexities allowing different aspects of the modeled to be scaled back when detailed data isn't required. The model is configured using a graphical user interface. SCIPUFF will even provide an estimate of the uncertainty for the predicted concentrations. (L3 Communications Titan Group, 2006)

There are many more dispersion models than the ones listed here. Many of them have been created for very specific cases. The models can become more complex as available computer resources grow. You will always see the less complex models though for situations that require a quick and simple solution. While a number of ways for solving for the dispersion of a plume have been created, there will never be a single model to do everything. When modeling a case you must choose the model that was designed for the situation being modeled and take into account the limitations of that model.

Table 1 Stability lookup table for Gaussian models (UCAR, 2002).



When No σ_θ or σ_W Is Available

Meteorological Conditions Defining Pasquill Turbulence Types*

A: Extremely unstable conditions
B: Moderately unstable conditions
C: Slightly unstable conditions
D: Neutral conditions†
E: Slightly stable conditions
F: Moderately stable conditions

Surface wind speed, m/sec	Daytime insolation		
	Strong	Moderate	Slight
< 2	A	A-B	B
2-3	A-B	B	C
3-5	B	B-C	C
5-6	C	C-D	D
> 6	C	D	D

Surface wind speed, m/sec	Nighttime conditions ‡	
	Thin overcast or ≥ 4/8 low cloud	≤ 3/8 cloud
2-3	E	F
3-5	D	E
5-6	D	D
> 6	D	D

Formulas Recommended by Briggs (1973) for $\sigma y(x)$ and $\sigma z(x)$ ($10^2 < x < 10^4$ m)

Pasquill type	σ_y, m	σ_z, m
Open-Country Conditions		
A	$0.22x\,(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x\,(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x\,(1 + 0.0001x)^{-1/2}$	$0.08x\,(1 + 0.0002x)^{-1/2}$
D	$0.08x\,(1 + 0.0001x)^{-1/2}$	$0.06x\,(1 + 0.0015x)^{-1/2}$
E	$0.06x\,(1 + 0.0001x)^{-1/2}$	$0.03x\,(1 + 0.0003x)^{-1}$
F	$0.04x\,(1 + 0.0001x)^{-1/2}$	$0.016x\,(1 + 0.0003x)^{-1}$
Urban Conditions		
A-B	$0.32x\,(1 + 0.0004x)^{-1/2}$	$0.24x\,(1 + 0.001x)^{1/2}$
C	$0.22x\,(1 + 0.0004x)^{-1/2}$	$0.20x$
D	$0.16x\,(1 + 0.0004x)^{-1/2}$	$0.14x\,(1 + 0.0003x)^{-1/2}$
E-F	$0.11x\,(1 + 0.0004x)^{-1/2}$	$0.08x\,(1 + 0.00015x)^{-1/2}$

*From F.A. Gifford, *Nuclear Safety*, 17(1):68-86 (1976).

†Applicable to heavy overcast day or night.

‡The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

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