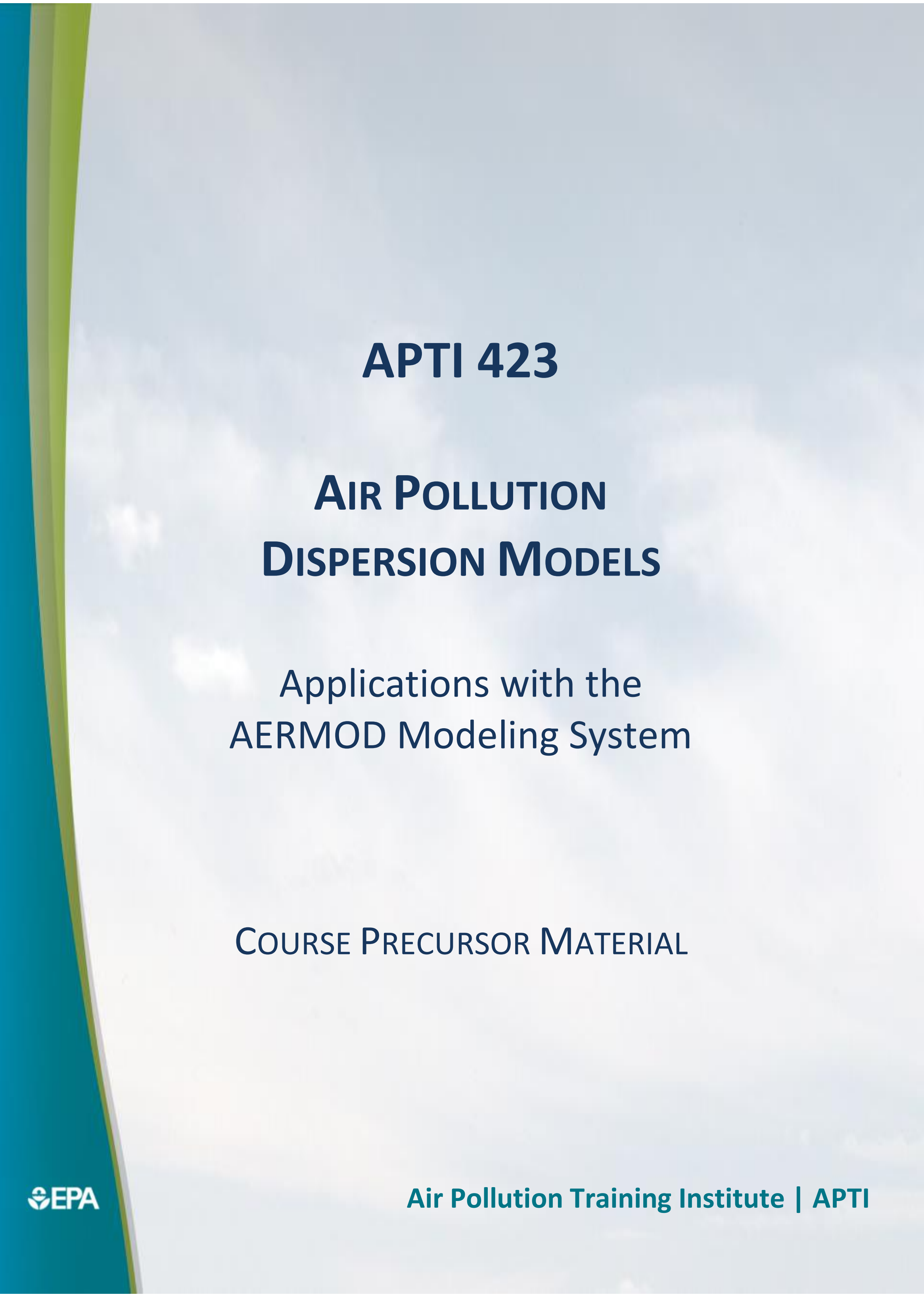

APTI 423

AIR POLLUTION DISPERSION MODELS

Applications with the AERMOD Modeling System

COURSE PRECURSOR MATERIAL

Air Pollution Training Institute | APTI

WELCOME AND INTRODUCTION

Welcome to APTI 423, "Air Pollution Dispersion Models: Applications with the AERMOD Modeling System!" Although APTI 423 is intended to be conducted by an instructor in a classroom, the COVID pandemic requires that this course be conducted through distance learning. Thus, the course content will not be delivered face-to-face by an instructor. Rather, the instructor will be presenting the material as a webinar. Although this will not allow for the type of interaction that is optimal for a course of this type, efforts have been made to minimize the issues that invariably arise from a hands-on course that requires considerable execution of many computer programs. This document contains precursor material and should be reviewed prior to the beginning of the course. The content provided herein is a refresher on the basic principles of dispersion in the atmosphere and an overview of the AERMOD modeling system. It is not intended to be a comprehensive study of these topics, but rather, a brief review to help prepare participants for the content that will be presented in the course. A second course is being developed that will provide a comprehensive study of the physics behind the AERMOD modeling system as well as sensitivity analyses of various parameters, and an in-depth analysis of model results. Please take time to review the content presented herein prior to attending.

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CHAPTER 1: DISPERSION BASICS

DEFINITION OF ATMOSPHERIC BOUNDARY LAYER (ABL)

As the wind blows across the surface of the earth, interaction with the earth's surface has a direct effect on the air flow immediately above it. The earth's topography and land cover are obstructions that exert a frictional force on the air flow. The resulting drag on the air flow creates turbulence. Physical processes such as solar heating of the ground and evapotranspiration are sources of heat and moisture which lead to convection and instability in the daytime atmosphere. Thermal convection from heat exchange at the earth's surface is also a source of atmospheric turbulence.

The effects of these surface forcing effects on air flow are greatest nearer to the earth's surface and decrease with height until the effects are nominal or nonexistent. Wind speed tends to increase with height as these effects on air flow decrease. The layer of the atmosphere affected by this interaction with earth's surface is called the atmospheric boundary layer (ABL), also commonly known as the planetary boundary layer (PBL). The region above the ABL where the impact of these surface forcing effects are negligible is known as the free atmosphere.

It is in the ABL that the dispersion of pollutants takes place due to the mixing of the air from turbulent motion. In the sections that follow, several concepts that are required to understand the structure of the ABL and the process of dispersion are presented. These include the surface energy balance, atmospheric stability, turbulence, and mixing.

SURFACE ENERGY BALANCE

Solar radiation provides the energy to generate both the large-scale winds as well as the turbulence in the atmospheric boundary layer. The flux of radiant solar energy entering the earth's atmosphere at any point in time is approximately 1350 Watts per square meter (W/m^2). Atmospheric gases in the upper atmosphere absorb about 3% of the total solar energy. A further 17% is absorbed by water vapor and scattered by particles in the atmosphere, so that about 80% of the radiation incident on the earth's atmosphere reaches the earth's surface. This situation is altered considerably in the presence of clouds, which can scatter most of the energy from solar radiation that enters the atmosphere. Part of this scattered energy goes back into space, while the rest is directed towards the earth.

At the interface between the soil and the atmosphere there is a balance between the incoming and outgoing fluxes of energy. As shown in Figure 1, a portion of the solar radiation reaching the ground is reflected, and part of it is absorbed. The absorbed solar radiation is converted into other forms through an energy balance at the ground. Notice that the radiative input to the surface has been separated into incoming solar and incoming thermal radiation. Solar radiation refers to the radiation from the sun and thermal radiation refers to energy emitted at temperatures typical of the earth's surface. The incoming solar radiation, which is predominantly short-wave, interacts with the atmosphere in a variety of ways. A portion (≈30%) is reflected back into space, while ≈23% is absorbed and reemitted by atmospheric gases such as water vapor and carbon dioxide. The remaining ≈47% of the incoming solar radiation is absorbed by the earth. The earth's surface and the atmospheric gases reradiate most of this energy as long-wave thermal radiation.

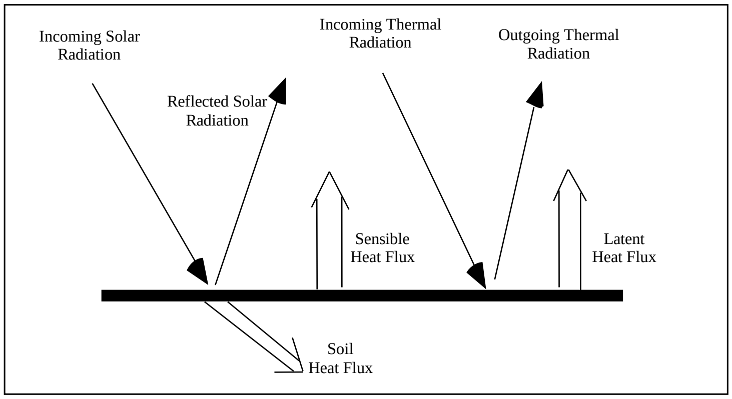

Figure 1. Components of energy fluxes at the ground-air interface.

During the daytime, the largest incoming stream is the short wave, or solar, radiation from the sun. This incoming solar radiation depends on the time of year and day, and the cloud cover. As noted above, part of the solar radiation that reaches the ground is reflected back to the atmosphere. The fraction of the incoming radiation that is reflected by the ground is referred to as the *albedo*, a concept that will be discussed during the course.

The ground emits long wave thermal radiation which depends on the temperature of the ground. The atmosphere also emits thermal radiation, only a fraction of which reaches the ground. The incoming thermal radiation depends on the effective temperature of the atmosphere, which is generally less than that of the ground. This implies the outgoing thermal radiation is larger than the incoming atmospheric thermal radiation. Clouds, especially at lower heights, have temperatures that are greater than the effective atmospheric temperature (the environment outside the clouds), increasing the downward thermal radiation by emitting radiation at a higher temperature than the effective atmosphere. The deficit between outgoing and incoming thermal radiation is largest under clear skies, and smallest under cloudy skies.

The radiative energy flux reaching the ground is balanced by three components: 1) heat transfer into or from the boundary layer, 2) energy transfer to evaporate water at the surface, and 3) heat transfer from or into the soil. The first component is called *sensible heat flux*, and the second is referred to as *latent heat flux*. The ratio of the sensible to latent heat flux is called the *Bowen ratio*, another concept that will be discussed during the course. The third component is referred to as the *soil heat flux*.

The sensible heat flux (*H*) is the energy flux between the atmosphere and the ground due to temperature differences between the atmosphere and the ground. During the daytime, energy flows away from the ground into the atmospheric boundary layer when the ground is typically warmer than the atmosphere immediately above it. During the night, when the ground is cooling, the boundary layer supplies energy to the ground.

The latent heat flux (*L*) refers to the energy used to evaporate moisture from the surface. The soil heat flux (*G*) refers to the energy that is supplied to the ground, and which ultimately determines the temperature of the soil layer.

The energy flux balance at the interface between the atmospheric boundary layer and the soil can be written as:

$$S(1-\alpha)-(T_o-T_i)=R_N=H+L+G \qquad \text{Eqn. 1}$$

where: S is the incoming solar radiation, T_i is the incoming thermal radiation, and T_o is the outgoing thermal radiation. In the equation, α is the surface albedo (the fraction of the incoming flux reflected by the ground) and $(1-\alpha)$ is the fraction of the solar radiation that is absorbed by the ground. AERMET, the meteorological preprocessor for AERMOD, requires an estimate of the noon-time albedo and adjusts it according to time of day and latitude. By definition, the net radiation, R_N, is the difference between the solar radiation absorbed at the surface ($S(1 - \alpha)$) and the net thermal radiation emitted by the surface ($T_o - T_i$) and is also equal to the sum of the sensible, latent, and soil fluxes.

HEAT FLUXES

The sensible heat flux, *H*, plays a major role in the production and destruction of turbulence. It determines the level of turbulence both during the day and the night and governs the evolution of the daytime atmospheric boundary layer. *H* is estimated using the surface energy balance discussed above.

Sensible heat is transferred from the ground to the boundary layer when parcels of air next to the heated ground acquire higher temperatures than the surrounding air. As they are heated, they expand and become buoyant, inducing vertical motion and pressure differences that produce turbulent motion in all three directions. These rising parcels transfer their energy to their surroundings, and are thus responsible for transfer of heat from the heated ground to the boundary layer above during the daytime.

During the day, *H* is usually greater than zero, meaning heat is supplied to the atmosphere from the earth’s surface. During the night, *H* is usually less than zero, meaning heat is drawn to the earth’s surface from the atmosphere above and the ground below as R_N becomes negative and the earth’s surface starts to cool. The cooling can be inhibited in the presence of clouds which radiate energy towards the ground.

Latent heating (L) is associated with the energy carried away by water vapor when moisture at the ground is first converted into water vapor and then transferred to the dryer boundary layer.

When the ground is moist, much of the incoming radiation is used in the evaporation of the moisture (i.e., latent heat). The Bowen ratio is the ratio of sensible heat to latent heat which gives an indication of how much of the available energy is transferred as latent heat. During the daytime, in a dry environment in which there is little moisture to evaporate, the Bowen ratio is a value greater than one ($H > L$), and most of the energy is sensible heat. Conversely, in a very moist environment, the Bowen ratio may be less than one ($H < L$) meaning that more energy is transferred as latent heat than sensible heat.

The last component of the energy balance, the soil heat transfer (*G*), is associated with conduction through the soil in response to temperature gradients in the soil. This value is generally small compared to the net radiation, often simplified to 0.1*R_N, as in AERMET.

STABILITY

A *parcel* of air is a theoretical, relatively well-defined volume of air (a constant number of molecules) that acts as a whole such that the properties of the parcel are uniform throughout. Self-contained, it does not readily mix with the surrounding air. The exchange of heat between the parcel and its surroundings is minimal, and the temperature within the parcel is generally uniform. The air inside a balloon is an analogy for an air parcel.

The degree of stability of the atmosphere is determined by the temperature difference between an air parcel and the surrounding air. This difference can cause the parcel to move vertically (i.e., rise or fall). This movement is characterized by four basic conditions that describe the general stability of the atmosphere.

In **stable** conditions, vertical movement is inhibited. When a parcel is displaced vertically from its original position, it tends to return to the original position. During the daytime, the temperature of the air just above the earth's surface tends to decrease with height. During the night, when the heat flux is negative, the temperature of the air just above the earth's surface typically tends to increase with height (inversion). When conditions are extremely stable, cooler air is trapped by a layer of warmer air above it. This condition, called an **inversion**, allows virtually no vertical air motion. Inversions can be surface based or elevated.

In **unstable** conditions, when an air parcel is displaced vertically, it tends to continue moving in the direction of the displacement. In other words, a parcel that is displaced upward will continue rising.

When conditions neither encourage nor discourage air movement beyond the rate of adiabatic heating or cooling, conditions are considered **neutral**, a very transient atmospheric state.

Figure 2 shows the stable and unstable states. The x-axis is potential temperature (defined as the temperature that a parcel of air would have if it were moved adiabatically to a height that corresponds to 1000 mb of pressure) and the y-axis is height. The solid, red, angled lines in Figure 2 represent the profile of the environment's potential temperature while the shaded circles represent an air parcel whose stability is being examined. The dashed blue line represents the parcel's potential temperature which is constant with height if the parcel is displaced vertically and the motion is assumed to be adiabatic (i.e., no heat is exchanged between the parcel and the environment). Consider the chart on the right in which the environment's potential temperature decreases with height. If the air parcel is moved upward, the temperature of the air parcel will be warmer than the temperature of the environment at the same height. A parcel that is warmer than the surrounding environment is less dense and positively buoyant and will tend to keep moving upward. This represents an unstable condition. Conversely, the temperature of the parcel in the chart on the left will be colder and denser than the environment when it is moved upward. Because of the lack of buoyancy of the parcel, it will want to return to its original place of equilibrium with the environmental air.

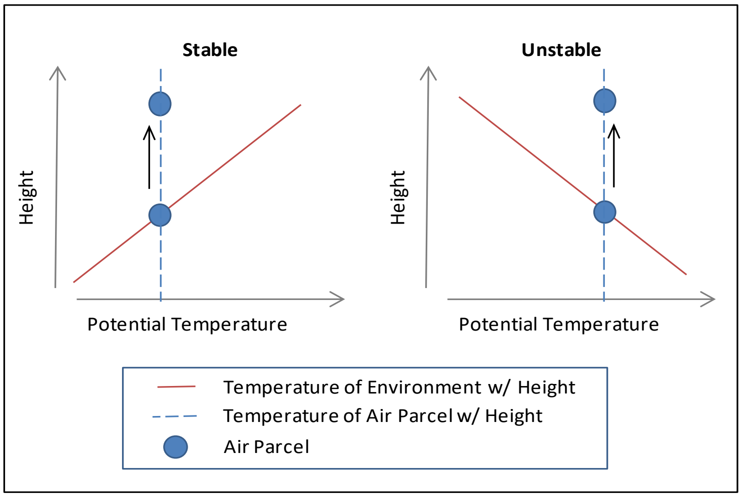

Figure 2. Stability of an air parcel.

TURBULENCE

The concept of turbulence is familiar to most of us. We think of turbulence as irregular, chaotic, and random motions. Because of its random nature, discussions of turbulence in the literature often begin by decomposing scalar quantities (e.g., wind components, temperature) into mean and fluctuating components in the equations of motion and other equations for the atmosphere, then apply mathematical procedures and assumptions to characterize turbulence. Even in controlled field experiments, statistical analyses are required since conditions are not repeatable.

As a result, for this course, rather than a mathematical treatment of turbulence, we present a general discussion of turbulence, characteristics of turbulence, and the generation of turbulence in the atmosphere.

Measurements of velocity made near the ground indicate that the three components of velocity (u, v, and w) vary considerably in both space and time. The impact of this motion in the atmosphere on pollutant concentrations is most conveniently analyzed by assuming that the instantaneous velocity is the sum of two components: a mean velocity obtained by averaging the measured velocity over a period of time, and a fluctuating, or turbulent, component. The behavior of material released into the atmosphere then is modeled in terms of transport away from the source by the mean velocity and dispersion in all three directions by the turbulent fluctuations. Turbulent motion is described in terms of statistics, the most relevant of which for dispersion are the standard deviations of the turbulent components about the mean velocity components. These standard deviations are denoted by σ_u, σ_v, and σ_w.

Characterizing Turbulence

Arya (1988) and Tennekes and Lumley (1972) provide a good overview of some general characteristics or properties of turbulence. These include:

- Irregularity or randomness, making turbulence unpredictable and making a deterministic approach (i.e., predictable in terms of defined laws) to turbulence problems impossible;
- Three-dimensional and rotational;
- Ability to mix properties (diffusive) – Arya (1988) notes that this is probably the most important property, where applications are concerned; diffusivity causes rapid mixing and increased rates of heat, momentum, and mass transfer;

- Dissipative, where kinetic energy is converted to internal energy or heat by viscosity; and
- Multiple scales of motion (the range of the sizes of eddies).

With regard to these last points, a short poem by Lewis F. Richardson[1] states it well:

"Big whorls have little whorls,
that feed on their velocity;
little whorls have smaller whorls,
and so on unto viscosity."
(Note there are slight variations of a few words, but the meaning is retained).

What this poem refers to is that turbulence causes the presence of eddies (whorls) of many different sizes (multiple scales of motion). Energy cascades from larger to smaller and smaller sizes, producing a hierarchy of eddies. This process continues until the sizes of the eddies become so small that the turbulence is dissipated due to viscosity.

Generation of Turbulence

Turbulent motion in the atmosphere, especially in the vertical direction, is most vigorous in the ABL. Turbulence in the atmospheric boundary layer is generated and maintained by two mechanisms: 1) wind shear which refers to the variation of wind speed with height and 2) buoyancy associated with radiative heating at the ground.

The first mechanism, wind shear, is associated with the interaction between the horizontal force exerted by one layer of air on an adjacent layer (shear) and the gradient of the mean velocity with height. This is referred to as the mechanical or shear production of turbulence. The velocity of the wind at the ground is zero. Thus, high mean velocities near the ground lead to a large mean velocity gradient and high turbulent velocities. The presence of obstacles such as trees and buildings also increase the mechanical production of turbulence. This mechanism operates during both the daytime and nighttime.

The second mechanism for turbulence production is related to buoyant air parcels originating from the ground heated by solar radiation. This mechanism, which operates only during the daytime, is governed by the energy balance at the ground.

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[1] As an epilogue to his paper, "The Supply of Energy from and to Atmospheric Eddies" in the Proceedings of the Royal Society of London A, July 1920, 97:686, pp. 354-373.

During the daytime, sensible heating at the surface results in parcels of air that are warmer, and hence less dense, than their surroundings. These parcels are subject to buoyancy forces that accelerate them upwards. The mixing induced by these moving parcels gives rise to the boundary layer or mixed layer, whose growth is inhibited by a layer in which the rising parcels are denser than their surroundings.

Turbulence levels in the daytime boundary layer are much higher than those in the nighttime boundary layer because buoyancy and shear production are both positive contributors during the day, while at night shear production, a positive contributor, is counteracted by buoyancy destruction, a negative contributor.

We conclude with two quotes regarding turbulence that illustrate the difficulty of understanding turbulent motions.

John Wyngaard[2] states, “Turbulence is a notoriously difficult subject.”

Horace Lamb, author of the classic text *Hydrodynamics*, published in 1895, is credited with saying "I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic."

ATMOSPHERIC BOUNDARY LAYER STRUCTURE

The structure and height of the ABL varies diurnally. The height of the ABL can vary from a few tens of meters to several thousand meters. Figure 3[3] shows the general structure and diurnal variation of the ABL structure. The ABL height over water varies more slowly in space and time because the water surface temperature varies more slowly in space and time. Over the land the ABL height varies more rapidly in space and time because surface conditions vary more rapidly in space (topography, land cover) and time (diurnal heating and cooling).

The ABL is composed of multiple parts, with those components depending on the time of day:

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[2] Wyngaard, J.C., 1992: Atmospheric Turbulence. Annual Rev. Fluid Mech., 24: 205-233.

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1. Convective mixed layer,
    a. Surface layer
    b. Well-mixed layer
2. Entrainment zone/capping inversion,
3. Residual layer, and
4. Stable boundary layer.

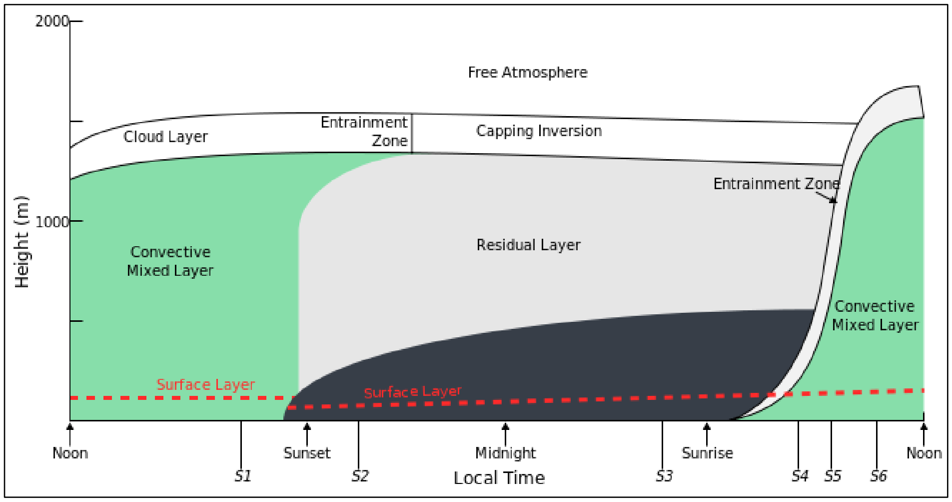


Figure 3. Atmospheric boundary layer structure (NikNaks, 2012 based on Stull, 1988).

The free atmosphere, where the effects of the surface are considered negligible, is above the ABL. Another layer may also exist, the cloud layer. In Figure 3, the cloud layer is at the top of the daytime convective mixed layer. The change of the virtual potential temperature profile over the course of a day, corresponding to Figure 3, is shown in Figure 4. The identifiers S1-S6 at the upper left of each profile correspond to the same time period on the x-axis in Figure 3.

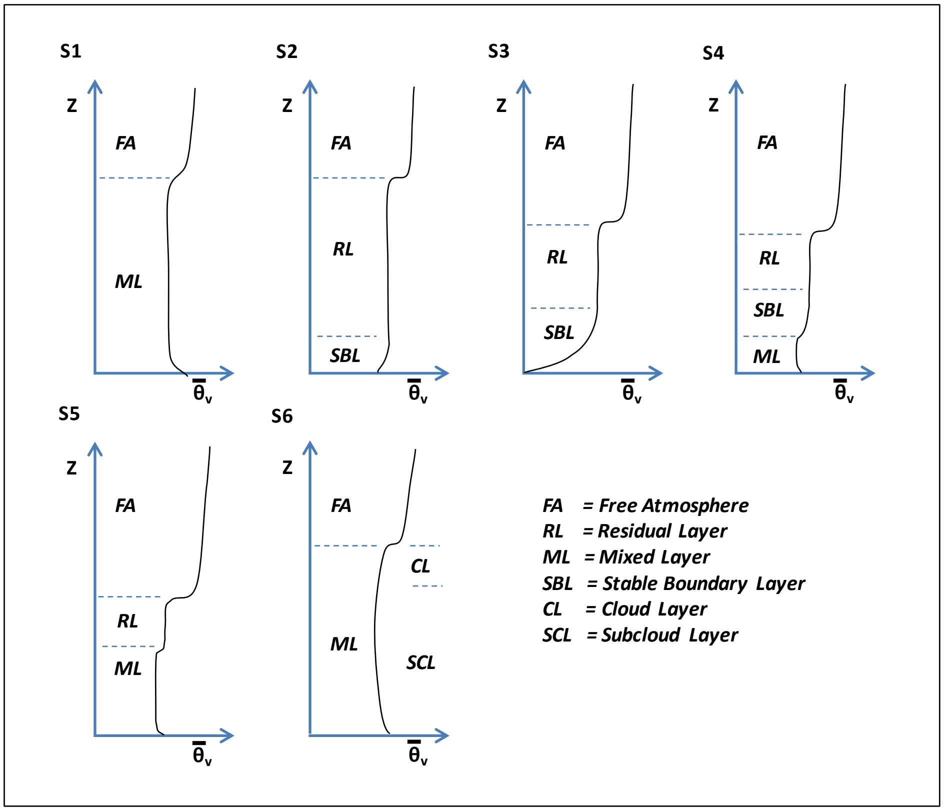


Figure 4. Profiles of mean virtual potential temperature over one day (adapted from Stull, 1988).

Each of these layers is explained below, with the discussion of the convective mixed layer divided into the surface layer and well-mixed layer.

Surface Layer

The surface layer is a shallow fraction of the convective mixed layer next to the earth's surface, typically considered the lowest 10% of the ABL and most often associated with the daytime ABL, or convective boundary layer (CBL). It is characterized by strong wind shear and super adiabatic temperature lapse rate. The surface layer is sometimes referred to as the constant flux layer because the vertical transfer of heat, moisture, and momentum is approximately constant within the layer. Figure 5 shows typical average daytime profiles of virtual potential temperature (θ_v), wind speed (U), water vapor mixing ratio (r), and pollutant concentration (C) with height (Z) that show the strong gradients in the CBL.

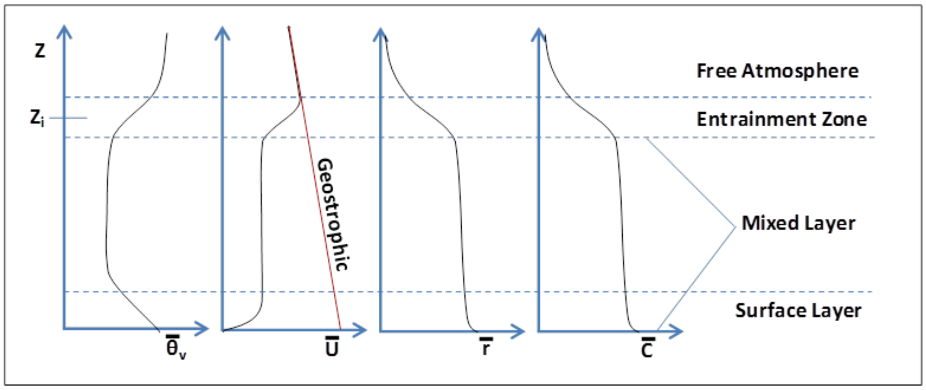


Figure 5. Daytime profiles of mean virtual potential temperature (θv), wind speed (U), water vapor mixing ratio (r), and pollutant concentration (C) with height (Z) where Zi is the mixing height (adapted from Stull, 1988).

Convective Mixed Layer

The convective mixed layer, also referred to as the well-mixed layer or convective boundary layer, is characterized by rising buoyant plumes due to surface heating. At the top of this layer there may be a cloud layer where radiative cooling may cause the air to descend. Both conditions can occur simultaneously. These vertical motions create vigorous turbulence which, in turn, causes (virtual) potential temperature, moisture, and other scalar quantities to be relatively constant with height, as seen in Figure 5.

The height of the daytime ABL layer is primarily determined by the surface heat flux. A simple model for its height variation assumes that the growth results from energy input into the boundary layer at the surface (from heating by the sun). This model results in a boundary layer that grows with time from its initial value at sunrise to its maximum when the surface heating vanishes. This is the model used in AERMET and is based on the work of Weil and Brower (1983).

Entrainment Zone / Capping Inversion

The entrainment zone at the top of the convective mixed layer is the region where the drier air from above the ABL is mixed (entrained) into the convective mixed layer. This layer is generally stable and limits the height to which vigorous turbulence is observed. If the layer is strong enough, this region can be classified as a temperature inversion capping the convective mixed layer. This temperature gradient is one of the computations made by AERMET using the upper air soundings and passed to AERMOD.

Residual Layer

Around sun set, the rising motions in the convective mixed layer cease. Over a period on the order of an hour, the turbulence created by rising air in the mixed layer collapses. This results in a layer of air where the initial mean state variables are the same as those of the recently-decayed convective mixed layer. The residual layer does not have direct contact with the ground; a nocturnal stable layer forms (see the next section for details).

The residual layer is neutrally stratified and turbulence is nearly equal in all directions resulting in pollutants that tend to disperse at equal rates vertically and laterally. A plume released into this layer may be referred to as lofting.

When the sun rises the next day and the surface begins to heat, the growing convective mixed layer erodes the residual layer and fumigation (downward mixing) occurs.

Stable Boundary Layer (SBL)

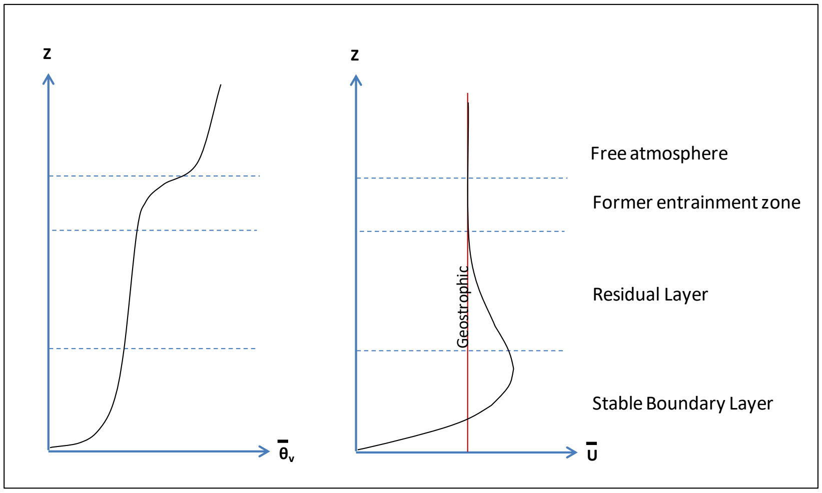
Once the solar radiation input at the earth's surface ceases, the surface cools, and a point is reached at which the ground becomes colder than the layers above in the atmosphere. At this stage, the surface boundary layer becomes stable with the potential temperature increasing with height (inversion). In addition, a phenomenon known as the low-level jet or nocturnal jet may develop that enhances wind shear aloft and is the primary mechanism for the production of turbulence. Figure 6 shows the profiles of the virtual potential temperature and wind speed.

The stable potential temperature gradient in the nocturnal boundary layer suppresses the production of turbulence. Under these circumstances, shear production of turbulence is matched by the destruction associated with the stable temperature gradient (and viscous dissipation which is not discussed here). This balance between these processes of production and destruction leads to relatively small levels of turbulence in the nocturnal boundary layer and pollutants emitted into the SBL disperse relatively little in the vertical.

Compared to the daytime ABL, which typically has a well-defined top, the top of the SBL is poorly defined. Therefore, estimating the height of the SBL is an uncertain exercise. One method to estimate the height is to assume the height is proportional to some power of the surface friction velocity (friction velocity is discussed below). This is the method used in AERMET and is based on the work of Venkatram (1980).

Free Atmosphere

Figure 6. Nighttime profiles of mean virtual potential (θ_v) temperature and wind speed (U) (adapted from Stull, 1988).



The region of the troposphere above the ABL is known as the free atmosphere. In this region, the effects of the earth's surface forcings, particularly friction and heating/cooling, are negligible. While this region may not be important in pollutant dispersion for near-surface releases, tall stacks may extend into this part of the atmosphere in the early morning or at night, and release emissions that may not necessarily reach the ground. A vigorously growing convective layer with a vigorous entrainment zone could become high enough to capture pollutants released in the free atmosphere where they can then be dispersed to the ground.

MIXING HEIGHT

Generally speaking, the mixing height defines the upper extent through which pollutants are mixed. If you have flown into a city like Los Angeles in the summer, on the decent you may notice a brown layer extending from the ground up to several hundreds of meters. Above that layer the air is usually much cleaner. The top of that ‘brown layer’ defines the mixing height. The height is not abrupt, but there is a distinct separation between the atmospheric boundary layer below it from the free atmosphere above it.

Looking back at Figure 3, the mixing height is not identified. For daytime convective conditions, some might choose the base of the entrainment zone, others might choose the top. A similar point can be made looking at the mean virtual potential temperature in Figure 4 and Figure 5. Either way, it becomes a subjective exercise when an individual is involved. AERMET uses an objective scheme based on the potential temperature from the morning upper air sounding (in the U.S.) and the heat input at the surface (Weil and Brower, 1983). For nighttime stable conditions, the definition of the mixing height is not easily identified and in fact usually cannot be identified from a sounding. The schemes to estimate both the mixing height for convective and stable conditions will be discussed in more detail when the course turns to AERMET.

GAUSSIAN DISPERSION

A Gaussian dispersion model incorporates some form of the Gaussian distribution equation (Eqn. 2). As discussed in D. B. Turner's *Workbook of Atmospheric Dispersion Estimates*, the Gaussian distribution equation uses relatively simple calculations requiring only two dispersion parameters (σ_y and σ_z, the horizontal and vertical dispersion coefficients, respectively) to approximate the variation of pollutant concentrations away from the center of the plume (Turner, 1994). These dispersion coefficients are the standard deviation of the pollutant concentration on the Gaussian distribution curve in the y (horizontal crosswind) and z (vertical) directions and are based on time-averaged atmospheric variables (e.g. temperature, wind speed). The Gaussian model assumes a steady-state plume in which the emission rate is constant and continuous, and the wind speed and direction are uniform.

$$C(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u}\, e^{\left(-\frac{z^2}{2\sigma_z^2}\right)} e^{\left(-\frac{y^2}{2\sigma_y^2}\right)} \qquad \text{Eqn. 2}$$

where:

C = ground level pollutant concentration

Q = mass of pollutant emitted per unit time

x = downwind distance from source

y = horizontal distance across the plume from plume center (crosswind distance)

z = vertical distance from ground

σ_y = standard deviation of pollutant concentration in the horizontal direction

σ_z = standard deviation of pollutant concentration in the vertical direction

u = time averaged wind speed at the source height.

Though an instantaneous snapshot of the plume's concentration cannot be obtained, when time averages of ten minutes to one hour are used to calculate the time averaged atmospheric variables needed, the pollutant concentrations in the plume can be assumed to be normally distributed as shown in Figure 7. As we will see in the next section, the

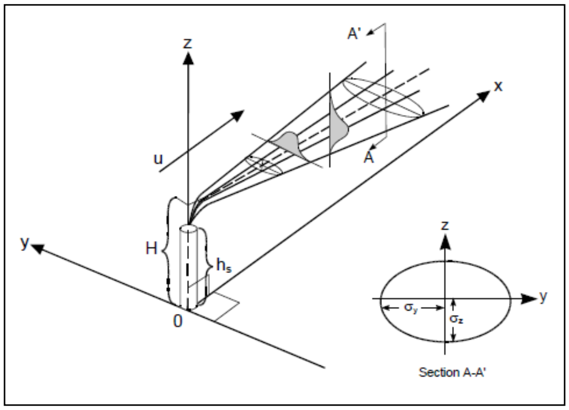


Figure 7. Schematic Representation of Gaussian plume.

assumption of a normally distributed pollutant distribution is not true for the vertical distribution in the CBL.

The Gaussian distribution requires that the material in the plume be maintained (i.e., mass conservation). In other words, the plume edge must be allowed to reflect from the ground without losing any mass. In addition, the Gaussian distribution depends on the ground being relatively flat along the path of the plume. Topography affects atmospheric wind flow and stability, and therefore, uneven terrain caused by hills, valleys, and mountains will affect the dispersion of the plume so that the form of the Gaussian distribution must be modified. The Gaussian distribution is also affected by the height from which emissions are released into the atmosphere. As a result, the Gaussian distribution equation can take on different forms as it is adapted for different release types and conditions. It is beyond the scope of this brief discussion to describe the details of other forms of the dispersion equations.

Dispersion in the Convective Boundary Layer (CBL)

In the convective boundary layer, both the mean wind and turbulence levels are relatively uniform above a height of about 1/10th of the atmospheric boundary layer height. The Gaussian equation has to be modified to account for the observation that turbulent vertical velocities in the middle of the convective boundary layer are governed by long lived updrafts and downdrafts as shown in Figure 8. The vertical extent of these updrafts and downdrafts is limited by the height of the boundary layer, which also represents the maximum vertical spread of material released in the CBL.

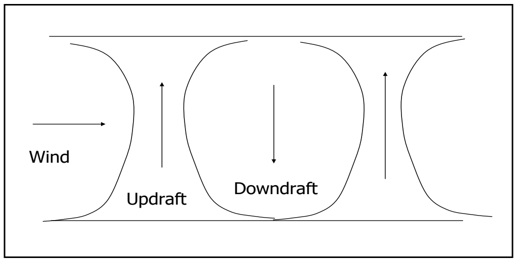


Figure 8. Updrafts and downdrafts in the convective boundary layer.

The updrafts consist of heated air originating from the surface, while the downdrafts consist of downward moving cooler air, which compensates for the surrounding upward motion. Velocities in the updrafts are larger than in the downdrafts, but downdrafts occupy a larger horizontal area. Observations indicate that the velocities in the downdrafts and in the updrafts can be described with Gaussian distributions. However, these distributions have different parameters. For example, the absolute value of the mean of the updraft velocity distribution is larger than that of the downdraft velocity distribution, and the updrafts and downdrafts cannot be represented by a single distribution.

For the convective boundary layer, AERMOD computes the vertical distribution of concentration by combining two different Gaussian distributions corresponding to the updrafts and the downdrafts. The downdraft component is called the “direct plume”, and the updraft component is called the “indirect” plume because it affects the ground-level concentration after it interacts with the top of the boundary layer. The emission rate associated with each plume is determined by the proportion of the horizontal area occupied by updrafts and downdrafts. AERMOD also accounts for a third component, called the “penetrated” plume, which is the material that has enough buoyancy to penetrate the top of the mixed layer, but some or all is then eventually entrained into the growing CBL. Recall that there can be an inversion at the top of the CBL. The strength of this inversion controls how much plume material penetrates the top of the mixed layer. Each plume component is described with a Gaussian distribution, but each has its own characteristics. The key point is that the vertical concentration distribution is not Gaussian because the sum of the three individual Gaussian distributions cannot be described by a single, composite Gaussian distribution.

On the other hand, the horizontal distribution of concentrations in AERMOD is taken to be Gaussian. The horizontal spread in the CBL is an interpolation between a surface-based equation and an equation that depends on the standard deviation of the horizontal fluctuations in the upper part of the boundary layer.

Dispersion in the Stable Boundary Layer (SBL)

The SBL dispersion model is based on the Gaussian equation for both horizontal and vertical dispersion and is similar to that used in many other steady-state plume models.

Vertical motion is inhibited by the positive potential temperature gradient in the stable boundary layer and the standard deviation of vertical velocity fluctuations decreases with height in the stable boundary layer.

CHAPTER 2: APPLICATIONS OF AERMOD

REGULATORY APPLICATIONS

Permit Modeling

As part of the 1977 Clean Air Act (CAA) Amendments, Congress established the New Source review (NSR) permitting program. NSR is a preconstruction permitting program that serves the following purposes.

- Ensures that air quality is not significantly degraded from the addition of new and modified factories, industrial boilers and power plants. In areas with unhealthy air, NSR assures that new emissions do not slow progress toward cleaner air. In areas with clean air, especially pristine areas like national parks, NSR assures that new emissions do not significantly worsen air quality.
- Assures people that any large new or modified industrial source in their neighborhoods will be as clean as possible, and that advances in pollution control occur concurrently with industrial expansion.

There are three components of the NSR permitting program:

1. Prevention of Significant Deterioration (PSD), for a new major source[4] or a major source making a major modification in an attainment area;
2. Nonattainment Area (NAA), for a new major source or major sources making a major modification in a nonattainment area; and
3. Minor source in both attainment and nonattainment areas.

The type of permit a source needs depends on a stationary source's location and the pollutants and amounts it will emit. A stationary source may have to meet one or more of the permitting requirements.

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[4] What constitutes a major source varies according to what type of permit is involved, the pollutant(s) being emitted, and the attainment designation of the area where the source is located.

Components of a PSD permit application include:

1. Installing best available control technology (BACT);
2. **Performing an air quality analysis** (i.e., demonstration of compliance with National Ambient Air Quality Standards (NAAQS) and PSD increments);
3. Assessing impacts from project-caused growth to soils, vegetation, and visibility; and assessing impacts on a Class I area, if applicable (i.e., PSD increment compliance and impacts to visibility and air quality related values); and
4. Providing opportunity for public involvement.

For an NAA permit application, the following conditions must be met:

1. Meet an emission limitation which specifies the lowest achievable emission rate (LAER) for that particular source;
2. Certify that all other facilities it owns or operates are in compliance with all applicable requirements;
3. The source must obtain emission reductions, or “offsets”, from existing sources in the same area of the proposed source or source modification. Offsets are based on actual emissions and can only be intra-pollutant (e.g. SO_2 for SO_2);
4. Emission offsetting must provide a positive net air quality benefit in the nonattainment area. **Dispersion modeling may also be needed** to determine whether the new source or modification, in combination with all other sources in the area plus the areas general background concentration, will attain the ambient air quality standards.

For a minor source permit application, the Clean Air Act is somewhat silent on specific requirements, with some requirements found in 40 CFR 51.160-51.164, especially regarding minor source baseline dates (for an increment analysis). Minor sources cannot violate NAAQS or control strategies set forth in a federal implementation plan (FIP)/state implementation plan (SIP)/ transportation improvement plan (TIP) or interfere with the attainment or maintenance of the NAAQS for that area.

In any case, an ambient air quality modeling assessment of the impact of the new or modified source is required to ensure compliance with the NAAQS, as shown in Table 1, and increment levels, and to ensure acceptable impacts to other air quality related attributes.

Table 1. NAAQS for Criteria Pollutants

Pollutant [final rule]	Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide [76 FR 54294, Aug 31, 2011]	primary	8-hour	9 ppm	Not to be exceeded more than once per year
		1-hour	35 ppm	
Lead [73 FR 66964, Nov 12, 2008]	primary and secondary	Rolling 3 month average	0.15 µg/m3	Not to be exceeded
Nitrogen Dioxide [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996]	primary	1-hour	100 ppb	98th percentile, averaged over 3 years
	primary and secondary	Annual	53 ppb	Annual Mean
Ozone [73 FR 16436, Mar 27, 2008]	primary and secondary	8-hour	0.075 ppm	Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 years
PM2.5 Particle Pollution Dec 14, 2012	primary	Annual	12 µg/m3	annual mean, averaged over 3 years
	secondary	Annual	15 µg/m3	annual mean, averaged over 3 years
	primary and secondary	24-hour	35 µg/m3	98th percentile, averaged over 3 years
PM10 Particle Pollution Dec 14, 2012	primary and secondary	24-hour	150 µg/m3	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973]	primary	1-hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	secondary	3-hour	0.5 ppm	Not to be exceeded more than once per year
For more information: http://www.epa.gov/air/criteria.html.				

The U.S. Environmental Protection Agency's (EPA's) Support Center for Regulatory Atmospheric Modeling (SCRAM) website provides guidelines and links to documentation for conducting air dispersion modeling (http://www.epa.gov/scram001/guidance_permit.htm). The guidelines "promote consistency in the use of modeling with the air quality management process." The website provides guidelines in three areas: Appendix W Guidance, Screening Guidance, and Other Permit Modeling Guidance.

In addition to these guidelines, an individual State's air quality modeling guidelines should be consulted to determine if there are other conditions, requirements, or pollutant limits that need to be addressed. Contacting the State's modeler is also recommended to provide guidance and assistance and to avoid having to reanalyze and resubmit a modeling demonstration.

Title V of the 1990 Federal CAA Amendments is designed to standardize air quality permits and the permitting process for major sources of emissions. Minor sources are not required to apply for a Title V permit. EPA defines a major source as a facility that emits or has the potential to emit (PTE)[5] any criteria pollutant or hazardous air pollutant (HAP) at levels equal to or greater than an applicable pollutant threshold. This threshold varies depending on the attainment status of the geographic area in which the source is located, the source category, and the pollutant. For criteria pollutants in an attainment area, this threshold is: 100 tons per year (tpy) or 250 tpy PTE (depending on source category); for HAPS, the threshold is 10 tpy for an individual HAP or 25 tpy for combined HAPs. In nonattainment areas, these thresholds are lower.

Title V operating permits are legally enforceable documents issued after the source has begun to operate. Most Title V permits are issued by state, local, and tribal permitting authorities. These permits are often called part 70 permits because the regulations that establish minimum standards for State permit programs are found in the Code of Federal Regulations at 40 CFR 70.

In addition to demonstrating compliance with the NAAQS and state AAQS, a modeling demonstration showing compliance with PSD increment may be required. An increment is the amount of pollution an area is allowed to increase. PSD increments prevent the air quality in clean areas from deteriorating to the level set by the NAAQS.

The NAAQS is a maximum allowable concentration "ceiling" and applies to all criteria pollutants. A PSD increment, on the other hand, is the maximum allowable increase in concentration that is allowed to occur above a baseline concentration for a pollutant. The only pollutants subject to PSD increment are PM-2.5, PM-10, SO2, and NO2. Table 2

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[5] PTE is the maximum capacity of a source to emit a pollutant under its physical and operational design (8760 hours/year and includes enforceable emission control technology)

shows the maximum allowable increase for each pollutant and averaging time. For any period, other than an annual period, the applicable maximum allowable increase may be exceeded during one such period per year at any one location.

Table 2. Ambient Air Increments

Pollutant	**Maximum Allowable Increase (µg/m^3)**		
	Class I Area	Class II Area	Class III Area
PM-2.5			
Annual	1	4	8
24-hr maximum	2	9	18
PM-10			
Annual	4	17	34
24-hr maximum	8	30	60
SO_2			
Annual	2	20	40
24-maximum	5	91	182
3-hr maximum	25	512	700
NO_2			
Annual	2.5	25	50

The **baseline concentration** is defined for each pollutant and, in general, is the ambient concentration that exists at the time the first complete PSD permit application affecting the area is submitted. **Significant deterioration** is said to occur when the amount of new pollution would exceed the applicable PSD increment. It is important to note, however, that the air quality cannot deteriorate beyond the concentration allowed by the applicable NAAQS, even if not all of the PSD increment is consumed. You will have to check with a state's regulations, guidance, or air quality modeler to determine the appropriate baseline date and identify the facilities to use for each pollutant.

Prior to performing and submitting an air quality modeling analysis, some states recommend, and others may require, that a modeling protocol be prepared and submitted prior to submitting the actual permit application and environmental evaluation. A modeling protocol is a detailed plan on how the applicant intends to perform an air dispersion modeling analysis, which is the primary component of the overall environmental evaluation submitted with an air quality permit application. This step can resolve issues early on in the process and help avoid unnecessary delays in obtaining a permit.

The level of sophistication of the modeling analysis will be dictated by the size and complexity of the proposed project, the nature of the surrounding terrain, and the available meteorological data. For simple projects with relatively small emissions, a simple “screening” analysis may be appropriate. For more complex facilities, facilities located close to “complex terrain” (defined as terrain higher than the final plume height of a particular stack), or facilities with significant building downwash, more sophisticated or “refined” models may be required.

Modeling analyses may be performed in two phases: a preliminary project impact analysis and a cumulative impact analysis. In the preliminary analysis, the applicant assesses ambient concentrations resulting from emissions for new sources or modifications alone. Impacts from nearby and other background sources, including background concentrations, are not considered in the significant impact analysis. The highest estimated concentration is compared to the applicable significant impact level (SIL) to determine whether the impacts are significant. The SILs for Class I and Class II areas are shown in Table 3.[6]

It is important to note that the applicant should consider emissions and stack data at the various operating loads that may occur to ensure that project impacts are not underestimated. The maximum load may not yield the maximum impact.

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[6] In January 2013, the District of Columbia Circuit Court of Appeals revoked the PM-2.5 SIL. Regulatory changes may be forthcoming from EPA. Check EPA websites periodically and before you begin a review to see if new regulations have been put in place.

Table 3. Significant Impact Levels for Class II and Class I Areas

Pollutant	Averaging Period	SIL (μg/m^3)	
		Class II	Class I
SO2	Annual	1	0.08
	24-hr	5	0.2
	3-hr	25	1
	1-hr	7.9	*not yet established*
PM10	Annual	1	0.32
	24-hr	5	0.2
PM2.5	Annual	0.3 6	
	24-hr	1.2 6	
NO2	Annual	1	0.1
	1-hr	7.5	*not yet established*
CO	8-hr	500	-
	1-hr	2000	-

If a SIL is exceeded, the applicant must perform a cumulative impact analysis for the pollutant(s) and averaging time(s) associated with the exceedance(s) to demonstrate compliance with the applicable ambient air quality standard or increment. In a cumulative impact analysis, the scope of the analysis is expanded to include impacts from other sources at the facility, neighboring sources, and background concentrations.

In previous guidance, a full impact analysis was conducted for a significant impact area (SIA), which was a fairly rigid circular area with a radius extending out to the most distant point where the modeling predicts a significant ambient impact. The prescriptive nature of the SIA has been discarded in favor of the concept of a significant concentration gradient. EPA makes no attempt to define "significant concentration gradient" but defers to professional judgment. All sources expected to cause a significant concentration gradient should be considered, although the number of such sources is expected to be small. Larger, substantive sources should probably be considered initially. Impacts from sources with small emissions that have steep but localized gradients may have a far less impact on the larger scale. This significant concentration gradient is introduced in Section 8.2.3 of EPA's Guideline on Air Quality Models at http://www.epa.gov/scram001/guidance/guide/appw_05.pdf. EPA's March 1, 2011 memorandum "Additional Clarification Regarding Application of Appendix W Modeling

Guidance for the 1-hour NO_2 National Ambient Air Quality Standard"[7] provides additional information.

Assessing impacts from potential co-contributing sources may also be required in the cumulative NAAQS analyses. The factors to be reviewed include the type of source, distance between the facilities, location of potential impact, pollutants emitted, and emission rates of pollutants of interest. If impacts of neighboring sources, on receptors showing a significant impact from the sources subject to the permitting action, are not adequately accounted for by the background concentration used, then emissions from those sources must be modeled.

When conducting cumulative NAAQS modeling, the sources not explicitly included in the model (e.g., mobile sources; small, stationary sources; some fugitive sources; and large, distant sources) are accounted for by adding a background concentration representative of the air quality in the area. Background concentrations are based on ambient air monitoring data collected in the area or from similar areas determined to be reasonably representative. Background concentrations may be found on a state's air quality web page or obtained from a State's air quality modeler.

Acceptable Ambient Levels

The concentration of a toxic air pollutant (TAP) above which the pollutant may be considered to have an adverse effect on human health can be referred to as the acceptable ambient level (AAL). The level may depend on the whether the substance is non-carcinogenic or carcinogenic. The AAL is generally associated with state guidelines for TAPs. The number of AALs varies by state. For example, North Carolina identifies 97 pollutants/chemicals, but Rhode Island identifies over 250 pollutants/chemicals.

The NAAQS set specific limits for ambient concentration of criteria pollutants, whereas the AALs are used in permitting to insure that TAPs from new or modified sources do not make toxic air pollutant levels worse, on a case by case basis. When modeling a TAP, the AAL is not to be exceeded at or beyond the closest property boundary point.

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[7] US EPA, Additional Clarification Regarding Application of Appendix W Modeling Guidance for the 1-hour NO2, National Ambient Air Quality Standard , March 1, 2011
http://www.epa.gov/ttnnaaqs/aqmguide/collection/nsr/appwno2_2.pdf

State Implementation Plan (SIP) – Transportation Conformity

The Clean Air Act requires states to develop a general plan to attain and maintain the NAAQS in all areas of the country and a specific plan to attain the standards for each area designated nonattainment for a NAAQS. The state's plan, known as a State Implementation Plan or SIP, consists of a compilation of legally enforceable rules and regulations prepared by a State or local air quality agency and submitted by the State's governor or the governor's designee to EPA for approval. EPA's website states that:

"The SIPs serve two main purposes:

1. Demonstrate that the state has the basic air quality management program components in place to implement a new or revised NAAQS.
2. Identify the emissions control requirements the state will rely upon to attain and/or maintain the primary and secondary NAAQS.

"The SIPs are designed to prevent air quality deterioration for areas that are in attainment with the NAAQS and to reduce common or criteria pollutants emitted in nonattainment areas to levels that will achieve compliance with the NAAQS."

The SIP assigns emissions reductions for each pollutant or precursor for each source type (on-road motor vehicles, non-road equipment and vehicles, stationary, and area sources). As the NAAQS change for a pollutant, states must submit revisions to the SIP to demonstrate attainment and maintenance of those new or revised NAAQS and to meet other statutory requirements.

The following discussion is taken from the Federal Highways Administration's guide on transportation conformity.[8]

> The concept of transportation conformity was introduced in the Clean Air Act (CAA) of 1977 which included a provision to ensure that transportation investments conform to a State's air quality implementation plan (SIP) for meeting the Federal air quality standards. Conformity requirements were made substantially more rigorous in the CAA Amendments of 1990. The transportation conformity regulations [Title 40 CFR Parts 51 and 93] that detail implementation of the CAA requirements were first issued in

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[8] U.S. Department of the Interior, Federal Highway Administration, 2010: Transportation Conformity A Basic guide for State & Local Officials, Revised 2010.

November 1993, and have been amended several times. The regulations establish the criteria and procedures for transportation agencies to demonstrate that air pollutant emissions from metropolitan transportation plans, transportation improvement programs and projects are consistent with ("conform to") the State's air quality goals in the SIP.

Transportation conformity is required under CAA Section 176(c) to ensure that Federally supported transportation activities are consistent with ("conform to") the purpose of a State's SIP. Transportation conformity establishes the framework for improving air quality to protect public health and the environment. Conformity to the purpose of the SIP means Federal Highway Administration (FHWA) and Federal Transit Administration (FTA) funding and approvals are given to highway and transit activities that will not cause new air quality violations, worsen existing air quality violations, or delay timely attainment of the relevant air quality standard, or any interim milestone."

Conformity requirements apply in areas that either do not meet or previously have not met national ambient air quality standards (NAAQS) for ozone (O_3), carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$) or nitrogen dioxide (NO_2).

A conformity determination demonstrates that implementation of the metropolitan transportation plan, TIP, or project will not cause any new violations of the air quality standard, increase the frequency or severity of violations of the standard, or delay timely attainment of the standard or any interim milestone. For metropolitan transportation plan and TIP conformity, the determination shows that the total emissions from on-road travel on an area's transportation system are consistent with goals for air quality found in the SIP.

Project-level conformity determinations must be made for Federal highway and transit projects to demonstrate that the project is reflected in a conforming metropolitan transportation plan and TIP. Additionally, as part of these project-level determinations, in carbon monoxide and particulate matter nonattainment and maintenance areas, localized analysis requirements apply for Federally funded or approved projects. This analysis is called "hot-spot" analysis.

40 CFR 51, Subpart A, Section 93.101 (*Definitions*) defines a hot-spot analysis as an estimation of likely future localized pollutant concentrations and a comparison of those concentrations to the national ambient air quality standards. A hot-spot analysis assesses impacts on a scale smaller than the entire nonattainment or maintenance area, including, for example, congested roadway intersections and highways or transit terminals, and uses an air quality dispersion model to determine the effects of emissions on air quality.

40 CFR 51, Subpart A, Section 93.123 (*Procedures for determining localized CO, PM10, and PM2.5 concentrations (hot-spot analysis)*) states that for a carbon monoxide (CO) hot-spot analysis, the demonstrations required by §93.116 ("Localized CO, PM10, and PM2.5 violations") must be based on quantitative analysis using the applicable air quality models, data bases, and other requirements specified in 40 CFR part 51, Appendix W (Guideline on Air Quality Models).

In December 2010, EPA released final guidance for modeling local impacts on the $PM_{2.5}$ and PM_{10} NAAQS. This guidance is entitled *Transportation Conformity Guidance for Quantitative Hot-spot Analyses in PM2.5 and PM10 Nonattainment and Maintenance Areas.* EPA and the U.S. Department of Transportation have jointly developed a training course on completing quantitative PM hot-spot analyses according to the above guidance. More information can be found at: http://www.epa.gov/otaq/stateresources/transconf/training3day.htm.

Aviation

In the mid-1980's, the Federal Aviation Administration (FAA) developed the Emissions and Dispersion Modeling System (EDMS), a model capable of quantifying changes in pollutant emissions and ambient pollutant concentrations due to proposed airport projects. EDMS includes emission factors for the various airport sources and can be used to create an emissions inventory for any individual airport emission source or combination of emission sources. In 1993 EDMS was accepted as an EPA "Preferred Guideline" model for such applications. For dispersion analyses, EDMS generates input files to be processed by EPA's AERMOD model, which had been bundled with EDMS since May 2001.

AERMOD can be run from within EDMS, however the user may choose to run AERMOD external to EDMS with the generated input files. Because AERMOD requires both surface and upper air meteorological data, AERMET, AERMOD's meteorological preprocessor, is also bundled with EDMS. Similar to AERMOD, AERMET can be run either internally or externally to EDMS. EDMS also includes an interface to AERMAP, the terrain processor for AERMOD. Once the dispersion analysis is initiated within EDMS, the execution and control of AERMET, AERMAP and AERMOD is entirely transparent to the user.

FAA is replacing EDMS with the Aviation Environmental Design Tool (AEDT), a comprehensive software compliance tool to assess the interdependencies between aviation-related noise, criteria/HAPs/greenhouse gas (GHG) emissions, and fuel consumption. There will be no loss in functionality or capabilities between EDMS and AEDT. Rather, an improved accuracy for quantifying aircraft fuel burn and emissions will be realized.

AEDT can model aircraft performance in space and time to estimate fuel burn, emissions, and noise. Flight gate-to-gate analyses are possible for study sizes ranging from a single flight to scenarios at the regional, national, and global levels. The current version, AEDT 2a and publicly released in March 2012, focuses on air traffic airspace and procedure action analysis – specifically study areas that are larger than the immediate vicinity of an airport, incorporate more than one airport, or include proposed air traffic airspace and procedure actions above 3,000 feet above ground level (AGL).

Unlike many models developed by the government or its contractors, AEDT is only available to U.S. government users. In 2014, AEDT version 2b will become the next generation aviation environmental consequence tool and available to the public. It will replace the current public-use aviation air quality (EDMS) and noise analysis tools.

NON-REGULATORY APPLICATIONS

Human Exposure Modeling

Human exposure to pollutants can result from contact with contaminated air, water, soils, and food, as well as with drugs and consumer products. Exposures may be dominated by contact with a single medium, or concurrent contacts with multiple media may be significant. The nature and extent of such exposures depend largely on two things: (1) human factors and (2) the concentrations of a pollutant in the exposure media. Human factors include all behavioral, sociological, and physiological characteristics of an individual (or group of people that can be aggregated because the variation in exposure within the group is much less than the group-to-group variation across the population, referred to as a cohort) that directly or indirectly affect a person's contact with the substance of concern. Important behavioral factors are contact rates with air, water, food, and soils. Activity patterns, which are defined by an individual's or cohort's allocation of time spent in different activities at various locations, are also significant because they directly affect the magnitude of exposures to substances present in different indoor and outdoor environments. Information on activity patterns are taken from measured data collected during field and telephone surveys of individuals' daily activities, the amount of time spent engaged in those activities, and the locations where the activities occur.

Exposure is defined as the contact between a target organism and a pollutant at the outer boundary of the organism. Exposure may be quantified as the amount of the pollutant available at the boundary of the receptor organism per specified time period. From an exposure modeling standpoint, the principal goal is to estimate exposure as a function of both the relevant human factors and the measured or estimated pollutant concentrations in the contact or exposure media.

Human exposure modeling relates pollutant concentrations in the larger environmental media to pollutant concentrations in the immediate exposure media with which a human population has direct contact. Most human exposure models simulate the movement of either individuals or cohorts according to activity patterns through locations (called microenvironments) in a defined physical or political region (i.e., exposure districts). The movement of individuals or cohorts coincides with pollutants at varying concentrations. This creates the potential for contact between individuals or cohorts and pollutants, thus allowing the estimation of exposures of various individuals or cohorts within the population to the pollutants of interest.

EPA’s Air Toxics Risk Assessment Reference Library, Volume 2,[9] states that a human health risk assessment may be based on a tiered analysis, ranging from relatively simple, health-protective risk estimates based on limited information to complex, more realistic estimates involving more intensive data collection and calculations. Each successive tier represents more complete characterization of variability and/or uncertainty as well as a corresponding increase in complexity and resource requirements.

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[9] Air Toxics Risk Assessment Reference Library, Volume 2 Facility-Specific Assessment, Office of Air Quality Planning and Standards, EPA-453-K-04-001B, Research Triangle Park, NC, April 2004.

- Tier 1 is represented as a relatively simple, screening-level analysis using health-protective exposure assumptions and relatively simple modeling (e.g., receptors are located in the area with the highest estimated concentrations and a model is used that requires few inputs, most of which can be "generic," yet health-protective such as a screening dispersion model).
- Tier 2 is represented as an intermediate-level analysis using more realistic exposure assumptions (e.g., use of actual receptor locations and meteorological conditions) and more detailed modeling (e.g., a model that requires additional facility/source-specific inputs), using a refined atmospheric dispersion model such as AERMOD.
- Tier 3 is represented as an advanced analysis, capable of using probabilistic analysis for some input variables and more detailed and/or intensive modeling.

CHAPTER 3: OVERVIEW OF THE AERMOD MODELING SYSTEM

PROMULGATION

For thirty years prior to the end of 2006, the Industrial Source Complex (ISC) model was the workhorse regulatory model used in the construction of most State Implementation Plans (SIPs), new source permits, risk assessments, and exposure analyses for toxic air pollutants. In February 1991, the EPA in conjunction with the American Meteorological Society (AMS) held a workshop with the goal to design and develop a new, state-of-the-science dispersion model that incorporated the most understanding of recent turbulence processes and dispersion in the planetary boundary layer. Another requirement was to use readily available meteorological data such as data observed by the National Weather Service (NWS). The result of that collaboration is the AMS/EPA Regulatory Model (AERMOD) developed under the direction of the AMS/EPA Regulatory Model Improvement Committee (AERMIC).

AERMOD was promulgated on November 9, 2005 through an update to the EPA's *Guideline on Air Quality Models* (40 CFR Part 51, Appendix W). The update established AERMOD as the preferred dispersion model for estimating near-source impacts out to a maximum distance of 50 kilometers (km). ISC was allowed to continue to be used for a period of one year (either ISC or AERMOD could be used during that year). At the end of the transition year ISC was permanently replacing, and AERMOD became the preferred model as of November 9, 2006.

Since its promulgation a number of issues related to AERMOD have arisen. Revisions designed to address these issues plus certain enhancement were made to the AERMOD modeling system. This latest revised version of AERMOD was promulgated in a final FRN dated January 17, 2017 with the effective date of the action having been deferred to May 22, 2017. Specifics regarding this action can be found at: https://www.epa.gov/ttn/scram/appendix_w-2016.htm.

AERMOD MODELING SYSTEM FOR REFINED MODELING – OVERVIEW

The AERMOD modeling system contains new or improved algorithms for: 1) dispersion in both the convective and stable boundary layers; 2) plume rise and buoyancy; 3) plume penetration into elevated inversions and re-entrainment; 4) computation of vertical profiles of wind, turbulence, and temperature; 5) the urban nighttime boundary layer; 6) the treatment of receptors on all types of terrain from the surface up to and above the plume height; 7) the treatment of building wake effects; 8) an improved approach for characterizing the fundamental boundary layer parameters; and 9) the treatment of plume meander.

The AERMOD modeling system is comprised of three primary components and several ancillary programs to aid with the development of the model inputs. The primary components include:

- AERMAP: the terrain preprocessor,
- AERMET: the meteorological preprocessor, and
- AERMOD: the dispersion model.

Though not directly considered part of the AERMOD modeling system, ancillary programs that may be helpful tools or even necessary to prepare model data input include:

- AERSURFACE: estimates surface characteristics using gridded land cover data,
- AERMINUTE: calculates hour-average wind speed and direction from archived 1-minute wind data, and
- BPIPPRM: develops building downwash parameters.

Figure 9 illustrates the relationships between the primary and ancillary programs and the data flow between these programs.

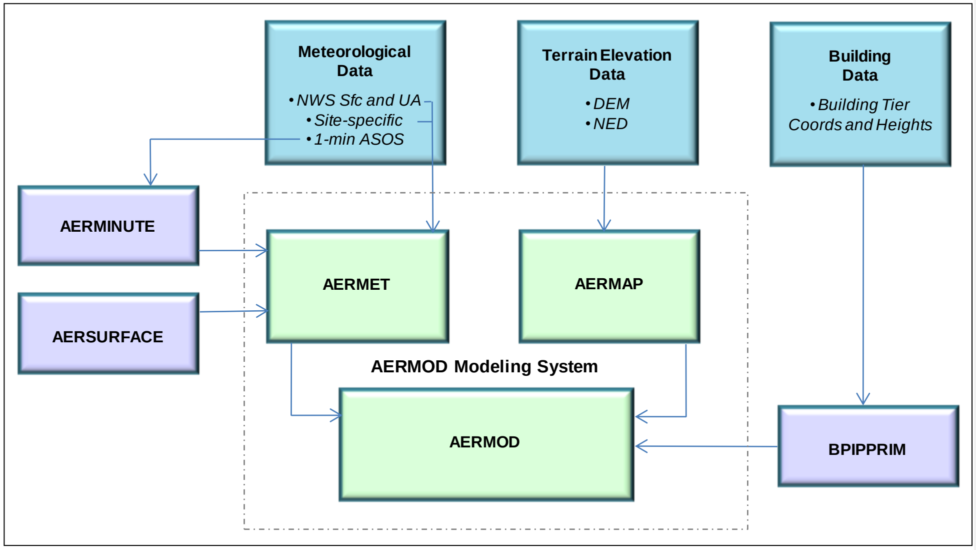

Figure 9. AERMOD primary and ancillary programs.

In addition to the programs listed above is the AERSCREEN screening model and the MAKEMET utility, used by AERSCREEN to generate screening level meteorology. Upon its release, AERSCREEN replaced SCREEN3 as the EPA's preferred screening model. An overview of each of the primary and ancillary programs listed above and the AERSCREEN and MAKEMET programs is provided in the sections that follow. Each of these programs is available from the EPA and can be downloaded for use from the EPA's SCRAM website at: http://www.epa.gov/ttn/scram/.

The May 21, 2017 revisions to EPA's modeling guideline (Appendix W) now considers the use of prognostic meteorological data processed through the U.S. EPA's Mesoscale Model Interface Program (MMIF) pre-processor an acceptable regulatory approach for developing meteorological inputs to AERMOD. Section 8.4.2(a) of Appendix W states: *"When processing prognostic meteorological data for AERMOD, the Mesoscale Model Interface Program (MMIF) should be used to process data for input to AERMET."* This new option provides stakeholders with an alternative to using the standard NWS airport data in situations where nearby observational data is not available or where meteorological conditions change rapidly with distance.

While there are several meteorological grid models, including the MM5 model that can be used to develop the needed inputs, the Weather Research and Forecasting (WRF) model is more commonly. The use of prognostic data in an AERMOD analysis will NOT be covered in this course.

Command-line Executable Files

The primary AERMOD modeling system components, ancillary programs, AERSCREEN, and MAKEMET are written in the Fortran programming language. The program files provided by the EPA have been compiled to run on the Microsoft (MS) Windows operating system as command-line executable files at the command prompt.

Primary AERMOD Components

AERMET

AERMET, the meteorological preprocessor, reads, extracts, and merges meteorological data of multiple types and archive formats, and uses that data along with user input to develop the boundary layer parameters required by AERMOD. AERMET accepts the following types of meteorological data: 1) standard hourly surface observations collected by the NWS and Federal Aviation Administration (FAA), 2) NWS twice-daily upper air soundings, 3) data collected from a site-specific measurement program such as from an instrumented tower or via remote sensing, and 4) 1-minute wind data from Automated Surface Observation System (ASOS) sites converted with AERMINUTE into 1-hour averages of wind direction and wind speed. This fourth type is commonly referred to as 1-minute ASOS data.

In addition to these archived data sets, AERMET requires representative values for the following surface characteristics based on land use patterns where the meteorological data are collected: noon-time albedo, Bowen ratio, and surface roughness length. These parameters are used by AERMET to compute the boundary layer parameters and can be derived with land cover data processed with AERSURFACE.

AERMET is designed to be run in three separate stages so the user can perform a thorough review of the output for each stage. A review of the output is necessary to ensure each stage completes successfully and no unanticipated problems with the data are encountered that render a data set insufficient for the dispersion modeling application.

During the first processing stage, one or more types of meteorological data are read and extracted from archive data files, and a basic quality assurance (QA) assessment of the data is performed. The QA assessment detects and reports data quality issues such as missing data, data that are outside of a valid range, and internal inconsistencies between related meteorological parameters. The second stage merges and organizes the different types of data in a single ASCII (text) file. It is also during the second stage that hourly averaged 1-minute ASOS wind data can be included, in which case the 1-minute ASOS wind data are used to replace the 1-hour wind data extracted from the standard NWS surface data file. In the third and final stage, the required boundary layer parameters are developed, and the data are formatted for input to AERMOD. The values previously developed for noon-time albedo, Bowen ratio, and surface roughness length are also input into AERMET during the third stage of processing.

The third stage generates two files required by AERMOD: 1) a “surface” file that includes hourly surface observations (e.g., wind speed, wind direction, temperature, precipitation, cloud cover), boundary layer parameters (e.g., sensible heat flux, surface friction velocity, Monin-Obukhov length, convective and mechanical mixing heights), and surface characteristics (albedo, Bowen ratio, and surface roughness length) and 2) a profile file that contains hourly wind and temperature data at one or more levels in the atmosphere, including the standard deviations of the wind direction and vertical wind speed when provided. These profiles are constructed in AERMET through a combination of the available vertical measurements of needed meteorological data and similarity profiling, before, in-between and above the actual vertical measurements.

Figure 10 illustrates the three data processing stages performed by AERMET. AERMET was designed to run with standard NWS hourly surface observations and upper air sounding data. The dashed lines in Figure 10 connecting the site-specific data and 1-minute hourly averaged data (i.e., 1-minute ASOS data) indicate these data are optional. It should be noted, if sufficient data are collected by a site-specific observation program then the standard NWS hourly surface observation data are not needed. This would include hourly values of the mixing height, which is the primary purpose of processing the upper air soundings in AERMET. AERMET data requirements and data preferences will be discussed in more depth during the instructor-led portion of the course.

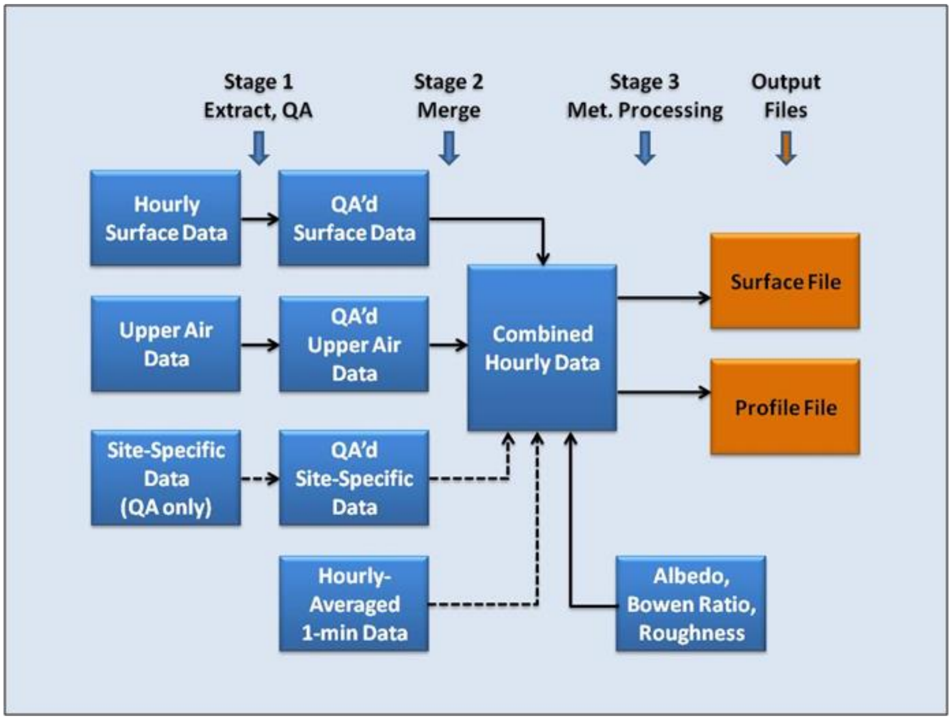

Figure 10. Three-stage AERMET processing.

AERMAP

AERMAP is the terrain preprocessor for AERMOD. AERMOD is designed to model dispersion in all types of terrain environments, from flat prairie-like terrain to complex mountainous terrain. When AERMOD is applied in areas with elevated terrain, AERMAP is used to derive the terrain-related inputs required by AERMOD from standard elevation data.

AERMOD requires the terrain elevation above mean sea level (MSL) at the location of each emission source and receptor as well as a hill height scale for each receptor. The hill height scale is used to compute a critical dividing streamline height (H_{crit}). H_{crit} informs how a plume responds to the terrain at the receptor. That is, what fraction of the plume impacts the terrain at the receptor and what fraction of the plume follows (flows over) the terrain.

AERMAP has been designed to process several standardized elevation data formats including 1-degree, 7.5-minute, and 15-minute terrain data in the U.S. Geological Survey (USGS) Digital Elevation Model (DEM) format and National Elevation Dataset (NED) data in GeoTIFF format. Data in either format must be stored based on geographic coordinates (latitude and longitude) or Universal Transverse Mercator (UTM) coordinates. As of February 2020, only 3 DEP Seamless DEM data are available from the USGS. However, the type and location of this data is still in flux. Therefore, before you begin any AERMOD analysis it would be prudent to check the SCRAM web-site for the latest information regarding how to access the needed data.

AERMOD

The AERMOD dispersion model uses the meteorological data from AERMET and the terrain data from AERMAP, along with building information processed with BPIPPRM (when applicable) and user-supplied source data to compute hourly pollutant concentrations at user-defined receptor locations for each hour of the modeling period. AERMOD was designed to support the EPA's regulatory modeling programs. As such, the default mode of operation includes the regulatory model options established by the EPA. Pollutant-specific averaging routines enable AERMOD to generate short-term and long-term averages using averaging methods consistent with comparison to the NAAQS. For example, when specified, AERMOD will provide the concentration for sulfur dioxide (SO_2) that represents the 99th-pecentile based on the annual distribution of daily maximum 1-hour values averaged over five consecutive years for comparison with the 1-hour NAAQS for SO_2.

In addition to concentration estimates, AERMOD can also compute wet and dry deposition values. Dry deposition requires information on the particle distribution for the modeled source(s). Wet deposition requires hourly precipitation information (amount and type be included in the AERMET surface file.

AERMOD also includes a regulatory 3-tiered approach for modeling 1-hour NO_2. The first tier, which is the most conservative, simply assumes that all NO is converted to NO_2. The second and third tier methods, the revised Ambient Ratio Method (ARM2 – tier 2), the Ozone Limiting Method (OLM – tier 3) and the revised Plume Volume Molar Ratio Method (PVMRM2 – tire 3), are described in detail in the AERMOD User's Guide, the addendum to the AERMOD Model Formulation Document and two documents (related to the changes in how AERMOD models NO_X) found at: https://www.epa.gov/ttn/scram/appendix_w-2016.htm.

AERMOD includes an option to identify and model sources located in an urban environment. To account for the dispersive nature of the “convective-like” boundary layer that forms during nighttime conditions due to the urban heat island effect, AERMOD enhances the turbulence for urban nighttime conditions over that which is expected in the adjacent rural, stable boundary layer. The magnitude of the urban heat island effect is driven by the urban-rural temperature difference that develops at night. AERMOD currently uses the population input keyword as a surrogate to define the magnitude of this differential heating effect.

Ancillary AERMOD Components

AERSURFACE

As previously stated, the AERMET meteorological processor requires input of noon-time albedo, daytime Bowen ratio, and surface roughness length (collectively known as surface characteristics) to estimate boundary layer parameters. Traditional methods for deriving surface characteristics include using topographic maps, aerial photography, tabulated values for a few land cover types, and 'professional judgment.' AERSURFACE was developed to aid users in obtaining realistic and reproducible values for these surface characteristics for a user-specified study area. The tool uses publicly available national land cover data and look-up tables of surface characteristics that vary by land cover type and season. AERSURFACE can process 1992, 2001, 2006 and 2011 National Land Cover Data (NLCD) available from the United States Geological Survey (USGS). As noted above you should check the SCRAM web-site to determine the latest procedure for accessing this data. These data are at a spatial resolution of 30 meters and based on 21-category (1992) and 16-category (2001, 2006 and 2011) classification schemes. Note that 1992 NLCD data is not available for Alaska.

AERSURFACE derives estimates for albedo, Bowen ratio, and surface roughness length for a location based on the average representative land use pattern for the immediate area surrounding a specified location, generally the location of the tower where the meteorological data are collected. AERSURFACE can estimate values on a monthly, seasonal, or annual basis. Surface roughness can be derived for up to 12 non-overlapping sectors around the meteorological tower to account for variations in roughness based on the direction from which the wind is blowing and the upwind fetch.

It should be emphasized that AERSURFACE is an ‘aid’ or a tool and the results should not be taken as absolute for several reasons. The NLCD data may be outdated for the current land use in an area, and the user may have more detailed and up-to-date knowledge of the study area than is available through the available NLCD data. AERSURFACE applies lookup tables of the surface characteristics by season to all years, and there may be reason to adjust the values for the specific years being modeled. There are also known deficiencies associated with generalizing surface roughness from certain 2001 and 2006 NLCD land cover category definitions. The specific challenges associated with the 2001 and 2006 land cover definitions will be discussed during the instructor-led portion of the course. Finally, terrain effects on surface roughness are not accounted for in the land cover data. The user should examine the results and assess whether or not the values produced by AERSURFACE are appropriate for the study area, and employ 'professional judgment' in accepting, rejecting, or modifying the values.

AERMINUTE

Beginning in 1992 and concluding in the mid-2000's, meteorological observation stations at U.S. airports were converted to Automated Surface Observing System (ASOS). A potential concern related to the use of ASOS data for dispersion modeling is the high incidence of calms and variable wind conditions reported at most NWS stations since the mid-1990’s. In the METAR coding used to report surface observations beginning July 1996, a calm wind is defined as a wind speed less than 3 knots and is assigned a value of 0 knots. The METAR code also introduced the variable wind observation that may include wind speeds up to 6 knots, but the wind direction is reported as missing if the wind direction varies more than 60 degrees during the 2-minute averaging period for the observation. AERMOD does not simulate dispersion under calm or missing wind conditions.

ASOS wind data consists of running 2-minute average winds, reported every minute, for commissioned ASOS stations. The National Climatic Data Center (NCDC) archives the 2-minute average wind speeds for each minute of the hour for most ASOS stations and makes this data freely available to the public. While these data have not undergone stringent quality control measures, they have also not been subjected to the METAR coding for calm and variable winds.

Archived 1-minute winds for the ASOS stations can be processed with AERMINUTE to calculate hourly average wind speed and directions. These data can then replace the standard archive of hourly observed winds on an hour-by-hour basis to reduce the number of calms and missing winds inherent in the standard NWS surface data measured with standard ASOS instrumentation. AERMET performs this replacement when the 1-minute data are included.

BPIPPRM

Complex airflow patterns over and around a building can force a plume down to the ground much sooner than it would if the building were not present, leading to higher ground level concentrations in the vicinity of the emission source. For example, the maximum hourly concentration for a short to medium stack (10 to 30 meters high) can be a factor of 5 to 10 times higher with building downwash present than in the absence of building downwash. Depending on the distance to ambient air, where the public is exposed to the plume, downwash can have a significant impact on compliance with local and federal air quality standards. Figure 11 identifies the wake regions (near wake and far wake) that result from building downwash.

The Building Profile Input Program (BPIP) was designed to incorporate the concepts and procedures expressed in the Good Engineering Practice (GEP) technical support document (EPA, 1985), the Building Downwash guidance (Tikvart, 1988; Tikvart, 1989; Lee, 1993), and other related documents into a program that calculates building heights and projected building widths.

The **P**lume **Ri**se **M**odel **E**nhancements (PRIME) model (Schulman et al., 2000), sponsored by the Electric Power Research Institute (EPRI) to develop and evaluate new, improved plume rise and building downwash algorithms, was designed to incorporate the two fundamental features associated with building downwash: enhanced plume dispersion coefficients due to the turbulent wake, and reduced plume rise caused by a combination of the descending streamlines in the lee of the building and the increased entrainment in the wake. PRIME downwash algorithms were integrated into the AERMOD dispersion model to address the entire structure of the wake, from the cavity immediately downwind of the building (near wake), to the far wake downwind. Figure 11 identifies the regions of the near wake and far wake relative to the building. BPIP was updated to BPIPPRM ("BPIP PRIME") to derive the additional building parameters required by the PRIME downwash algorithms in AERMOD.

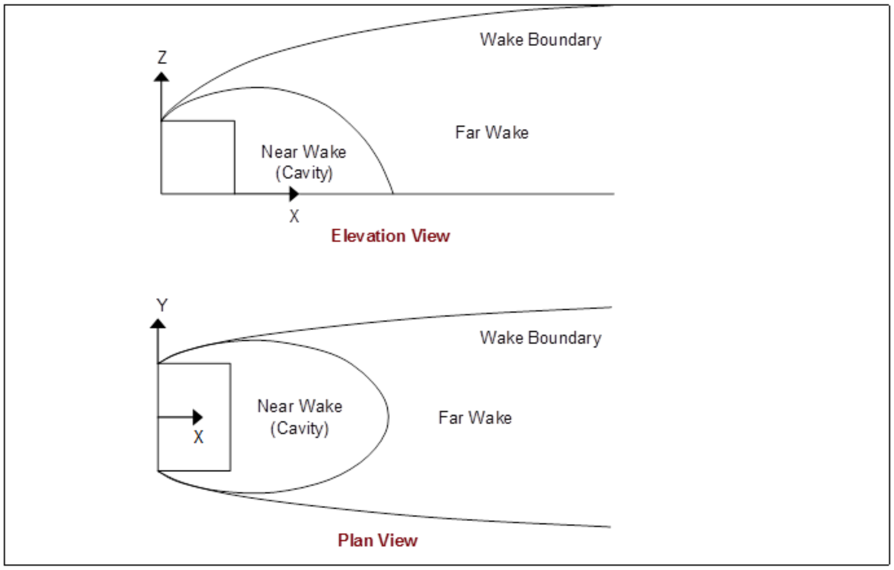

Figure 11. Buildings Wakes from Aerodynamic Downwash (adapted from Shulman *et al.*, 1997).

AERSCREEN and MAKEMET

AERSCREEN, the screening model for AERMOD, will produce estimates of regulatory design concentrations without the need for actual meteorological data. AERSCREEN is designed to produce concentrations that are equal to or greater than estimates produced by AERMOD when using AERMOD with a fully developed set of meteorological data.

The AERSCREEN model consists of two main components: 1) the AERSCREEN command-prompt interface (formerly called ASCREEN and developed by James Haywood of the Michigan Department of Environmental Quality) and 2) the MAKEMET utility which generates a site-specific matrix of meteorological conditions for input to the AERMOD model. AERSCREEN interfaces directly with MAKEMET to generate the matrix of meteorological data. Similarly, AERSCREEN interfaces with AERMAP and BPIPPRM to automate preprocessing the terrain and building information, respectively. To estimate dispersion and design concentrations, AERSCREEN interfaces with the AERMOD model which executes AERMOD in a screening mode. AERSCREEN supports version 09292 and later of AERMOD and will not work with earlier versions. The AERSCREEN program also includes averaging time factors for worst-case 3-hr, 8-hr, 24-hr and annual averages.

AERSCREEN is currently limited to modeling a single source which can be any one of the following types:

- vertically pointing stack,
- capped stack,
- horizontal stack,
- rectangular area,
- circular area,
- flare, or
- volume source.

In cases where building downwash is applicable, the user may directly enter building dimensions and location information relative to the source, when prompted, for a single tier rectangular or square shaped building. For multiple buildings or more complex building geometries, a building analysis can be performed separately, apart from AERSCREEN, and the user can enter the path and filename of an existing BPIPPRM input file. AERSCREEN determines the location of the maximum concentration for an array of receptors defined by the minimum distance from the source to ambient air and a maximum probe distance, which are entered by the user. In addition, the user may define up to 10 discrete receptor distances.

Commercially Available Integrated AERMOD Interfaces

While each of the software programs associated with the AERMOD system described to this point are provided by the EPA, free of charge, there are several graphical software packages developed by private vendors, for purchase, that can simplify the process of developing the data inputs and control files required to run AERMOD and AERSCREEN. Links to product information for known products are provided below as a courtesy to class participants. ***Mention of these products should not be interpreted as official EPA approval, endorsement, or recommendation.***

- BEE-Line Software by Oris Solutions (BEEST)
- Lakes Environmental (AERMOD View)
- Trinity Consultants (BREEZE AERMOD)

MODELING GUIDANCE AND SUPPORT DOCUMENTS

The EPA makes available numerous guidance resources and reference documents with which users of AERMOD should be familiar. Many of these are described briefly in the sections that follow.

EPA's Support Center for Regulatory Atmospheric Modeling (SCRAM)

Guidance and support documents offered by EPA are accessible from the Support Center for Regulatory Atmospheric Modeling (SCRAM) website. The SCRAM website is maintained by the EPA's Air Quality Modeling Group (AQMG) which also maintains the AERMOD source code and performs modeling analyses to support policy and regulatory decisions in the EPA's Office of Air and Radiation (OAR). SCRAM is somewhat of a one-stop website for regulatory atmospheric modeling where you can download guidance documents, source code, and executables for preferred and alternative models including dispersion, photochemical, and receptor models and related programs. The most recent additions and updates to the SCRAM website are provided via the SCRAM Rich Site Summary (RSS) Feed.

Guideline on Air Quality Models (40 CFR Part 51 Appendix W)

EPA's Guideline on Air Quality Models (40 CFR Part 51 Appendix W), commonly referred to as the *Guideline* or *Appendix W*, codifies the application of air quality models for assessing criteria pollutants under the Clean Air Act. The *Guideline*, last revised November 9, 2005, establishes AERMOD as the preferred dispersion model for most near-field applications (within 50 km) and AERSCREEN as the preferred screening tool, replacing ISC3 and SCREEN3, respectively. The *Guideline* addresses the regulatory default model options that should be used, treatment of building downwash, terrain, representativeness of meteorological data, and the minimum time period that must be modeled based on the type of meteorological data input into the model (site-specific versus standard NWS observations). The *Guideline* also provides guidance for the use of alternative models when appropriate as well as non-modeling solutions for demonstrating compliance with air quality standards under certain circumstances.

Model Change Bulletins

Whenever an official update to an EPA regulatory model is released, the source code and executable is accompanied by a Model Change Bulletin (MCB). The MCB identifies the official release date and model version. The MCB also identifies and describes the changes made to the source code since the previous version release. Model updates can be tracked and traced by version with the MCBs. In general, MCBs are text files in which the file names include either a sequence number the model version number. Most of the *Guideline* models and MCBs can be downloaded directly from the SCRAM website.

AERMOD Formulation Document

The AERMOD Formulation Document provides a detailed description of the technical formulation of AERMOD and its meteorological and terrain preprocessors AERMET and AERMAP, respectively. There is also a separate Addendum to the AERMOD Formulation Document that describes more recent changes to the technical formulation of AERMOD. The AERMOD Formulation Document and Addendum are available on the SCRAM website.

User's Guides/Addendums

Each of the models, related preprocessors, and utilities is accompanied by a User's Guide that instructs the user on the required data, input format(s), and program control options. For several of the programs, an Addendum to the User's Guide is provided to instruct the user on how to use newer features. In some cases, new features or changes to the program render the usage of older features or required input(s) and formats outdated or obsolete. The user should consult both the User's Guide and the Addendum, when available, for instruction on program options and their proper usage. User's Guides and Addendums can be downloaded directly from the SCRAM website for those models and related programs available on SCRAM.

AERMOD Implementation Guide

The AERMOD Implementation Guide provides information on the best use practices for the regulatory application of AERMOD. Guidance is provided on the recommended use of the AERMOD modeling system, including AERMET and AERMAP, to address a range of issues and types of applications. For example, guidance is provided on determining meteorological data representativeness, methods for determining surface characteristics, terrain data, urban applications, and modeling capped and horizontal stacks, to name a few.

Clarification Memos

Occasionally the EPA will issue clarification memos to clarify issues related to *Appendix W* and technical aspects of the models and related programs. Some of the more recent memos address the use of ASOS meteorological data in AERMOD and modeling guidance for the newer 1-hour SO_2 and NO_2 NAAQS.

Model Clearinghouse

The Model Clearinghouse (MC) is a central point for interpretation of modeling guidance when there is an unresolved regulatory modeling issue at a State or local office that is forwarded to the Regional Office (RO) for resolution. The RO will propose a solution to the MC which then facilitates a review to determine the appropriateness of the proposed solution. When a solution is finalized, a formal memorandum is sent to all ROs, and the solution is archived in the Model Clearinghouse Information Storage and Retrieval System (MCHISRS).

State/Local Modeling Guidance

Modelers should be aware of specific guidance provided by the State and/or local agency that will review the modeling for approval for regulatory purposes such as permitting activities. State/local-specific modeling guidance may vary from agency to agency which may include but are not limited to: model options that must be used or that are allowable for certain situations, treatment of building downwash, receptor grid development, meteorology, state/local SILs and acceptable ambient levels for toxic air pollutants (TAPs), and other guidance specific to modeling TAPs.

Useful Links

- AERMOD Modeling System:
  http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod
- AERMOD Formulation Document:
  http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_mfd.pdf
- AERMOD Formulation Document Addendum:
  http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_mfd_addm_rev.pdf
- AERMOD Implementation Guide:
  http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_implmtn_guide_19March2009.pdf
- EPA Air Quality Modeling Group Clarification Memos:
  http://www.epa.gov/ttn/scram/guidance_clarificationmemos.htm
- EPA’s Guideline on Air Quality Models (40 CFR Part 51 Appendix W):
  http://www.epa.gov/ttn/scram/guidance/guide/appw_05.pdf
- EPA Model Clearinghouse (MC):
  http://www.epa.gov/ttn/scram/guidance_clearinghouse.htm
- EPA Model Clearinghouse Information Storage and Retrieval System (MCHISRS):
  http://cfpub.epa.gov/oarweb/MCHISRS/
- EPA Support Center for Regulatory Atmospheric Modeling (SCRAM):
  http://www.epa.gov/ttn/scram/
- EPA SCRAM Rich Site Summary (RSS) Feed:
  http://www.epa.gov/ttn/scram/rss/scram_rss_feed.xml

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