Appendix G Atmospheric and Meteorological Concepts Relevant to Dispersal, Transport, and Fate of Air Toxics

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This Appendix defines and discusses atmospheric and meteorological concepts relevant to modeling dispersion, transport, and fate of air toxics. In addition, this appendix provides information on sources of meteorological data that can be used for air toxics modeling. Much of this information was obtained from EPA's primer on air pollution meteorology (see http://www.epa.gov/oar/oaqps/eog/catalog/si409.html). Basic textbooks on meteorology provide more detailed discussions of the material summarized in this Appendix.

1.0 Structure and Composition of the Atmosphere

The atmosphere consists of mixture of about 78 percent nitrogen, 21 percent oxygen and one percent argon up to about 90 km. Within this region trace gases include carbon dioxide, neon, helium, and water vapor. Although the water vapor content of the air is fairly small it is highly variable. Water vapor absorbs six times more radiation energy than any other atmospheric constituent and is therefore a very important component of the atmosphere. Similarly, carbon dioxide is highly variable and is important gas because it absorbs and re-radiates back some of the infrared radiation emitted by the earth.

The atmosphere has been divided into four regions (Exhibit 1) based on temperature changes with height: the troposphere, stratosphere, mesosphere, and ionosphere. The troposphere accounts for about three quarters of the mass of the atmosphere and contains nearly all of the water in the atmosphere (in the forms of vapor, clouds, and precipitation). The depth of the troposphere is on average about 16.5 km (54,000 ft) over the equator and about 8.5 km (28,000 ft) over the poles. The troposphere also tends to be thicker in summer (when the air is warmer) than in the winter. The depth of the troposphere changes constantly due to changes in atmospheric temperature. The troposphere is the most important layer of the atmosphere with respect to air toxics, because this is the region in which most of the air toxics are released. Of the other regions of the atmosphere only the stratosphere has a direct role for some air toxics. Some air toxic emissions can be circulated into the lower stratosphere via weather system or directly emitted from aircraft or volcanic eruption. Once air toxics reach the stratosphere they maybe transported very long distances.

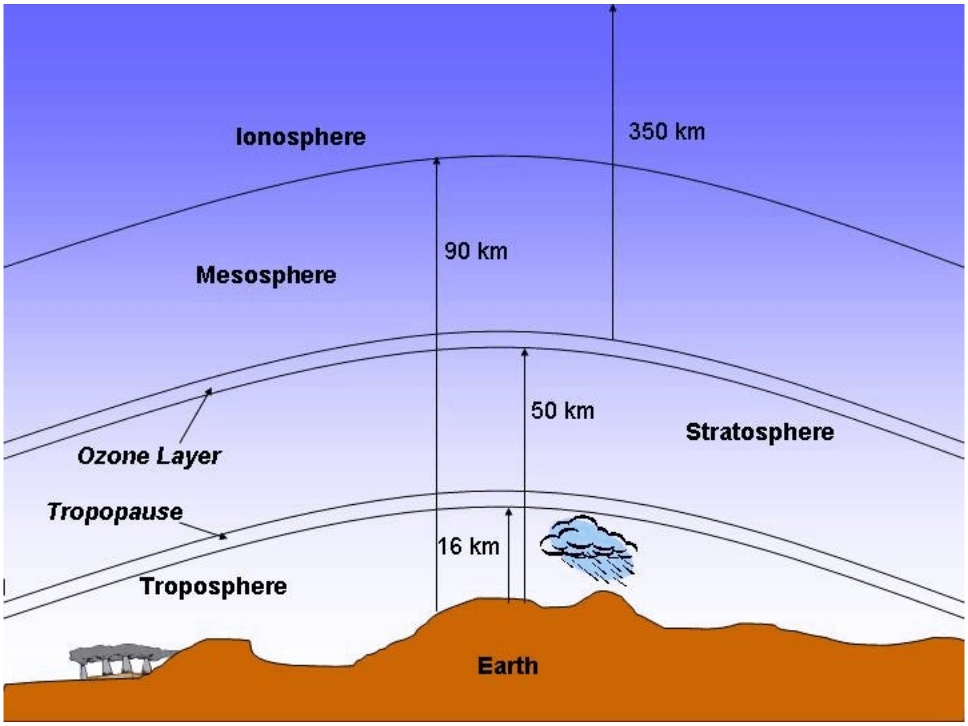
2.0 Atmospheric Energy

The troposphere is the most variable layer of the atmosphere and is the layer where weather occurs. It is where air masses, weather fronts, and storms reside. Weather conditions are governed by a number of factors, including solar radiation, atmospheric circulation, water vapor and topography. However, the underlying driving force in all cases is the radiant energy from the sun.

2.1 Solar Radiation and Differential Heating

The amount of incident sunlight influences the heating of the surface of the earth and the overlying atmosphere. The radiation received directly from the sun is called **solar radiation**. The amount of incoming solar radiation received at a particular time and location (insolation) on the earth is governed by:

Exhibit 1. Structure of the Atmosphere

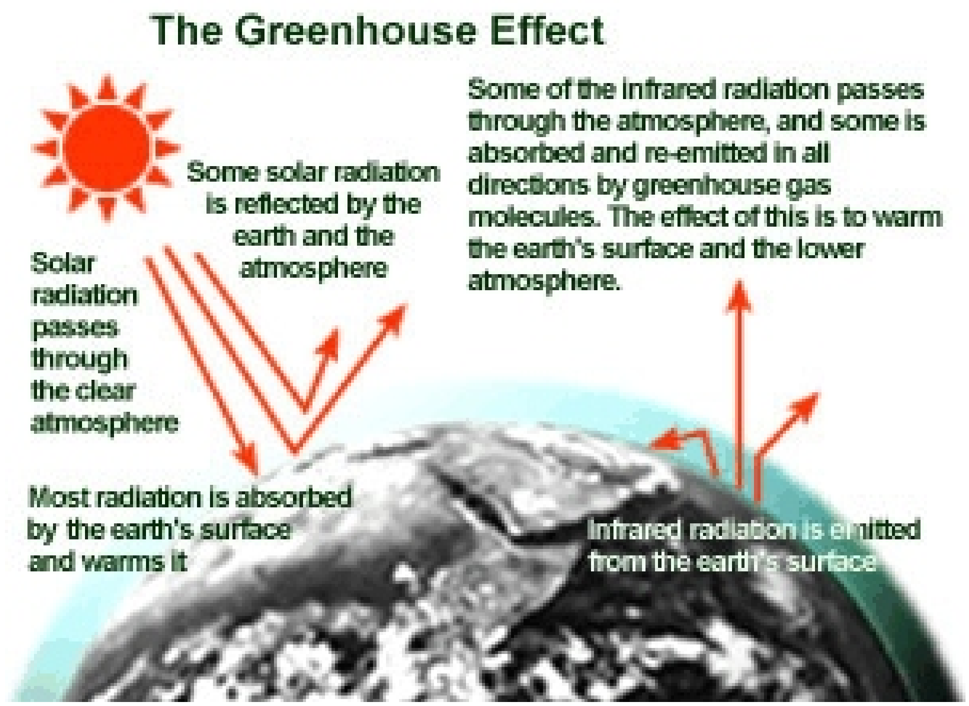


- The transparency of the atmosphere (for example, clouds reflect solar radiation);
- Hours of daylight; and
- The angle at which the sun's rays strike the earth.

The earth's surface absorbs short-wave solar radiation and emits longer wavelength **terrestrial radiation**. In the atmosphere, clouds, water vapor, and to a lesser extent carbon dioxide absorb terrestrial radiation, which causes the atmosphere to warm. The atmosphere absorbs much more terrestrial radiation than solar radiation. The atmosphere also radiates energy to outer space and back to the earth's surface. The earth-atmosphere system emits terrestrial radiation continuously. The atmospheric absorption of terrestrial radiation benefits the earth by retaining energy that would otherwise be radiated to space. This phenomenon explains how air temperatures are generally warmer on nights when cloud cover is present. The **greenhouse effect** is the descriptive name given to the result of the energy exchange process that causes the earth's surface to be warmer than it would be if the atmosphere did not radiate energy back to earth. Gases such as carbon dioxide and methane (and other similarly behaving gases often called **greenhouse gases**) also increase the ability of the atmosphere to absorb radiation (Exhibit 2).

The amount of solar radiation reaching the earth's surface varies from place to place. In addition, different types of earth surfaces (and man-made structures) vary in their ability to absorb and store heat energy. For example, land masses absorb and store heat differently than water masses. The color, shape, surface texture, vegetation and presence of buildings can all influence the heating and cooling of the ground. Generally, dry surfaces heat and cool faster than moist surfaces. Plowed fields, sandy beaches, and paved roads become hotter than surrounding meadows and wooded areas. During the day, the air over a plowed field is warmer than over a forest or swamp; during the night, the situation is reversed. The property of different surfaces which causes them to heat and cool at different rates is referred to as **differential heating**.

Exhibit 2. The Greenhouse Effect



Source: EPA's "Global Warming Kids Site."[1]

Heat is transferred within the atmosphere by conduction, convection, and advection. These processes affect the temperature of the atmosphere near the surface of the earth. **Conduction** is the process by which heat is transferred through matter without movement of the matter itself. For example, the handle of an iron skillet becomes hot due to the conduction of heat from the stove burner. Conduction occurs from a warmer to a cooler object. Heat transfer also occurs due to the movement of atmospheric gases. Meteorologists use the term **convection** to denote the transfer of heat that occurs mainly by vertical motion. Air that is warmed by a heated land surface will rise because it is lighter than the surrounding air. Likewise, cooler air aloft will sink because it is heavier than the surrounding air. Meteorologists use the term **advection** to denote heat transfer that occurs mainly by horizontal motion. All of these energy exchange processes, particularly between the earth surface and the atmosphere, produce the complex atmospheric motions of weather. As a result of these process air toxics maybe widely distributed far from their location of origin.

2.2 Effects of Topography

The physical characteristics of the earth's surface are referred to as **terrain features** or **topography**. Topography can be grouped into four general categories: flat, mountain/valley, land/water, and urban. Topography also causes two types of turbulence in the atmosphere. As noted above, topography causes **thermal turbulence** through differential heating. Topography causes **mechanical turbulence** as the result of the wind flowing over different sizes and shapes of objects. Physical features induce a frictional effect on wind speed and direction. For example, urban settings with dense construction and tall buildings exert a strong frictional force on the wind causing it to slow down, change direction, and become more turbulent.

Urban areas have a special effect on the atmosphere due to the high density of man-made features. Building materials such as brick and concrete absorb and store heat more efficiently than soil and vegetation found in rural areas. After sunset, the urban areas continue to radiate the stored heat from buildings and paved surfaces. Air is warmed by this urban complex and rises to create a dome (**heat island**) over an urban area. Large cities continue to emit heat throughout the night and generally never completely cool down to the more stable surrounding conditions before the sun rises and begins to heat the urban complex again. The overall effect of the urban landscape is to increase the dispersion of air toxics through increased mixing.

3.0 Atmospheric Motions

The differential heating of the earth's surface causes imbalances in **air pressure**. The atmospheric pressure at any point is due to the weight of the air pressing down from above due to gravity. In any gas such as air, molecules are moving around in all directions at very high speeds. The speed actually depends on the temperature of the gas. Air pressure is caused by the molecules of atmospheric gases bumping into each other and other surfaces and bouncing off. Air pressure is a function of the number of air molecules in a given volume and the speed at which they are moving. When air is warmed, the molecules speed up, and air pressure increases. As air cools, the molecules slow down, and air pressure decreases.

3.1 Horizontal Air Motions

Air moves in an attempt to equalize response to imbalances in pressure. The movement of air (**wind**) tends to move from areas of high to low pressure. Wind is the basic element in the general circulation of the atmosphere. Wind movements from small gusts to large air masses all contribute to transport of heat, moisture and as well as air toxics around the earth. Winds are always named by the direction from which they blow. Thus a "north wind" is a wind blowing from the north to the south and a "westerly wind" blows from west to east. When wind blows more frequently from one direction than from any other, the direction is termed the **prevailing wind**. Section 4.1 provides further information on how meteorologists measure and describe wind speed and direction.

Wind speed is heavily influenced by the presence or absence of friction ("drag") and increases rapidly with height about the ground level. Wind is commonly not a steady current but is made up of a succession of gusts, slightly variable in direction, separated by lulls. Close to the earth, wind gustiness is caused by irregularities of the surface, which create **eddies**, which are variations from the main current of wind flow. Larger irregularities are caused by convection (vertical transport of heat). These and other forms of turbulence contribute to the movement of heat, moisture, dust, and pollutants into the air. See Section 2.2 for additional information on how topography affects air motions.

Air masses cover hundreds of thousands of square miles and extend upward for several miles. They are relatively homogeneous volumes of air with regard to temperature and moisture, and they acquire the characteristics of the region over which they form and travel. Pollutants released into an air mass tend to travel and disperse within the air mass. Air masses develop more commonly in some regions than in others. Air masses are classified as maritime or continental according to their origin over ocean or land, and as arctic, polar, or tropical depending principally on the latitude of origin. Continental polar air masses are similar to arctic air masses, but not as cold and dry as arctic air masses. The chief air masses that affect the weather of North America are continental polar, maritime polar, and maritime tropical.

Frontal patterns are formed by the interaction of adjacent air masses. A cold front is a transition zone where a cold air mass is moving into the area previously occupied by a warm air mass. The rise of warm air over an advancing cold front and the subsequent expansive cooling of this air lead to cloud formation, and if sufficient moisture is available precipitation near the leading edge of the front. A warm front is a transition zone where a warm air mass is moving into the area previously occupied by a cold air mass. Precipitation commonly occurs in advance of a warm front, as the warm air slowly rises above the cold air.

3.2 Vertical Air Motions

When air is displaced vertically, atmospheric behavior is a function of atmospheric stability. A stable atmosphere resists vertical motion, and air that is displaced vertically in a stable atmosphere tends to return to its original position. This atmospheric characteristic determines the ability of the atmosphere to disperse pollutants. To understand atmospheric stability and the role it plays in pollution dispersion, it is important to understand the mechanics of the atmosphere as they relate to vertical atmospheric motion.

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 rise or fall. There are three general categories of atmospheric stability.

- In **stable** conditions, vertical movement tends not to occur. Stable conditions occur at night when there is little or no wind. Air that is lifted vertically will remain cooler, and therefore denser than the surrounding air. Once the lifting force is removed, the air that has been lifted will return to its original position.

- **Neutral** conditions (“well mixed”) neither encourage nor discourage air movement. Neutral stability occurs on windy days or when there is cloud cover such that there is neither strong heating nor cooling of the earth’s surface. Air lifted vertically will generally remain at the lifted height.

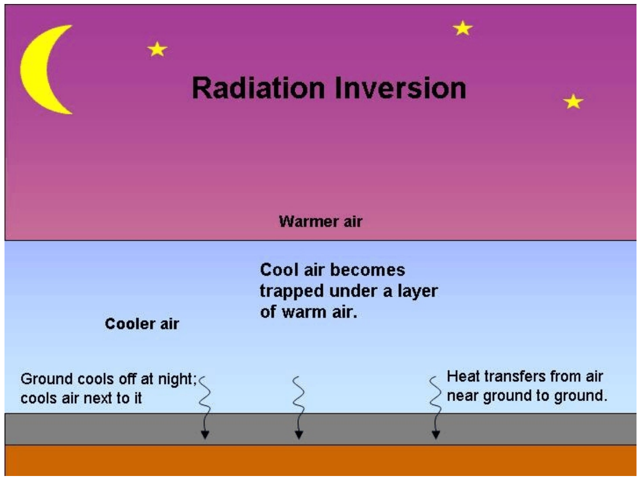
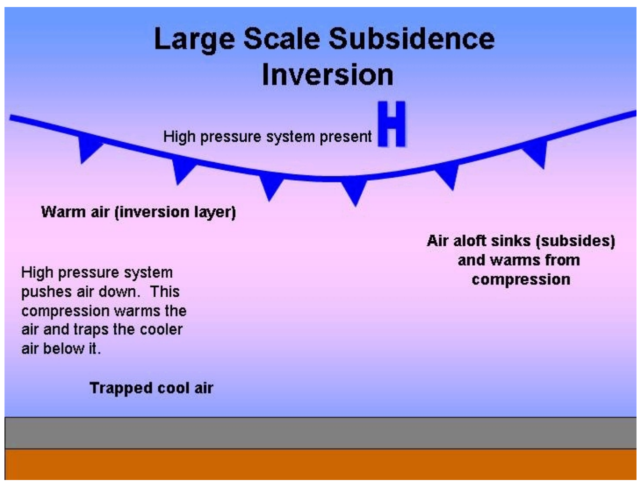
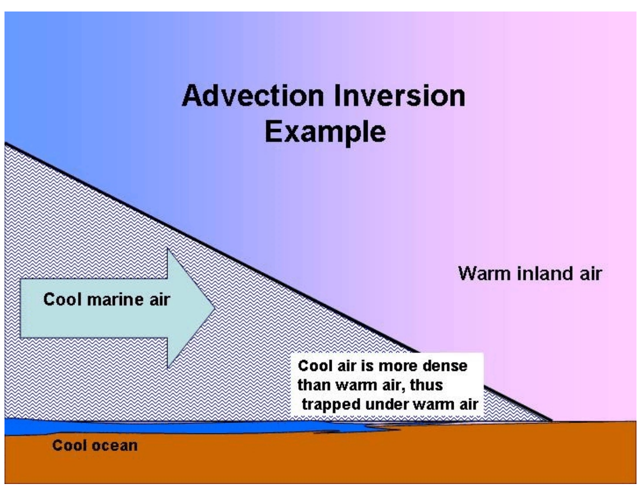
- In **unstable** conditions, the air parcel tends to move upward or downward and to continue that movement. Unstable conditions most commonly develop on sunny days with low wind speeds where strong solar radiation is present. The earth rapidly absorbs heat and transfers some of it to the surface air layer. As warm air rises, cooler air moves underneath. The cooler air, in turn, may be heated by the earth’s surface and begin to rise. Under such conditions, vertical motion in both directions is enhanced, and considerable vertical mixing occurs.

Inversions occur whenever warm over-runs cold air and "traps" the cold air beneath. Within these inversions there is little air motion, and the air becomes relatively stagnant. High air toxic concentrations can occur within inversions due to the limited amount of mixing between the "trapped" air and the surrounding atmosphere. Inversions can limit the volume of air into which emissions are dispersed, even from tall stacks. Exhibit 3 illustrates the three major types of inversions that are caused by different atmospheric interactions and can persist for different amounts of time.

Most common is the **radiation inversion**, which occurs when the earth's surface cools rapidly. As the earth cools, it also cools the layer of air close to the surface, which becomes trapped under the layer of warmer air above. Radiation inversions usually occur in the late evening through the early morning under clear skies with calm winds, when the cooling effect is greatest. In many cases, solar radiation following sunrise results in vigorous vertical mixing, which breaks down the inversion and disperses any trapped air pollutants. Under some conditions (e.g., thick fog), the daily warming may not be strong enough to break down the inversion layer. Inversions persisting for several days may lead to increased pollutant concentrations. This situation is most likely to occur in an enclosed valley, where nocturnal, cool, downslope air movement can reinforce a radiation inversion and encourage fog formation.

The **subsidence inversion** is almost always associated with high pressure systems. Air in a high pressure system descends and flows outward in a clockwise rotation in the Northern Hemisphere. As the air descends, the higher pressure present at lower altitudes enhances compression and warming. The inversion layer thus formed is often elevated several hundred meters above the ground surface during the day. At night, when the surface air cools, the base of the subsidence inversion often descends, even to the ground. The clear, cloudless days characteristic of high pressure systems encourage radiation inversions, so that there may be a surface inversion at night and an elevated inversion during the day. Although the layer below the inversion may vary diurnally, it will never become very deep. Subsidence inversions, unlike radiation inversions, last a relatively long time. They are associated with both the semi permanent high pressure systems centered on each ocean and the slow-moving high pressure systems that move generally from west to east across the United States. When a high pressure system stagnates, pollutant concentrations may become unusually high. The most severe air pollution episodes in the United States have occurred either under a stagnant high pressure system (for example, New York in November, 1966 and Pennsylvania in October, 1948) or under the eastern edge of the semi permanent high pressure system associated with the Pacific Ocean (Los Angeles).

Advection inversions are associated with air masses moving across surfaces of different temperatures than themselves. When warm air moves over a cold surface, the principles of conduction and convection cool the air nearer to the surface, causing a surface-based inversion. This inversion is most likely to occur in winter when warm air passes over snow cover or extremely cold land. The same type of inversion can occur when air cooled by a cold surface, such as the ocean, flows towards a warmer air mass, such as inland air in the summer.

Table 3. Types of Inversions




4.0 Meteorological Data

Measuring and recording meteorological variables provides the necessary information to manage the release of air contaminants into the atmosphere and to understand the transport and dispersion of emitted air pollutants. The most useful data in air pollution studies are wind speed and direction, ambient temperature and vertical temperature difference, solar radiation and mixing height. For indirect exposure, precipitation data are needed as well. These same variables can be used to make qualitative and quantitative predictions of ambient air toxic concentrations resulting from the release of air toxics, and to conduct quantitative risk assessments.

4.1 Wind Speed and Direction

It is common to consider wind speed and wind direction as separate variables. Wind speed determines the amount of initial dilution experienced by air toxics released into the atmosphere. Wind speed also influences the height to which the toxics will rise after being released from an elevated source - as wind increases, the air toxics are kept lower to the ground, allowing them to impact the ground at shorter distances downwind.

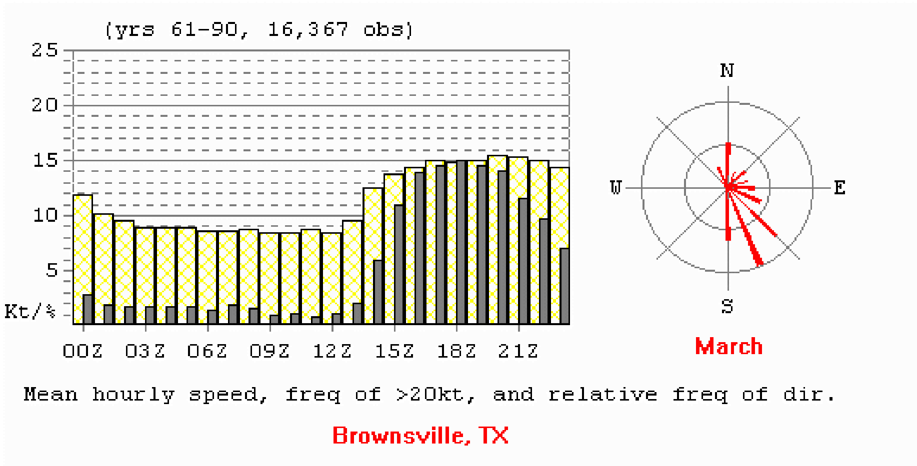
Wind direction for meteorological purposes is defined as the direction from which the wind is blowing. However, wind direction has both horizontal and vertical components. The horizontal and vertical components of the wind direction can be measured with a bi-directional wind vane or an anemometer.

Wind roses are often used to graphically depict the prevailing wind direction of an area. The wind rose depicts the relative frequency of wind direction, typically on a 16-point compass, with north, east, south, and west directions going clockwise. Each ring on the wind rose represents a frequency of the total. The WINDROSE program, which calculates and prints a frequency distribution for wind speed and wind direction for 36 (10 degree) sectors, can be obtained from EPA.[(2)]

Exhibit 4 presents an example wind rose for Brownsville, Texas. The right hand shows that the winds are predominantly from the south-southeasterly direction. The left hand side shows that the strongest winds occur between 14 and 21 UTC (8 A.M. to 3 P.M. CST). On average, 2 P.M. is the windiest time of day, averaging just over 15 knots (18 UTC). The shaded portion of the bar shows the frequency of winds over 20 knots. At noon CST, winds are over 20 knots approximately 15 percent of the time.

The distribution of pollutants is determined by the wind directions. A wind rose can provide information regarding the percentage of time that the direction(s) and speed(s) associated with a certain air quality can be expected over a time period. However, due to the influences of local terrain, possible coastal effects, exposure of the instruments, and temporal variability of the wind, the wind rose statistics from a nearby weather station may not always be representative of true wind speed and direction for the area of concern.

Exhibit 4. Example of a Wind Rose



Source: Brownsville CLIMATE page at:
http://www.srh.noaa.gov/bro/roshelp.htm

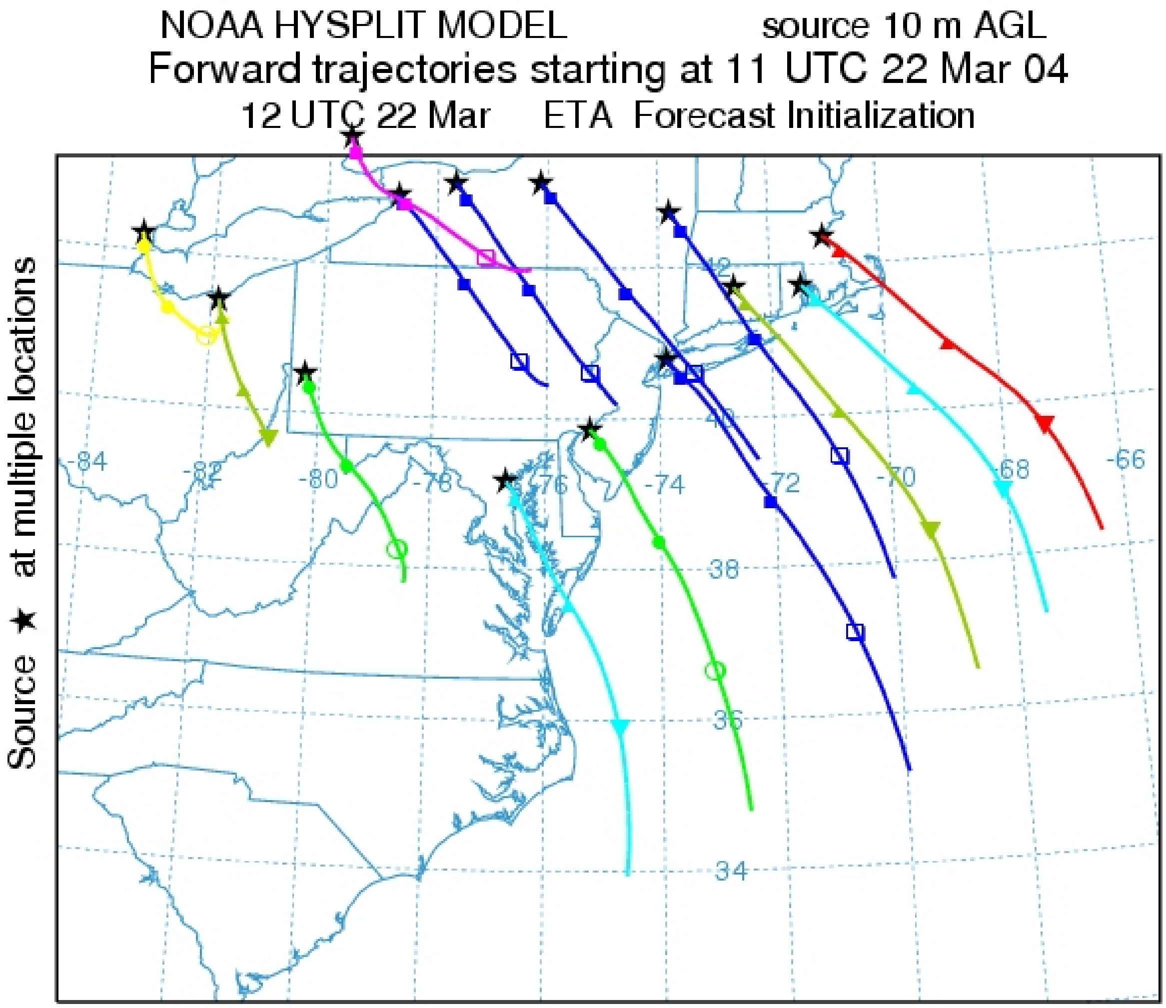
Another tool useful for understanding the distribution of pollutants is wind **trajectories**, which are aerial maps showing the path taken by a parcel of air over a period of time. Trajectories are important for understanding the transport of air toxics and/or the potential geographic regions from which sources of air toxics may emanate. Trajectories illustrate estimates of the general path that air has traveled over a recent time period in order to arrive at a particular location, and where it is likely to be going immediately afterward. The meteorological dynamics that cause air to rise or fall, and that determine its path, can affect air quality by carrying air toxics many miles from their sources. Exhibit 5 presents an example of a trajectory map for the Northeastern United States.

4.2 Other Important Meteorological Data

Both **ambient air temperatures** at a single level (typically 1.5 to 2 m) and **temperature differences** between two levels (typically 2 m and 10 m) are useful in air pollution studies. These temperature measurements are used in calculations of plume rise and can be used in determining atmospheric stability.

Solar radiation is related to the stability of the atmosphere. Cloud cover and ceiling height (height of the base of the cloud deck that obscures at least half the sky) data, taken routinely at National Weather Service (NWS) stations, provide an indirect estimation of radiation effects, and are used in conjunction with wind speed to derive an atmospheric stability category. If representative information is not available from routine NWS observations, it may be appropriate to measure solar radiation for use in determining atmospheric stability. For information on the use of cloud cover and ceiling height data in air toxics modeling, refer to EPA's Guideline on Air Quality Models.(3)

Exhibit 5. Example of a Trajectory Map



Source: National Oceanic and Atmospheric Administration (NOAA) HYSPLIT Model. [4]

The vertical depth of the atmosphere through which vertical mixing takes place is called the **mixing layer**. The top of the mixing layer is referred to as the **mixing height**. The mixing height is an important variable in air toxic studies, as it limits the vertical mixing of air toxics. Daytime mixing heights may reach as high as several kilometers during the day. Although mixing heights are not typically measured directly, they can be approximated from routine upper-air and surface meteorological measurements. In the daytime the mixing height is determined by the depth of the layer thorough which the sun's heating has established a well mixed conditions. On clear nights, radiational cooling might be expected to establish an inversions and reduce the mixing height to near zero. However, it has been found that in metropolitan areas, the urban heat island effect keeps the mixing height between 100 and 200 meters. The mixing heights are used in air quality models as an upper boundary to which air toxics can be mixed. The level of the mixing height is most important for elevated stacks and much less so for ground level sources.

4.3 Sources of Meteorological Data

The principal federal sources for meteorological data include:

- The National Climatic Data Center (NCDC) located in Asheville, NC.
- The National Weather Service (NWS) Forecast Centers
- The EPA Support Center for Regulatory Models (SCRAM) at Research Triangle Park, NC.

State climatological offices are excellent sources of meteorological data. Data can often be obtained in a text format, and can be used in conjunction with applications that are available as downloads from federal and state data Internet sites. Commercial and university Internet sites are also sources of current weather conditions.

The NCDC is the most extensive source of historical meteorological and climatological data. EPA's SCRAM site has surface and mixing height data that can be used to create wind roses and/or used in air dispersion models. These data are for the major NWS stations throughout the United States. The data are mostly for the years 1984 through 1992 (for surface data) or 1991 (for upper air data used for mixing heights). Exhibit 6 presents a list of Internet sites where meteorological data are available.

Exhibit 6. Internet Sites with Meteorological Data
National Climatic Data Center (http:// www.ncdc.noaa.gov/oa/ncdc.html) EPA SCRAM Site (http://www.epa.gov/scram001/) Weather Underground (http://www.wunderground.com/) UNSYSIS (http://weather.unisys.com/) NWS Pleasant Hill, MO (http://www.crh.noaa.gov/eax/) Western Regional Climate Center (http://www.wrcc.dri.edu/) Northeast Regional Climate Center (http://met-www.cit.cornell.edu/nrcc_home.html) Midwest Regional Climate Center (http://mcc.sws.uiuc.edu/) High Plains Regional Climate Center (http://www.hprcc.unl.edu/) Southern Regional Climate Center (http://www.srcc.lsu.edu/) Southeast Regional Climate Center (http://www.sercc.com/) WebMET.com (http://www.webmet.com/)

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3. U.S. Environmental Protection Agency. 2004. Technology Transfer Network. *Support Center for Regulatory Air Models, Guidance/Support, Modeling Guidance.* Updated March 22, 2004. Available at http://www.epa.gov/scram001/tt25.htm#guidance (Last accessed March 2004).

4. Rolph, G.D. 2003. Real-time Environmental Applications and Display sYstem (READY) Website. Available at: http://www.arl.noaa.gov/ready/hysplit4.html. NOAA Air Resources Laboratory, Silver Spring, MD. (Last accessed March 2004)