Beltsville PBL Air Quality Modeling – Atmospheric Chemistry
Air Pollution Meteorology
(Stockwell /McQueen/Rosa Fitzgerald)

Objective: Students will learn some of the meteorological factors that affect air quality and apply them.

Assignment

Part 1. Read the following pages of air pollution meteorology taken from the EPA document: "Guidelines for Developing an Air Quality (Ozone and PM2.5) Forecasting Program, EPA-456/R-03-002," U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards Information Transfer and Program Integration Division, AIRNow Program, Research Triangle Park, North Carolina, June 2003. We will discuss in a group.

Part 2 of the assignment follows the pages from the EPA report.

EPA-456/R-03-002
June 2003

Guidelines for Developing an Air Quality (Ozone and $PM_{2.5}$) Forecasting Program

U.S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Information Transfer and Program Integration Division
AIRNow Program
Research Triangle Park, North Carolina

2.3 METEOROLOGICAL CONDITIONS THAT INFLUENCE AIR QUALITY

This section presents the types of weather conditions that have a strong influence on $PM_{2.5}$ or ozone concentrations. Since daily weather variations best explain the day-to-day changes in air quality concentrations, understanding how weather influences air quality in a region is critical for producing accurate air quality forecasts.

Different scales of weather phenomena are important to air quality. The weather phenomena range from large storm systems that can encompass thousands of kilometers to small turbulent eddies that are a few meters in size. In general, large-scale weather phenomena are easier to characterize compared to small ones. In addition, weather forecast models typically do a better job of predicting large weather phenomena as opposed to small-scale, short lived phenomena. Therefore, to understand and predict air quality, it is usually best to use a large-scale to small-scale approach by first understanding the relationship between large-scale weather features and local air quality, and then understanding the relationship between local weather and air quality.

Meteorological conditions that strongly influence air quality include: transport by winds, recirculation of air by local wind patterns, and horizontal dispersion of pollution by wind; variations in sunlight due to clouds and season; vertical mixing and dilution of pollution within the atmospheric boundary layer; temperature; and moisture. The variability of these processes, which affects the variability in pollution, is primarily governed by the movement of large-scale high- and low-pressure systems, the diurnal heating and cooling cycle, and local and regional topography.

Figures 2-12 and 2-13 show the general relationships among meteorological phenomena and air quality. **Table 2-5** describes how specific meteorological conditions directly influence $PM_{2.5}$ and ozone concentrations. The remainder of this section discusses the key meteorological phenomena in these figures and tables. Educational resources on basic meteorology are available on the Internet (Cooperative Program for Operational Meteorology, 2002; University of Illinois Urbana-Champaign, 2002).

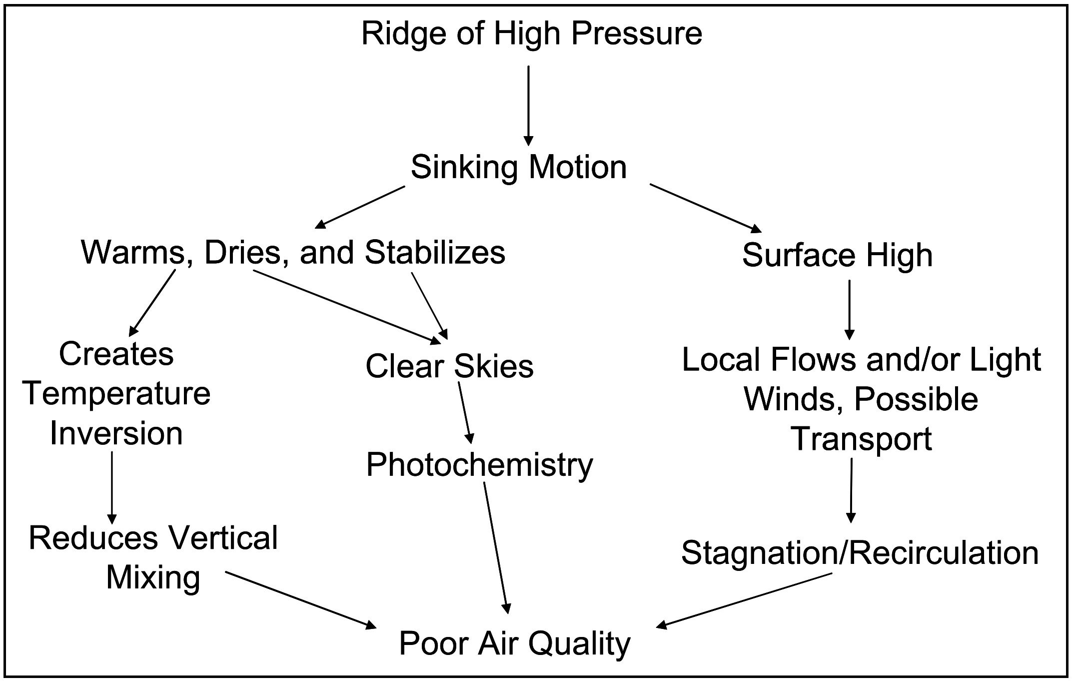

Figure 2-12. Schematic of the typical meteorological conditions and air quality often associated with an aloft ridge of high pressure.

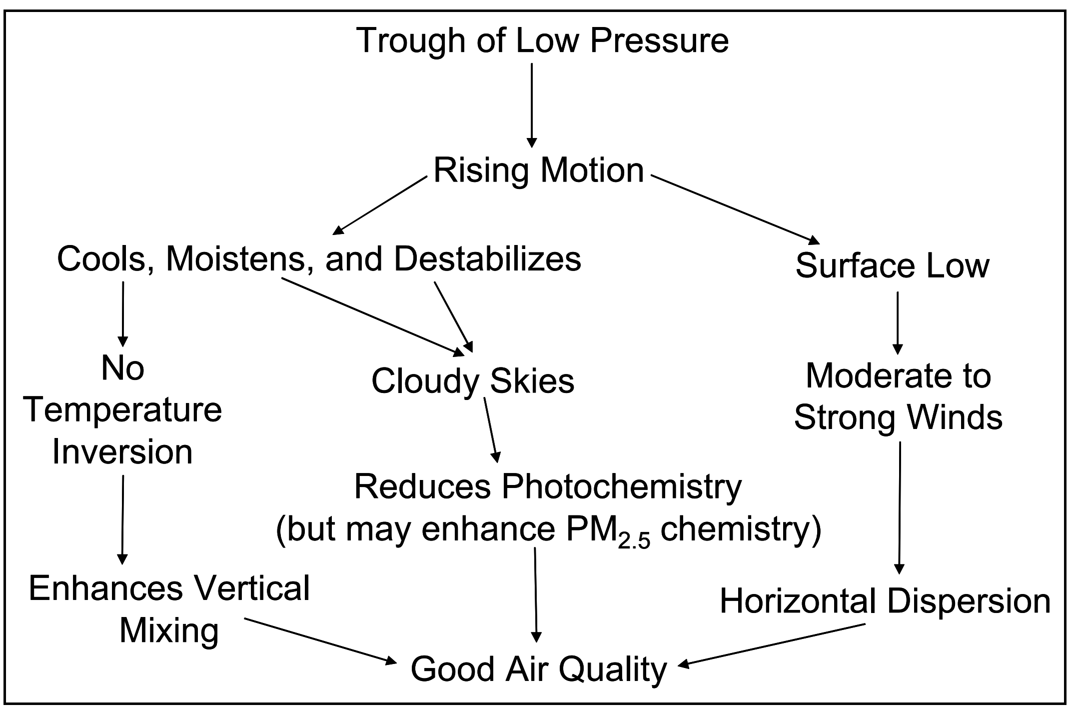

Figure 2-13. Schematic of the typical meteorological conditions and air quality often associated with an aloft trough of low pressure.

Table 2-5. Meteorological phenomena and their influence on $PM_{2.5}$ and ozone concentrations.

Phenomena	Emissions	Chemistry	Accumulation/Dispersion/Removal
Aloft Pressure Pattern	No direct impact.	No direct impact.	Ridges tend to produce conditions conducive for accumulation of $PM_{2.5}$ and ozone. Troughs tend to produce conditions conducive for dispersion and removal of PM and ozone. In mountain-valley regions, strong wintertime inversions and high $PM_{2.5}$ levels may not be altered by weak troughs. In addition, high $PM_{2.5}$ and ozone concentrations often occur during the approach of a trough from the west.
Winds and Transport	No direct impact.	In general, stronger winds disperse pollutants, resulting in a less ideal mixture of pollutants for chemical reactions that produce ozone and $PM_{2.5}$.	Strong surface winds tend to disperse $PM_{2.5}$ and ozone regardless of season. However, strong winds can create dust which can increase $PM_{2.5}$ concentrations. In the East and Midwest, winds from a southerly direction are often associated with high $PM_{2.5}$ and ozone, due to transport from one region to another.
Temperature Inversions	No direct impact.	Inversions reduce vertical mixing and therefore increase chemical concentrations of precursors. Higher concentrations of precursors can produce faster, more efficient chemical reactions that produce ozone and $PM_{2.5}$.	A strong inversion acts to limit vertical mixing allowing for the accumulation of $PM_{2.5}$ or ozone.
Rain	No direct impact.	Rain can remove precursors of ozone and $PM_{2.5}$.	Rain can remove $PM_{2.5}$, but has little influence on existing ozone.
Moisture	No direct impact.	Moisture acts to increase the production of secondary $PM_{2.5}$ including sulfates and nitrates.	No direct impact.
Temperature	Warm temperatures are associated with increased evaporative, biogenic, and power plant emissions, which act to increase both $PM_{2.5}$ and ozone. Cold temperatures can also indirectly influence $PM_{2.5}$ concentrations (i.e., home heating on winter nights).	Photochemical reaction rates for ozone increase with temperature.	Although warm surface temperatures are generally associated with poor air quality conditions, very warm temperatures can increase vertical mixing and dispersion of pollutants.
Clouds/Fog	No direct impact.	Water droplets can enhance the formation of secondary $PM_{2.5}$. Clouds can limit photochemistry, which limits ozone production.	Convective clouds are an indication of strong vertical mixing, which disperses pollutants.
Season	Forest fires, wood burning, agriculture burning, field tilling, windblown dust, road dust, and construction vary by season.	The sun angle changes with season, which changes the amount of solar radiation available for photochemistry.	No direct impact.

2.3.1 Aloft Pressure Patterns

Aloft large-scale (1000 km or more) atmospheric circulations have a strong influence on regional and local weather conditions. Meteorologists generally focus on the so-called "500-mb level" to evaluate the aloft large-scale pressure systems. In particular, they focus on the location, size, intensity, and movement of 500-mb high-pressure ridges and low-pressure troughs (mountains of warm air and cold air, respectively). In general, poor air quality conditions are associated with high-pressure ridges and good air quality conditions are associated with low-pressure troughs. However, high $PM_{2.5}$ levels can occur without the existence of aloft ridges, from a very strong $PM_{2.5}$ emission source, such as a forest fire. **Figure 2-14** shows an example of a 500-mb ridge over the eastern United States on July 17, 1999, a day with high $PM_{2.5}$ concentrations throughout the region, and on September 21, 1999, a day with low $PM_{2.5}$ concentrations throughout the region. The existence of ridges and troughs can be diagnosed by reviewing weather charts, which are widely available as observations and forecasts on the Internet.

2.3.2 Temperature Inversions and Vertical Mixing

A temperature inversion is a layer of warm air above a layer of relatively cooler air. An inversion acts to limit the vertical mixing of pollutants, which allows concentrations to build. Several temperature inversions can exist at different altitudes in the lower part of the atmosphere. Typically, a temperature inversion can form from 25 to 300 m agl when the ground (and air near the ground) cools at night, while air above remains warmer. This type of inversion is called a nocturnal inversion. Nocturnal inversions are strongest when skies are clear at night and in the winter when nights are long. In the presence of clouds or strong winds, nocturnal inversion are often weak or do not form at all. Nocturnal inversions trap emissions, released during the overnight hours, close to the ground. As the ground warms during the day, the air near the surface warms, which erodes the nocturnal inversion. Typically, a nocturnal inversion disappears by mid-morning, allowing the trapped pollutants to mix vertically. If a nocturnal inversion is strong or if solar heating is weak, the inversion may not break until late in the day or at all. Under these circumstances, pollutants do not mix vertical and high pollutant concentrations are typical.

When there is an aloft ridge of high pressure over an area, there is often another inversion above the nocturnal inversion, called a subsidence inversion. A subsidence inversion is caused by sinking air in the mid- to low-levels of the atmosphere associated with the aloft ridge. As the air sinks, it warms due to compression. The warmest temperatures associated with the sinking air are typically found from 500 to 2000 m agl. When there is a strong subsidence inversion as indicated by aloft temperatures, the daytime heating at the surface may not be strong enough to break this inversion. Under such circumstances, vertical mixing of pollutants is weak and pollutants remain trapped near the surface for the entire day. An aloft inversion can also form when winds transport warm air at a greater rate aloft compared to the surface. This differential warming typically occurs on the west side of an upper-level ridge, ahead of an upper-level trough.

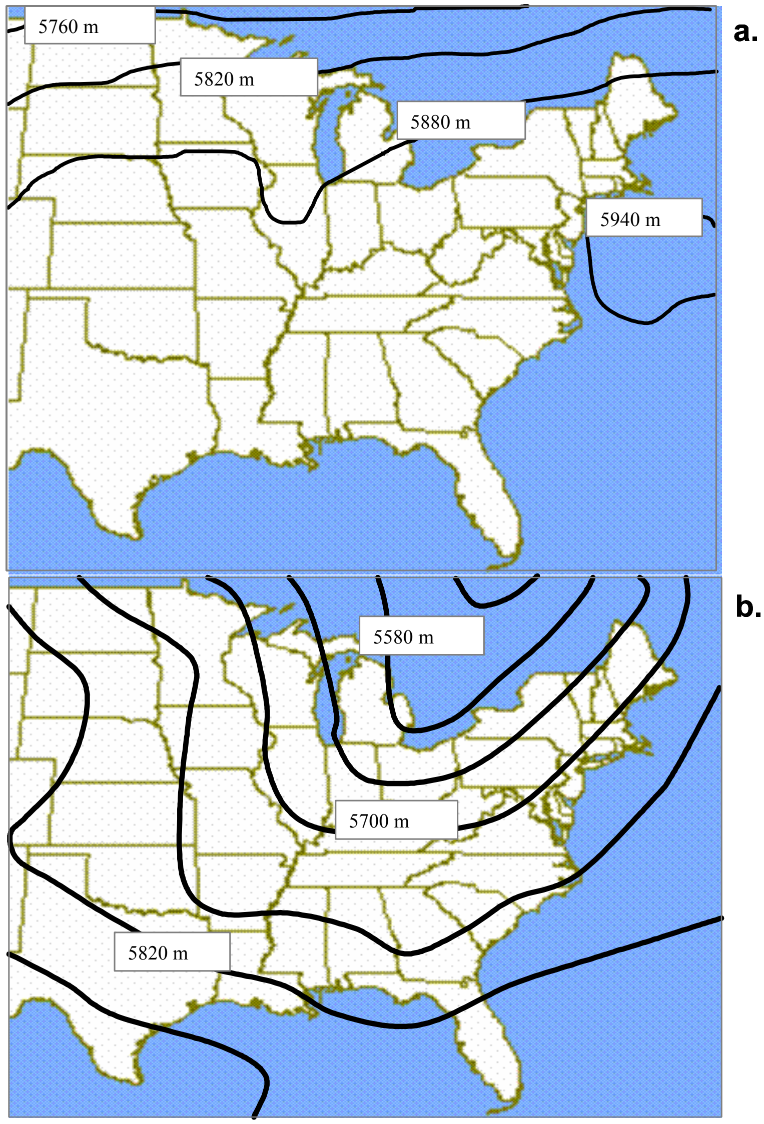

Figure 2-14. 500-mb heights (a) on the morning of July 17, 1999 (1200 UTC) and (b) on the morning of September 21, 1999 (1200 UTC).

Subsidence inversions do not form when there is an aloft trough over the region. This is because aloft troughs cause rising motion in the mid- to low-levels of the atmosphere. As the air rises, it cools due to expansion resulting in cooler air above warmer air. When there is cooler air above warmer air, the atmosphere is unstable. This instability causes vertical mixing, which dilutes pollutants whose source is near the surface.

Figure 2-15 shows the diurnal cycle of mixing, vertical temperature profiles, and boundary layer height on a day with a weak temperature inversion and on a day with a strong temperature inversion. On the day with the weak inversion, the convective boundary layer grows rapidly as the sun warms the ground during the day. The rapid growth of the convective boundary layer is associated with strong vertical mixing and the vertical dispersion of pollutants.

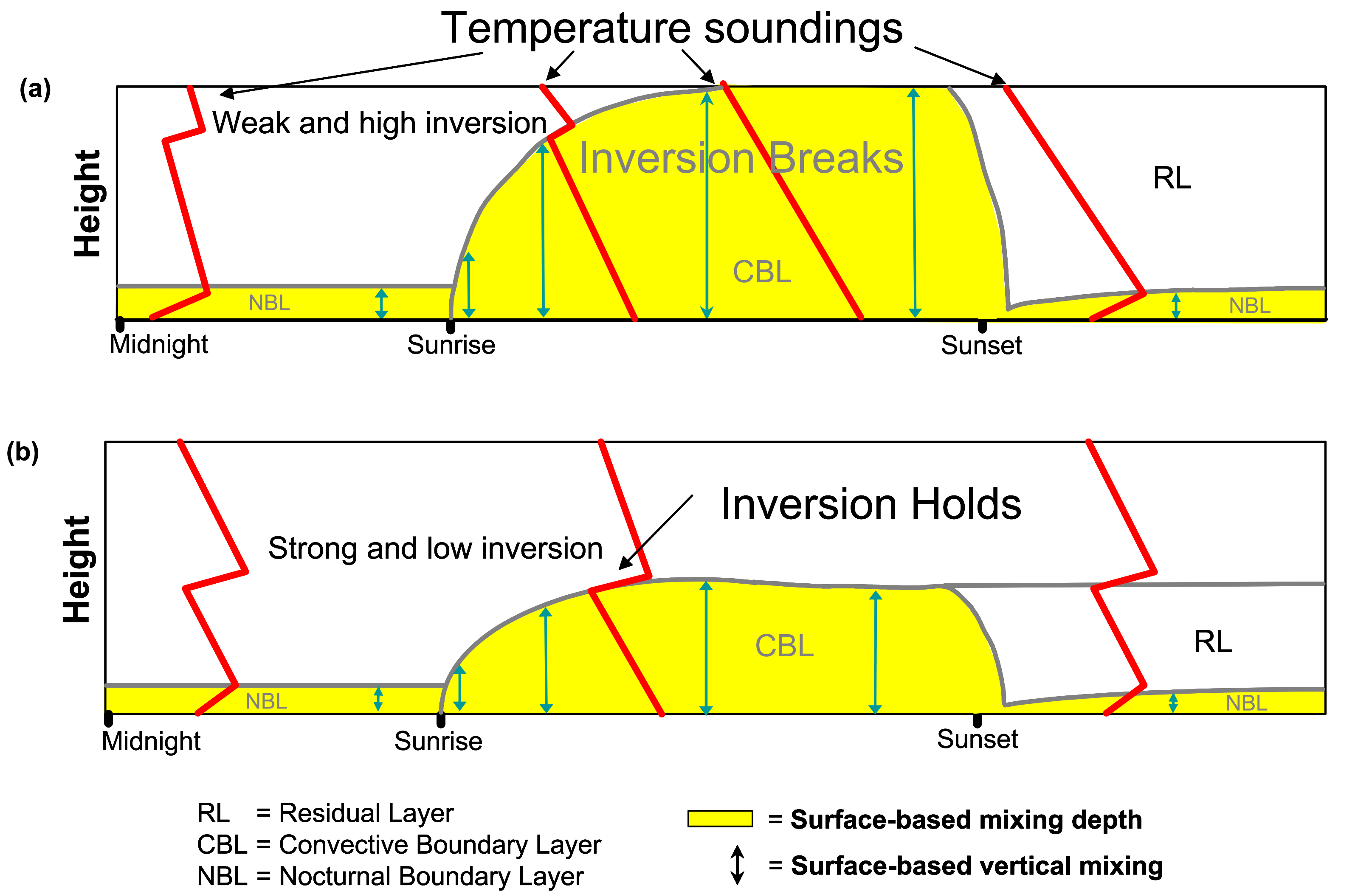

Figure 2-15. Schematic showing diurnal cycle of mixing, vertical temperature profiles, and boundary layer height (a) on a day with a weak temperature inversion and (b) on a day with a strong temperature inversion. In (a) the pollutants mix into a large volume resulting in low pollution levels and in (b) pollutants mix into a smaller volume resulting in high pollution levels.

On the day with the strong inversion, the convective boundary layer growth is inhibited. The limited growth of the convective boundary layer is associated with weak vertical mixing and limited vertical dispersion of pollutants.

2.3.3 Winds and Transport

Winds can be described as large-, regional-, and local-scale. The large-scale winds are driven by the pressure gradients between surface high- and low-pressure systems. Light, regional, surface winds often occur near the center of the surface-high, below the ridge of high pressure, where pressure gradients are weak. Light winds are not effective at dispersing pollutants and, therefore, often occur during high pollutant concentrations. Moderate to strong winds occur between surface high and low pressure systems or near the center of low pressure systems, provided that moderate to strong pressure gradients exist. Moderate to strong surface winds act to disperse pollution and thus are typically associated with low pollutant concentrations. However, high pollutant concentrations can occur during moderate to strong wind conditions, if the winds transport pollution from one region to another.

In general, surface lows occur under the leading half of aloft troughs (typically on the eastern side), whereas, surface highs occur under the leading half of aloft ridges. **Figures 2-16 and 2-17**, respectively, show a 500-mb ridge and an associated surface high and a 500-mb trough and an associated surface low. The ridge and surface high on January 7, 2002, created conditions conducive to high $PM_{2.5}$ concentrations in Salt Lake City, Utah, including light surface winds and reduced vertical mixing. The trough and surface low on January 22, 2002, created conditions conducive to low $PM_{2.5}$ concentrations including strong surface winds, clouds, and vertical mixing.

Local winds are driven by the interaction between the large-scale pressure patterns and local forcing mechanisms. The local forcing mechanisms are driven by the diurnal temperature cycle and topography. Local winds tend to dominate over the large- and regional-scale winds when the large-scale pressure patterns are weak (i.e., at the center of a surface high pressure). The local winds may include land breezes, sea breezes, morning downslope flows, afternoon upslope flows, and terrain channeled flows, which can combine in various ways to recirculate air and cause stagnation.

2.3.4 Clouds, Fog, and Precipitation

Clouds, rain, and fog all influence pollutant concentrations through a variety of mechanisms as detailed in Table 2-5. Clouds form when air is cooled and water vapor condenses. This cooling can be caused by rising motion or contact with a cool surface such as a body of water or cool land during the night. Rising motion is generated by aloft low-pressure systems, frontal boundaries, air flowing over mountains, and convective instability (warm air below cooler air). Clouds are important because they typically reduce the amount of sunlight available for photochemical reactions that participate in the production of ozone and $PM_{2.5}$. Fog is a type of cloud that is in contact with or near the ground. Fog and clouds can dramatically increase the conversion of sulfur dioxide to sulfate (a secondary type of $PM_{2.5}$). Precipitation is a removal mechanism for fine particles.

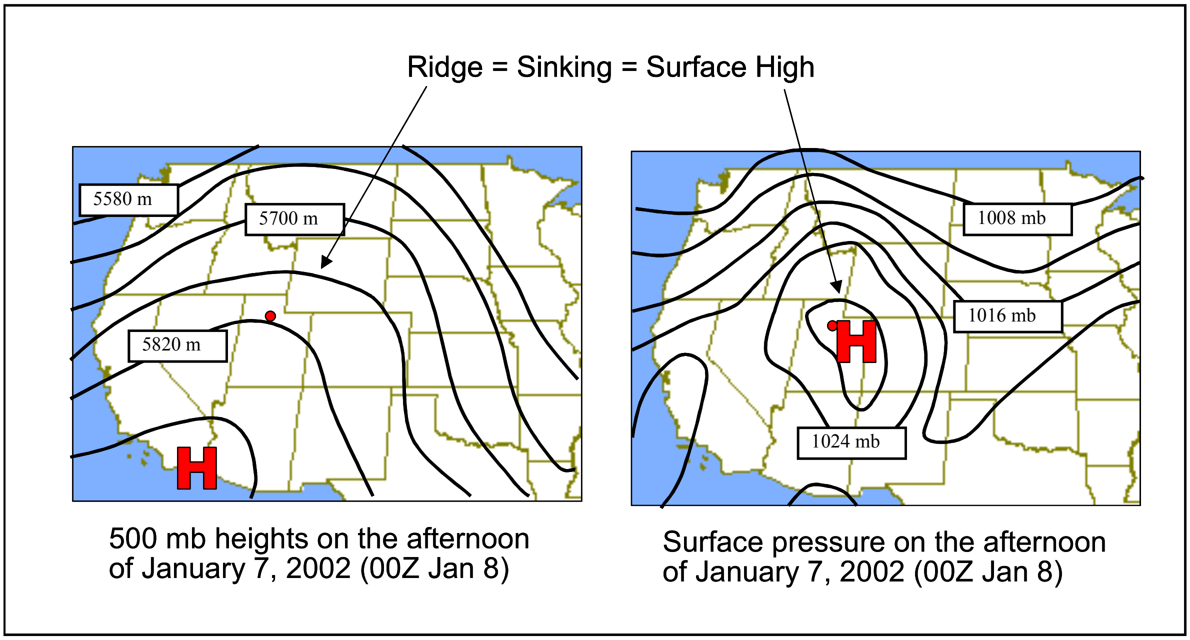

Figure 2-16. 500-mb heights (left) and surface pressure (right) on the afternoon of January 7, 2002 (0000 UTC on January 8).

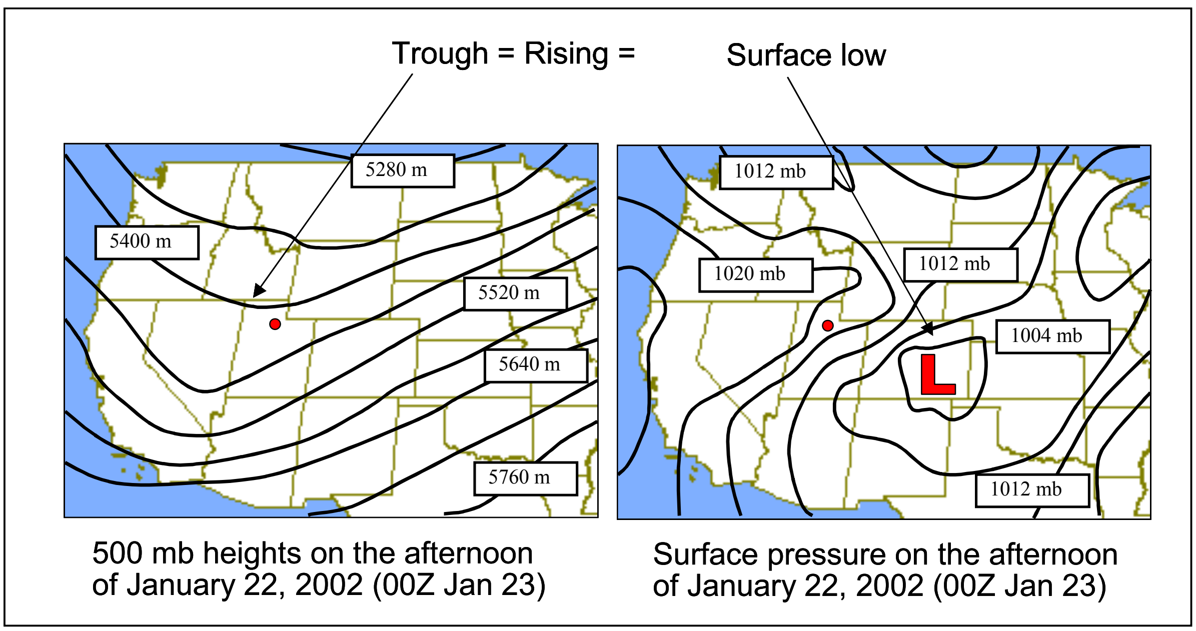

Figure 2-17. 500-mb heights (left) and surface pressure (right) on the afternoon of January 22, 2002 (0000 UTC on January 23).

2.3.5 Weather Pattern Cycles

Typically, a region will cycle between a ridge and trough pattern every 2 to 7 days, but more stationary patterns can develop. Studying and understanding these cycles and their impact on local weather and air quality will help improve forecasting capabilities. **Figure 2-18** shows the typical life cycle of large-scale weather patterns. The following meteorological descriptions are generic and may vary from one region to another and between pollutants:

Ridge—high pressure pattern (Figure 2-18a and b) is typically associated with poor air quality. This pattern occurs about one to two days after a cold front and trough have passed through an area. As surface high pressure develops in an area, winds become weak allowing for the accumulation of pollutants. Warming temperatures increase the biogenic and evaporative VOCs and lower humidity results in clearer skies, which are favorable for photochemistry. Sinking air (subsidence) warms and stabilizes the lower atmosphere, which suppresses cloud development and mixing. In addition, an aloft temperature inversion may form that inhibits vertical mixing and reduces dilution of pollutants. The aloft high pressure ridge typically occurs west of the surface high and can be diagnosed using 500-mb height fields.

Ridge—back side of high pattern (Figure 2-18c and d) occurs as the surface high pressure moves east of the region and the accumulated pollutants are transported to downwind locations. In some regions, warm air is advected into the region and winds may increase from a southerly to a westerly direction depending on the orientation of the high. This pattern typically produces warm temperatures and relatively clear skies, even with a low-pressure system approaching from the west. Pollutant levels can remain high on these types of days, and the potential for longer-range transport is greater.

Trough—cold front pattern (Figure 2-18e and f) is characterized by a low-pressure system at the surface and associated cold and warm fronts. Aloft at 500 mb, a trough of low pressure exists just upstream (west) of the surface low. This weather pattern produces clouds and precipitation that reduce photochemistry. Stronger winds and mixing also reduce pollutant concentrations.

Although aloft ridges and their associated regional and local weather conditions are generally associated with poor air quality, slight variations in the meteorological processes described above can have a dramatic affect on the spatial and temporal characteristics of air quality. It is these variations in meteorological processes that need to be analyzed and understood for different pollutants, seasons, and regions of interest to better understand the processes that produce air quality episodes.

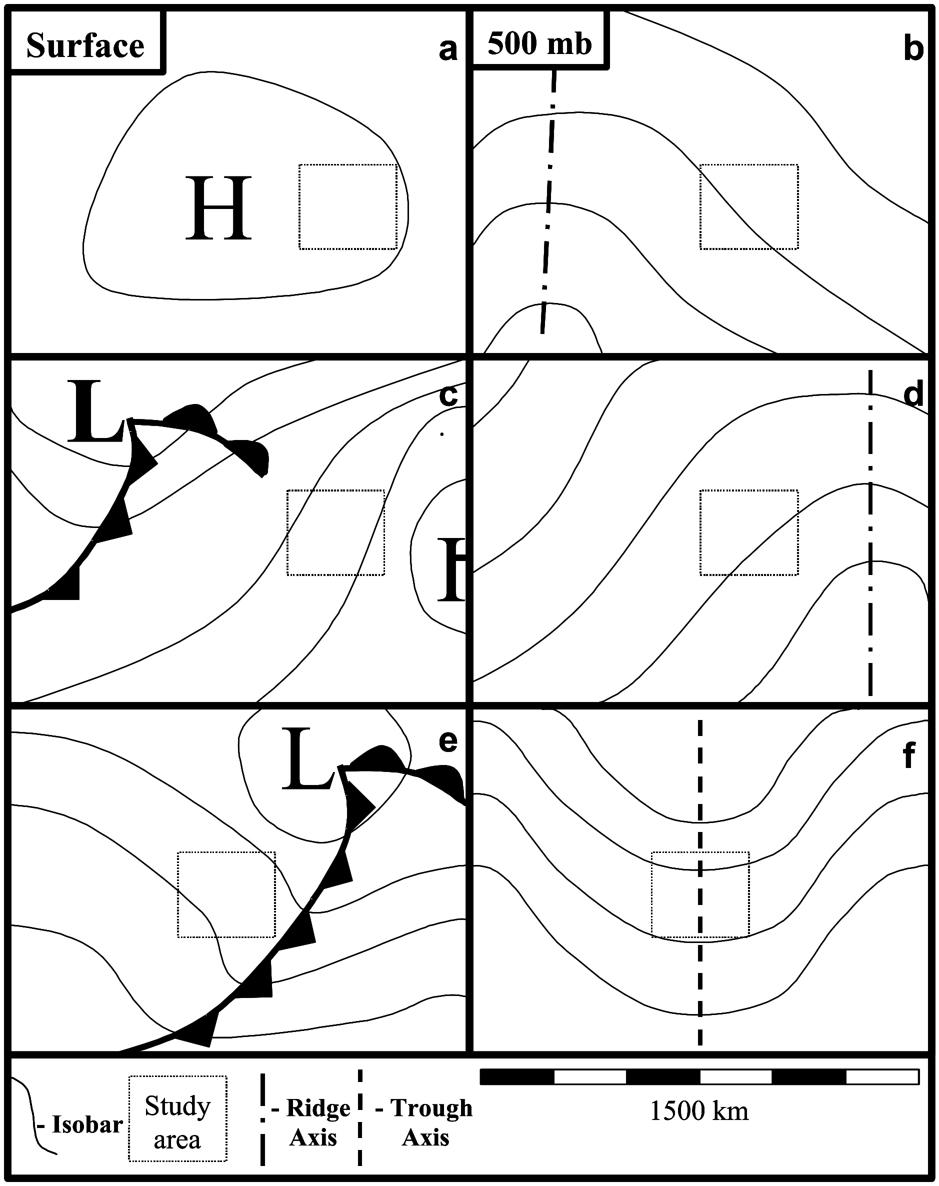

Figure 2-18. Life cycle of synoptic weather events at the surface and aloft at 500 mb for (a) and (b) Ridge—high pressure, (c) and (d) Ridge—back side of high, and (e) and (f) Trough—cold front patterns. Surface maps show isobars and frontal positions. The 500-mb maps show contours of equal height.

Assignment Part 2

Below are plots of the meteorological forecast, maximum ozone and total integrated smoke column across the continental United States (CONUS) for June 14, 2020. Examine these plots in view of the what you have just read. Be able to discuss, present or write how much these illustrate how meteorology affects air quality.

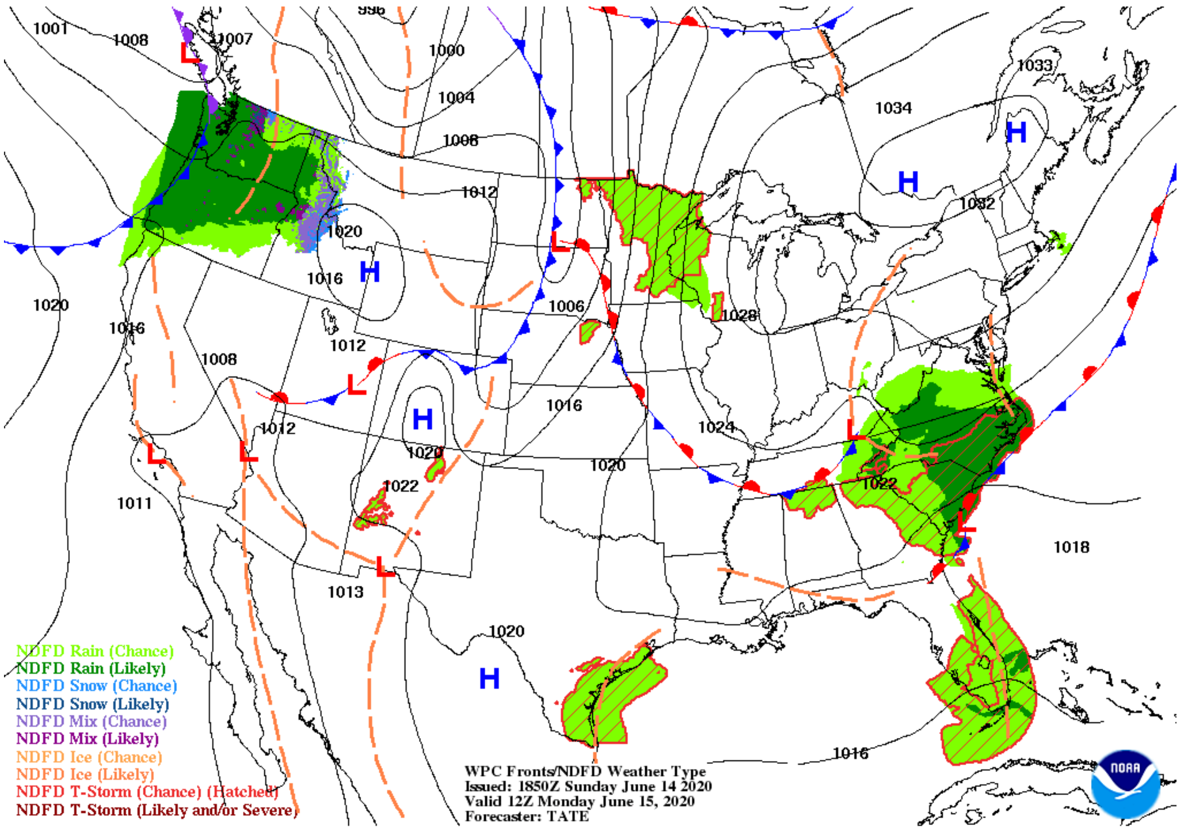

Figure 1. Meteorological forecast for June 15, 2020.

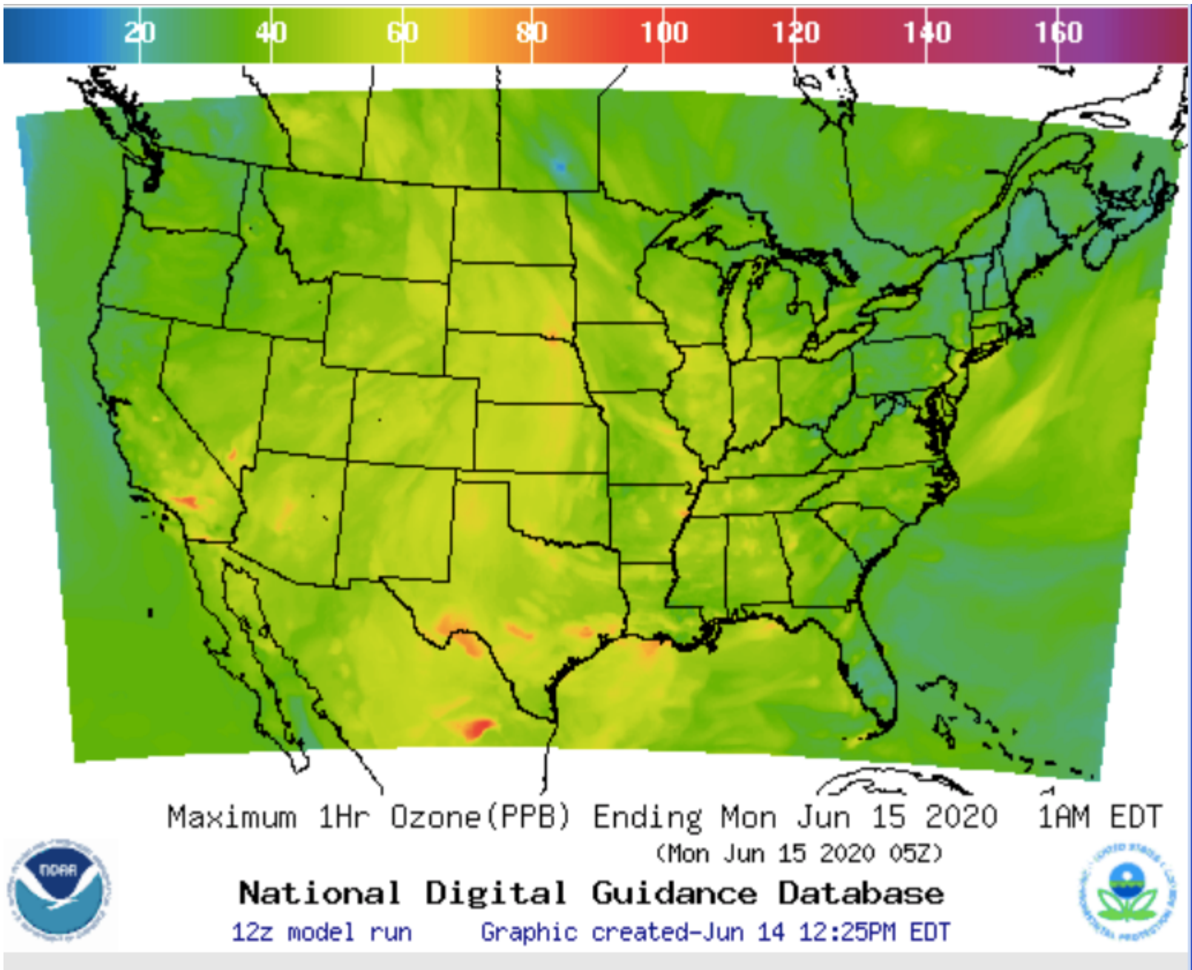

Figure 2. Air quality forecast for June 15, 2020. The ozone concentrations are given in units of ppbV.

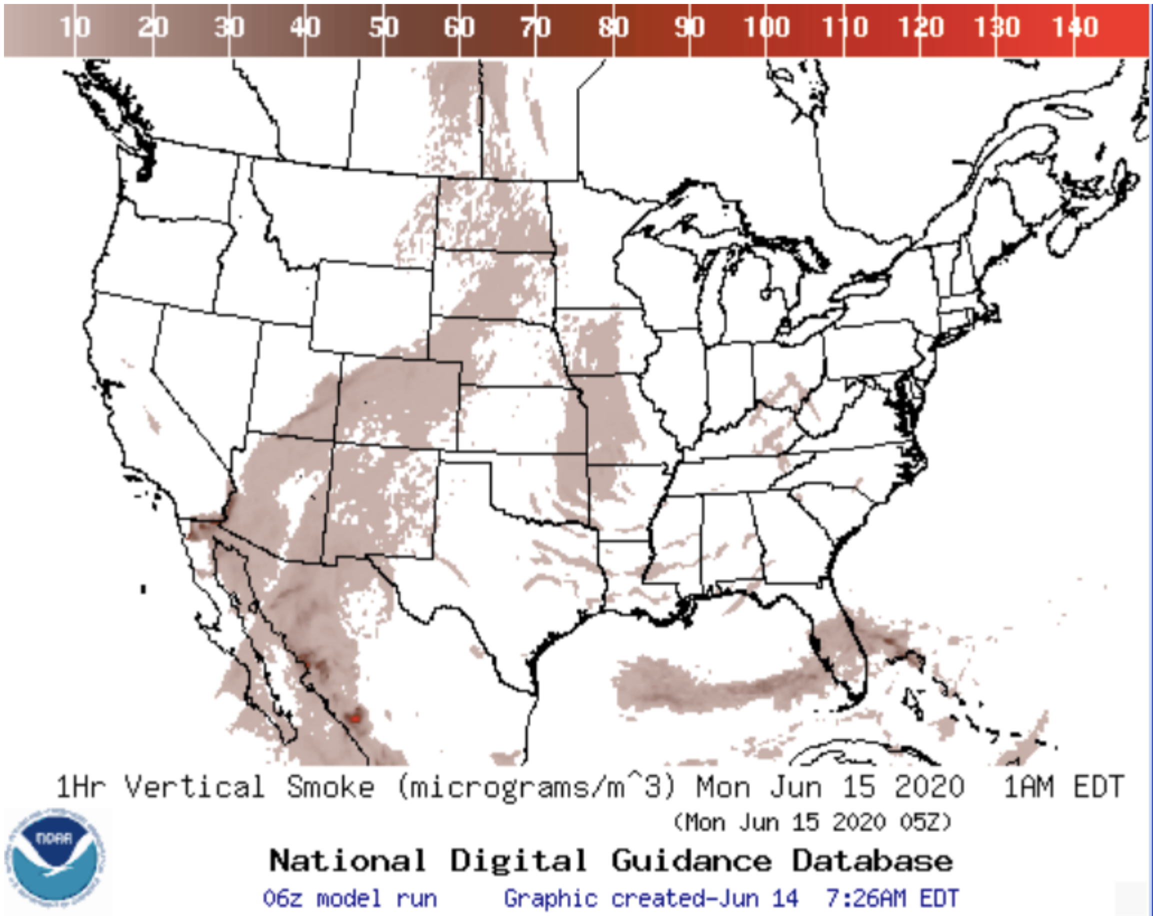

Figure 3. Vertical smoke forecast for June 15, 2020. The smoke concentrations are given in units micrograms m^{-3}.