Air Pollution: Concepts & Factors

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Concepts

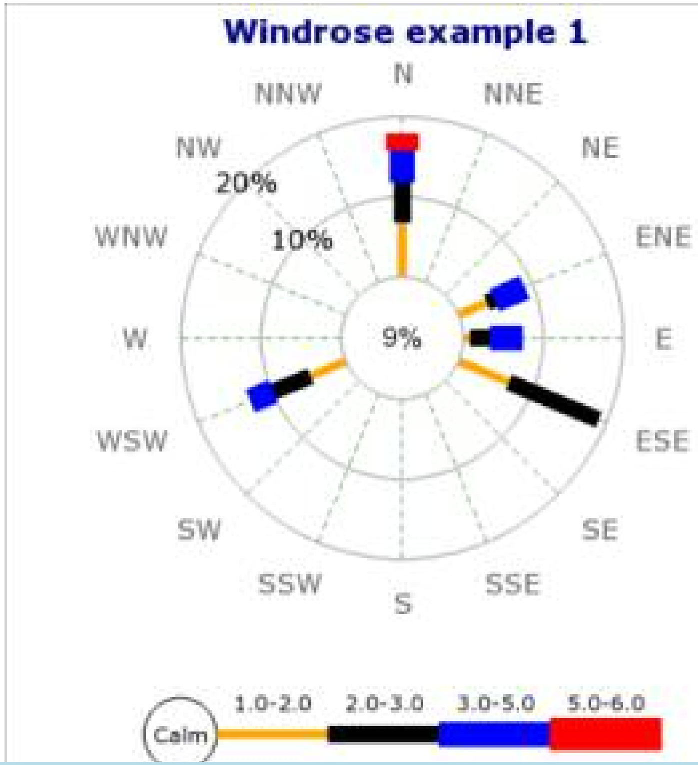
- High wind speeds result in lower pollutant concentrations,
- Seasonal wind directions and patterns identify communities that may be vulnerable to pollutant exposure,
- In urban areas, for example, a record of wind direction is used to estimate average concentrations of hydrocarbons, sulfur dioxide, and other pollutants,
- A wind rose is a diagram designed to depict the relative frequency with which the wind blows from the various directions around the compass. Specific information can be recorded for seasonal wind patterns as well as local fluctuations by time of day.

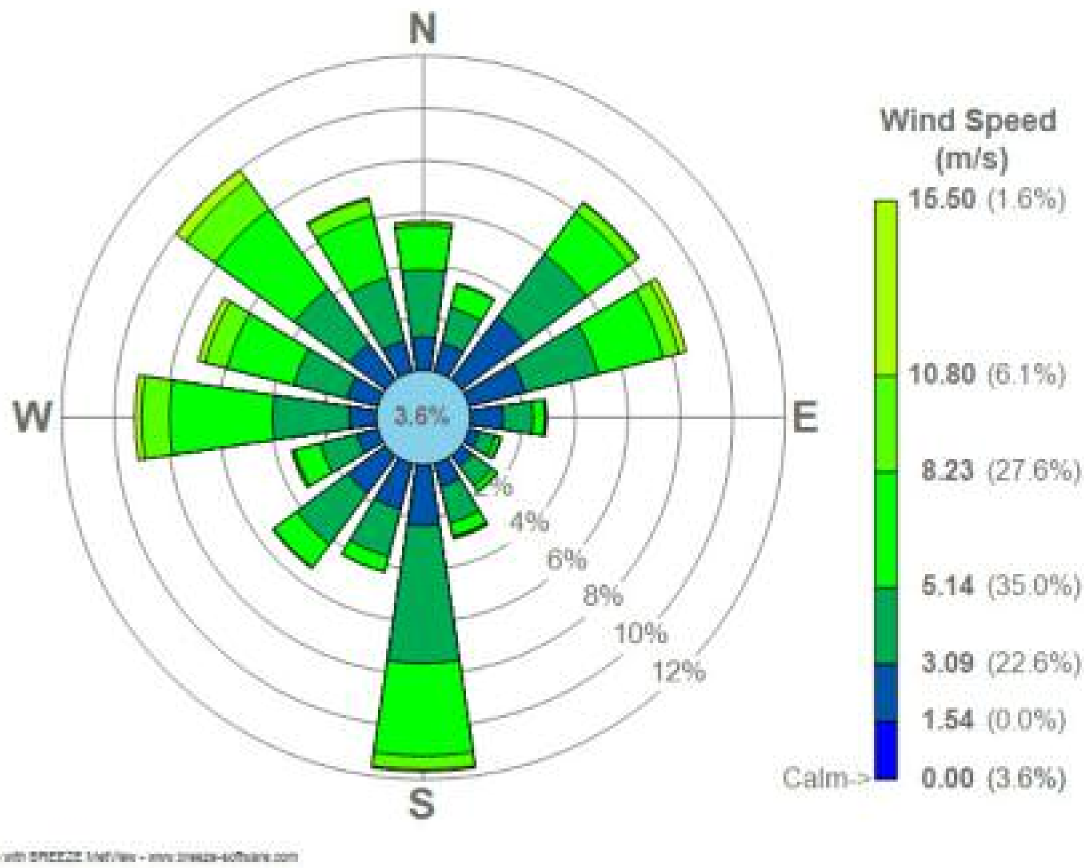
Rotating Cup Anemometer

Wind Direction Vane

Wind rose

A wind rose is a chart which gives a view of how **wind speed** and **wind direction** are distributed at a particular location over a specific period of time.





Atmospheric Stability

- While wind speed and direction generally relate to the horizontal movement of air, atmospheric stability relates to the forces that move air vertically.

- The vertical movement of air, or atmospheric stability, is most directly affected by high and low-pressure systems that lift air over terrain and mix it with the upper atmosphere.

- The mechanisms that are specifically responsible for the vertical movement of air are atmospheric temperature and pressure.

- Differential heating: Conduction & Convection (the vertical mixing of the air)

Principles Related to Vertical Motion

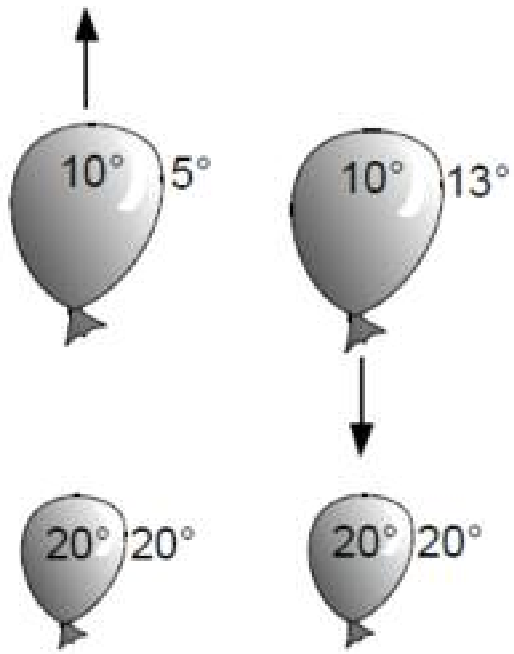
Parcel

- A *parcel* of air is theoretically infinitesimal parcel is a relatively well-defined body of air (a constant number of molecules) that acts as a whole.

- 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.



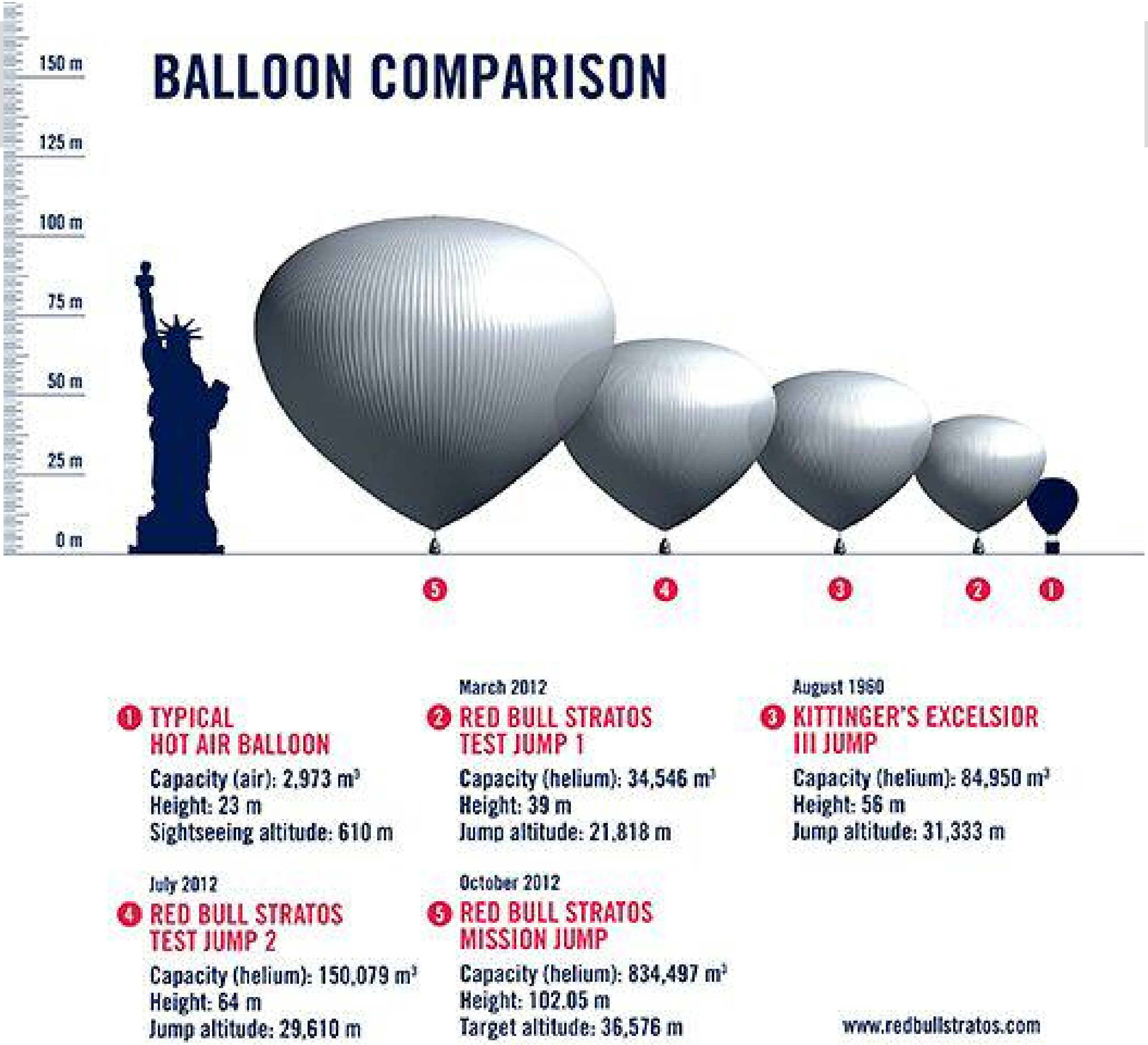
Buoyancy Factors

- Atmospheric temperature and pressure influence the buoyancy of air parcels. Holding other conditions constant, the temperature of air (a fluid) increases as atmospheric pressure increases, and conversely decreases as pressure decreases.
- With respect to the atmosphere, where air pressure decreases with rising altitude, the normal temperature profile of the troposphere is one where temperature decreases with height.
- An air parcel that becomes warmer than the surrounding air (for example, by heat radiating from the earth's surface), begins to expand and cool. As long as the parcel's temperature is greater that the surrounding air, the parcel is less dense than the cooler surrounding air. Therefore, it rises, or is buoyant. As the parcel rises, it expands thereby decreasing its pressure and, therefore, its temperature decreases as well. The initial cooling of an air parcel has the opposite effect.

In short, warm air rises and cools***, while*** cool air descends and warms

The extent to which an air parcel rises or falls depends on the relationship of its temperature to that of the surrounding air. As long as the parcel's temperature is greater, it will rise; as long as the parcel’s temperature is cooler, it will descend.

When the temperatures of the parcel and the surrounding air are the same, the parcel will neither rise nor descend unless influenced by wind flow.

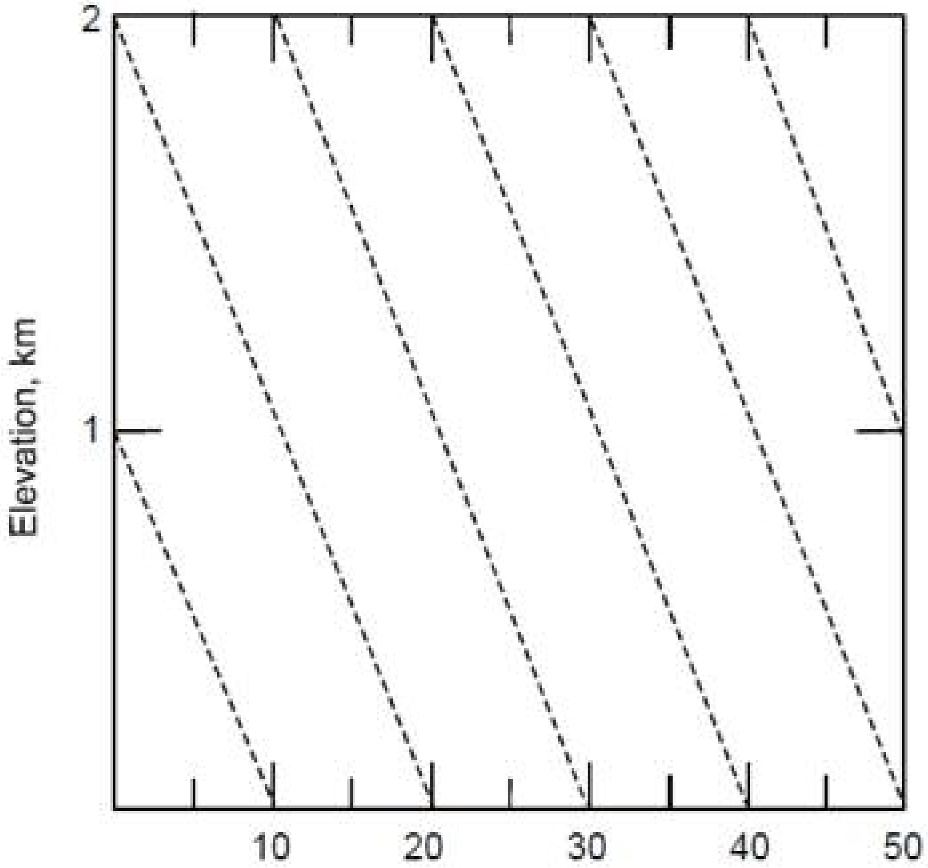

BALLOON COMPARISON
150 m
125 m
100 m
75 m
50 m
25 m
0 m
5
4
3
2
1
1 TYPICAL HOT AIR BALLOON
Capacity (air): 2,973 m³
Height: 23 m
Sightseeing altitude: 610 m
March 2012
2 RED BULL STRATOS TEST JUMP 1
Capacity (helium): 34,546 m³
Height: 39 m
Jump altitude: 21,818 m
August 1960
3 KITTINGER'S EXCELSIOR III JUMP
Capacity (helium): 84,950 m³
Height: 56 m
Jump altitude: 31,333 m
July 2012
4 RED BULL STRATOS TEST JUMP 2
Capacity (helium): 150,079 m³
Height: 64 m
Jump altitude: 29,610 m
October 2012
5 RED BULL STRATOS MISSION JUMP
Capacity (helium): 834,497 m³
Height: 102.05 m
Target altitude: 36,576 m
www.redbullstratos.com

Lapse Rates

- The **lapse rate** is defined as the rate at which air temperature changes with height.
- The actual lapse rate in the atmosphere is approximately −6 to −7°C per km (in the troposphere) but it varies widely depending on location and time of day.
- We define a temperature *decrease* with height as a negative lapse rate and a temperature *increase* with height as a positive lapse rate.

Dry Adiabatic lapse rate

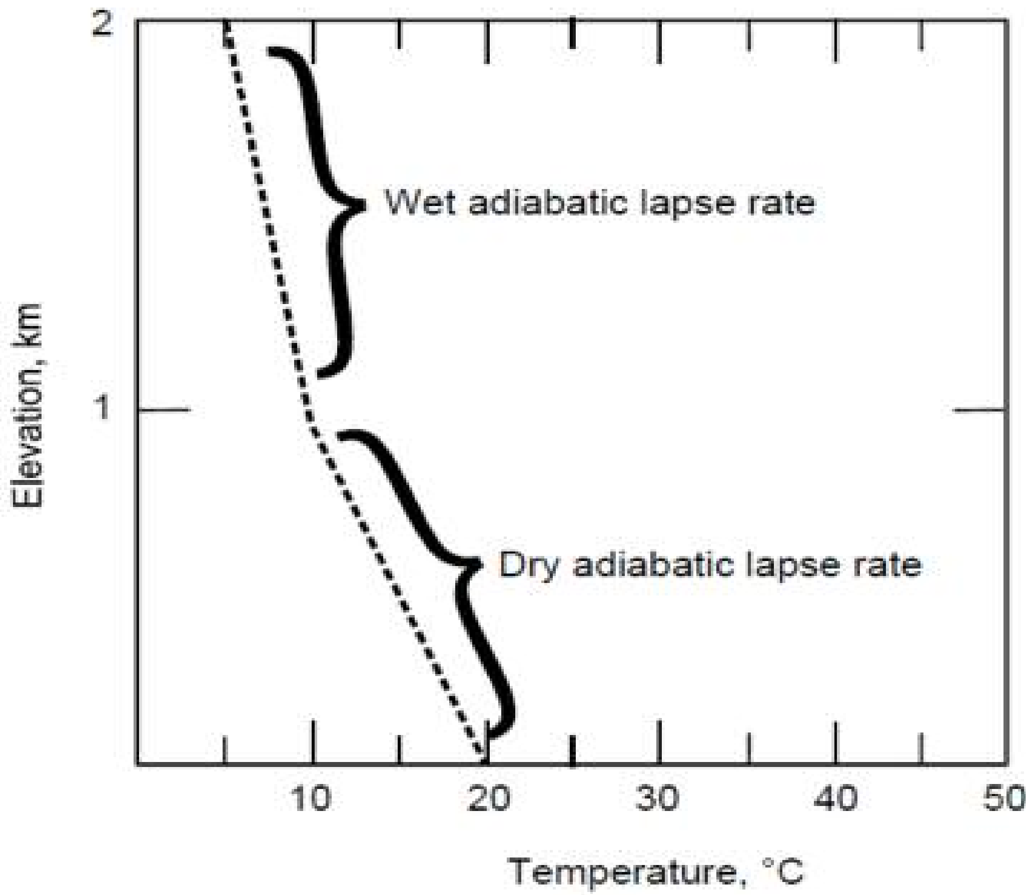
- The dry adiabatic lapse rate is a fixed rate, entirely independent of ambient air temperature.
- An air parcel that is warmer than the surrounding air does not transfer heat to the atmosphere.
- A dry air parcel rising in the atmosphere cools at the dry adiabatic rate of 9.8°C/1000m and has a lapse rate of −9.8°C/1000m. Likewise, a dry air parcel sinking in the atmosphere heats up at the dry adiabatic rate of 9.8°C/1000m and has a lapse rate of 9.8°C/1000m. Air is considered dry, in this context, as long as any water in it remains in a gaseous state.



In an adiabatic process, compression results in heating and expansion results in cooling.

Wet Adiabatic lapse rate

- A rising parcel of dry air containing water vapor will continue to cool at the dry adiabatic lapse rate until it reaches its condensation temperature, or dew point. At this point the pressure of the water vapor equals the saturation vapor pressure of the air, and some of the water vapor begins to condense.
- Condensation releases latent heat in the parcel, and thus the cooling rate of the parcel slows.



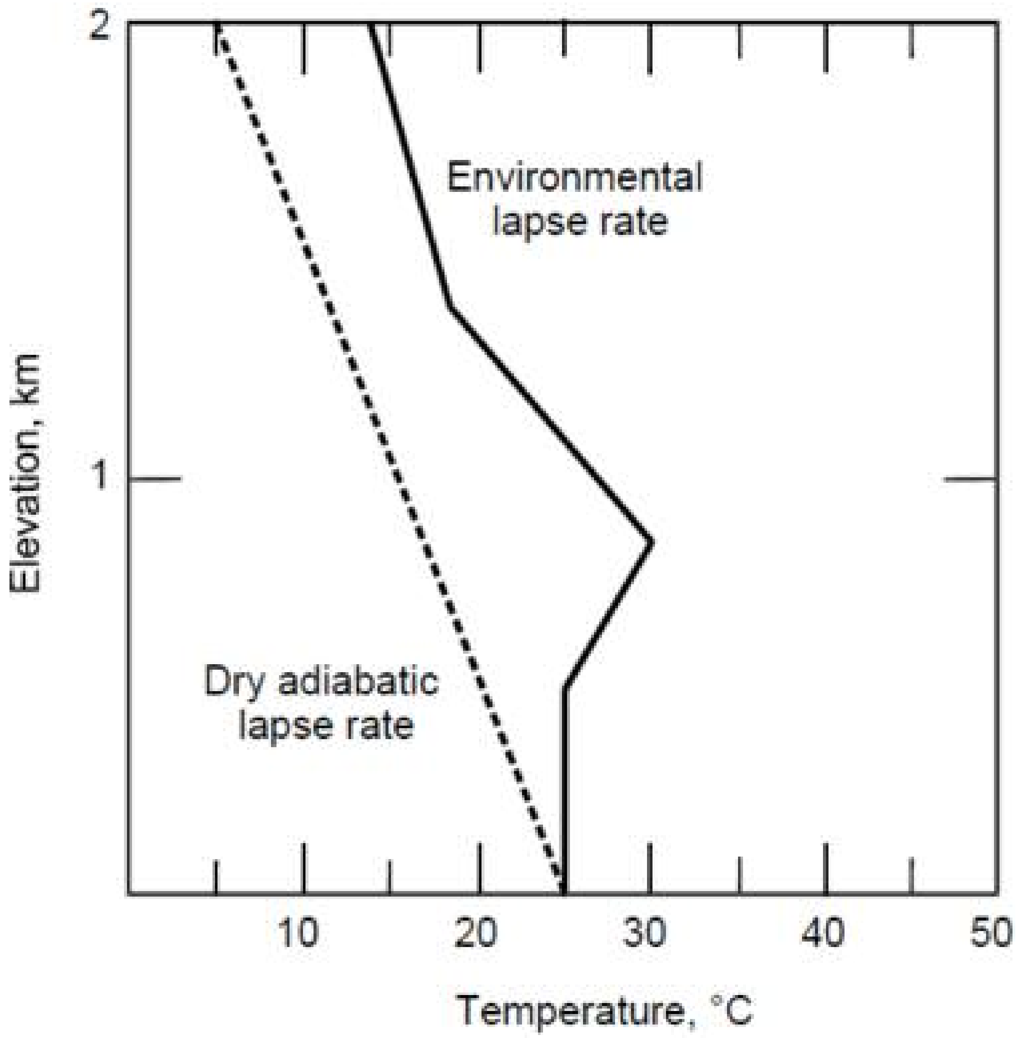
Unlike the **dry adiabatic lapse rate**, the **wet adiabatic lapse rate** is not constant but depends on temperature and pressure. In the middle troposphere, however, it is assumed to be approximately −6 to −7^{o}C/1000 m.

Environmental lapse rate

The actual temperature profile of the ambient air shows the **environmental lapse rate**.

Sometimes called the **prevailing** or **atmospheric lapse rate**, it is the result of complex interactions of meteorological factors, and is usually considered to be a decrease in temperature with height.

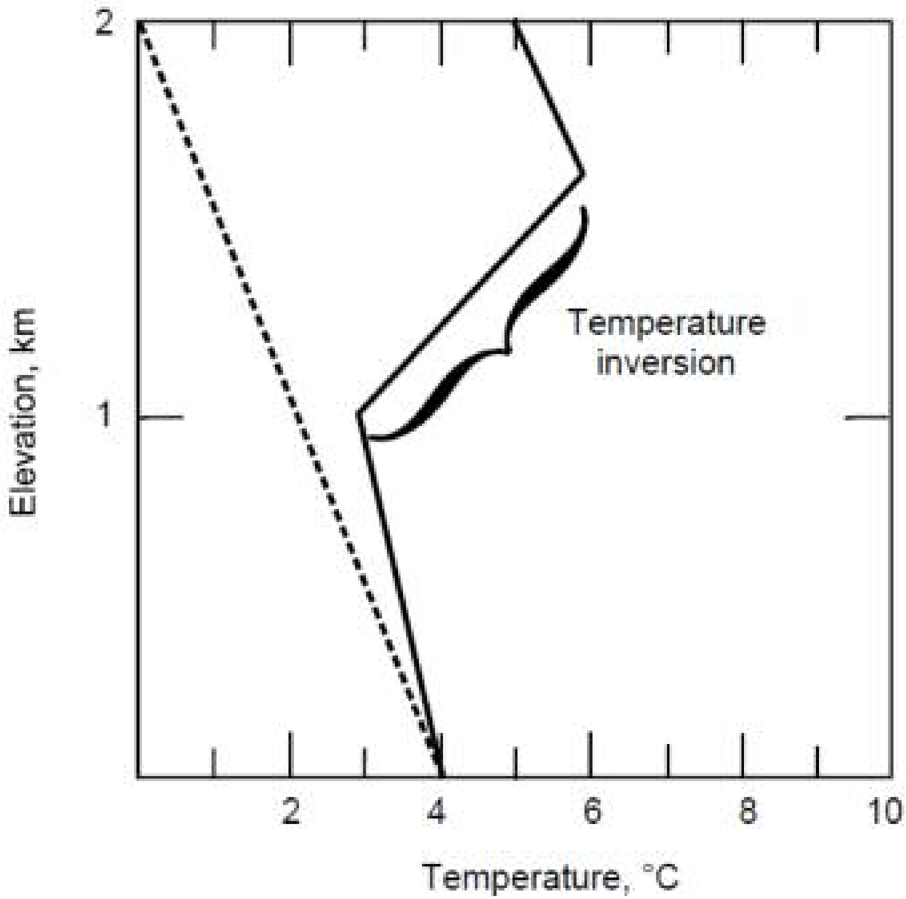
It is particularly important to vertical motion since surrounding air temperature determines the extent to which a parcel of air rises or falls.



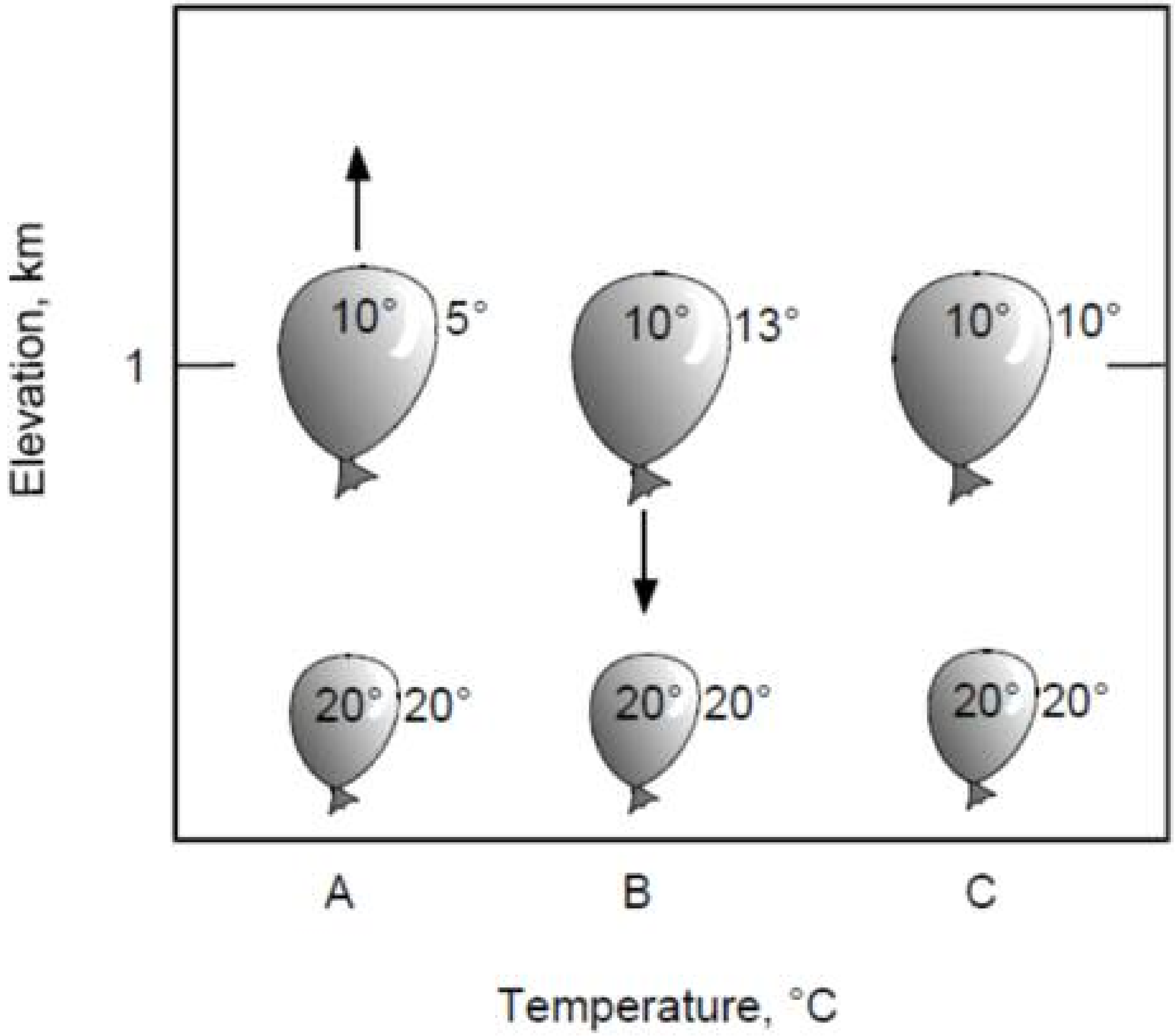
- The temperature profile can vary considerably with altitude, sometimes changing at a rate greater than the dry adiabatic lapse rate and some times changing less.

- The condition when temperature actually increases with altitude is referred to as a **temperature inversion**.

- The temperature inversion occurs at elevations of from 200 to 350 m. This situation is particularly important in air pollution, because it limits vertical air motion.



Relationship of adiabatic lapse rate to air temperature

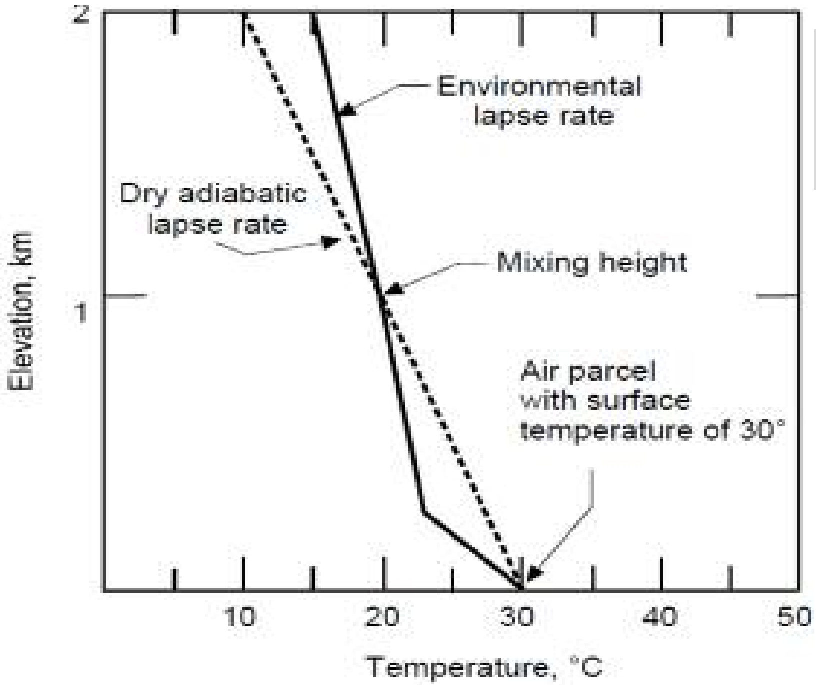


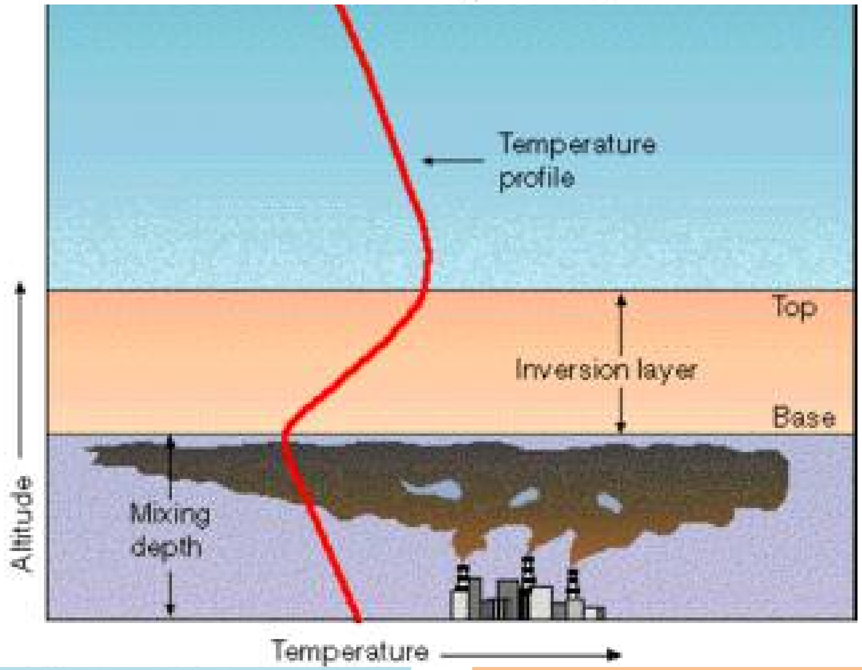
Mixing Height

In an adiabatic diagram, the point at which the air parcel cooling at the dry adiabatic lapse rate intersects the ambient temperature profile "line" is known as the **mixing height**.

This is the air parcel's maximum level of ascendance. In cases where no intersection occurs, the mixing height may extend to great heights in the atmosphere.

The air below the mixing height is the **mixing layer**. The deeper the mixing layer, the greater the volume of air into which pollutants can be dispersed.





Atmospheric Stability

- The degree of stability of the atmosphere is determined by the temperature difference between an air parcel and the air surrounding it.

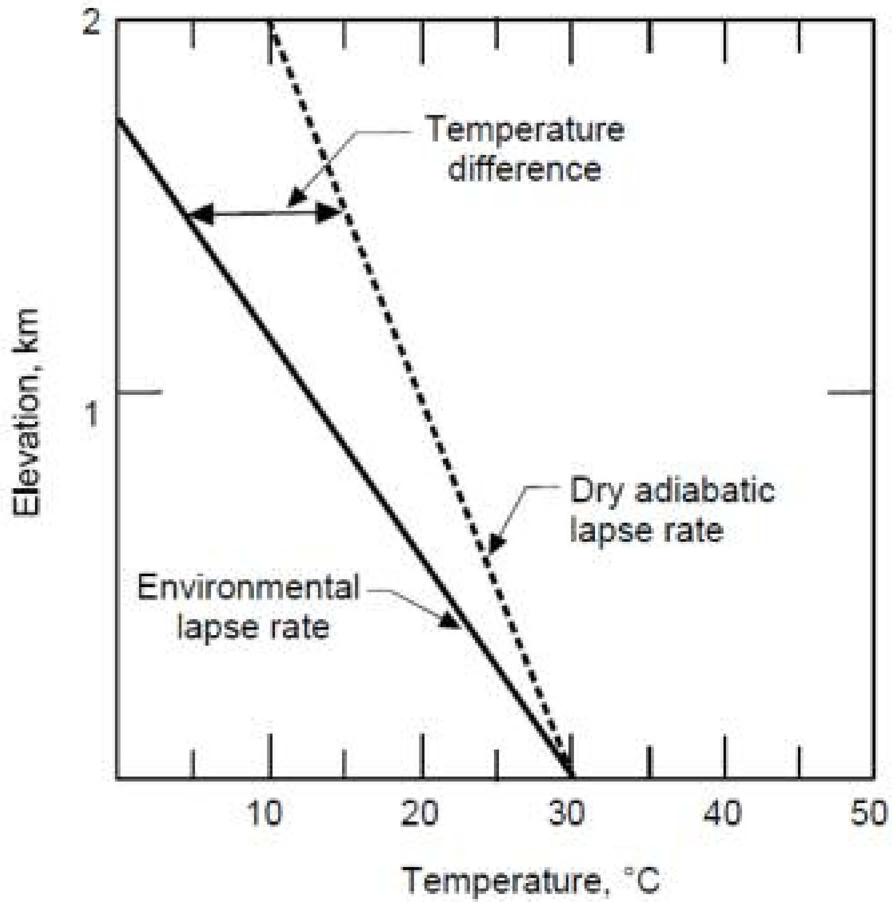
- This difference can cause the parcel to move vertically (i.e., it may rise or fall). This movement is characterized by four basic conditions:

  - In **stable** conditions, this vertical movement is discouraged,
  - in **unstable** conditions the air parcel tends to move upward or downward and to continue that movement,
  - In **neutral** conditions, the conditions which neither encourage nor discourage air movement beyond the rate of adiabatic heating or cooling,
  - **Inversion** conditions, which are extremely stable, cooler air near the surface is trapped by a layer of warmer air above it.

Unstable Conditions

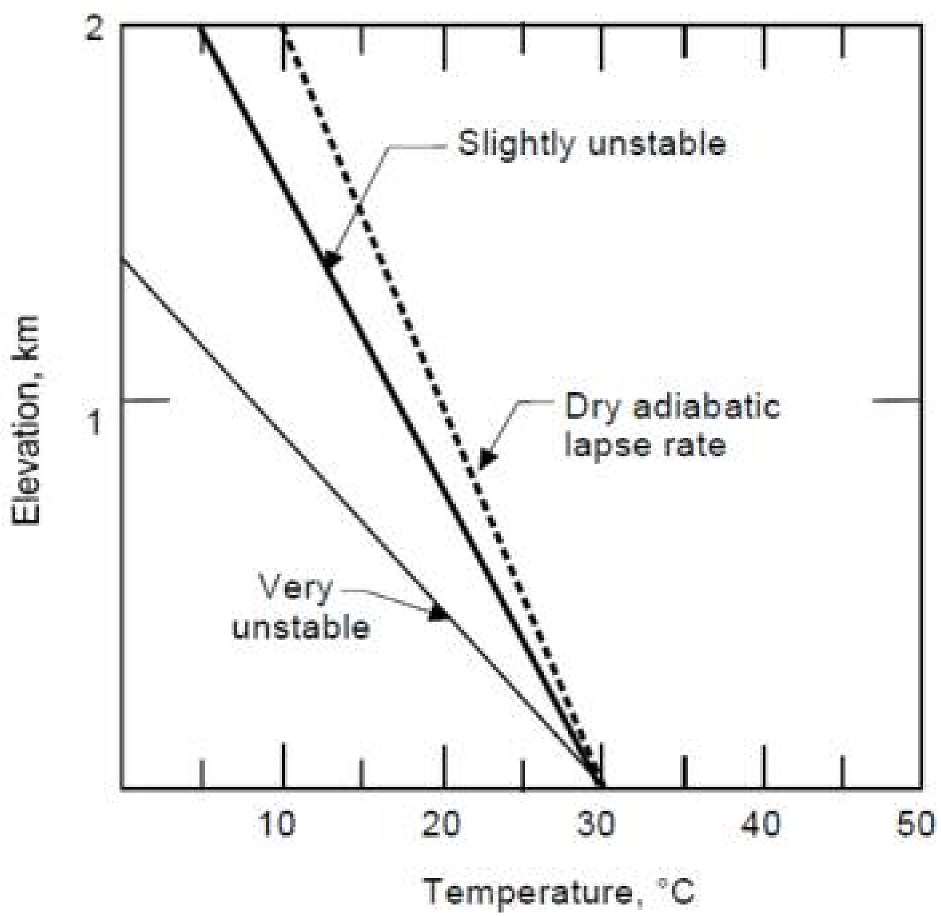
- This assumes that the surrounding atmosphere has a lapse rate greater than the adiabatic lapse rate (cooling at more than 9.8°C/1000 m), so that the rising parcel will continue to be warmer than the surrounding air. This is a **superadiabatic lapse** rate.

- the temperature difference between the actual environmental lapse rate and the dry adiabatic lapse rate actually increases with height, and buoyancy is enhanced.



As the air rises, cooler air moves underneath. It, 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. The degree of instability depends on the degree of difference between the environmental and dry adiabatic lapse rates.

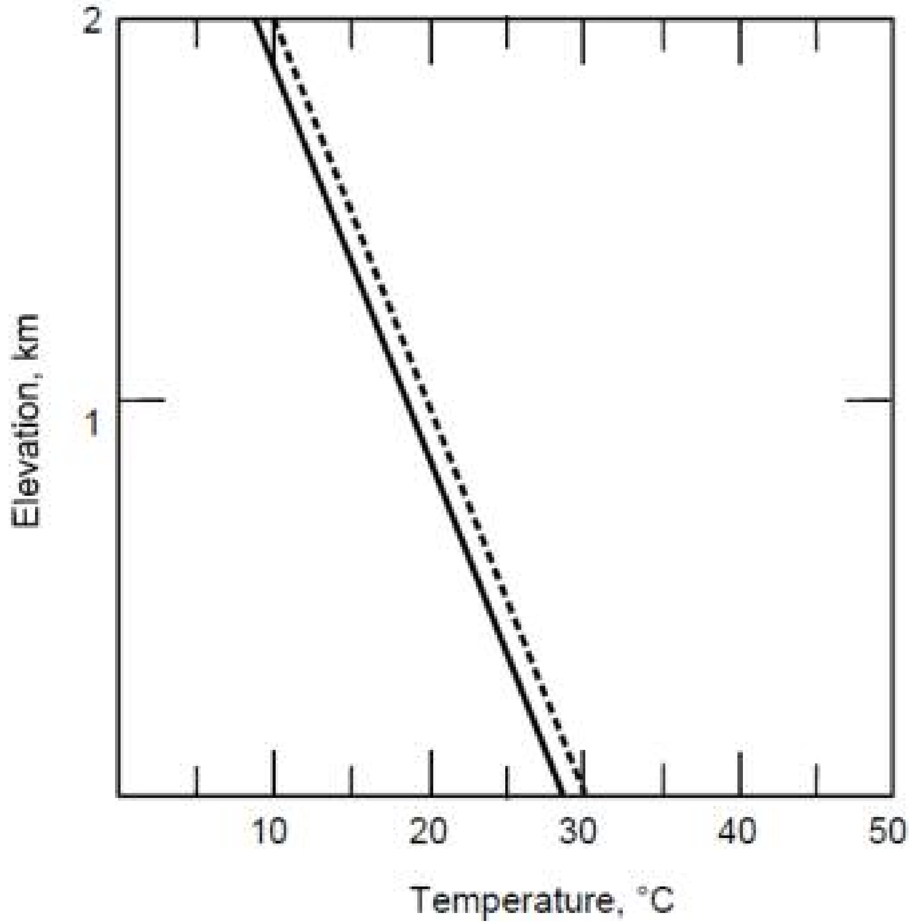
Unstable conditions most commonly develop on sunny days with low wind speeds where strong insolation is present.



Neutral Conditions

When the environmental lapse rate is the same as the dry adiabatic lapse rate, the atmosphere is in a state of neutral stability.

Neutral stability occurs on windy days or when there is cloud cover such that strong heating or cooling of the earth's surface is not occurring.

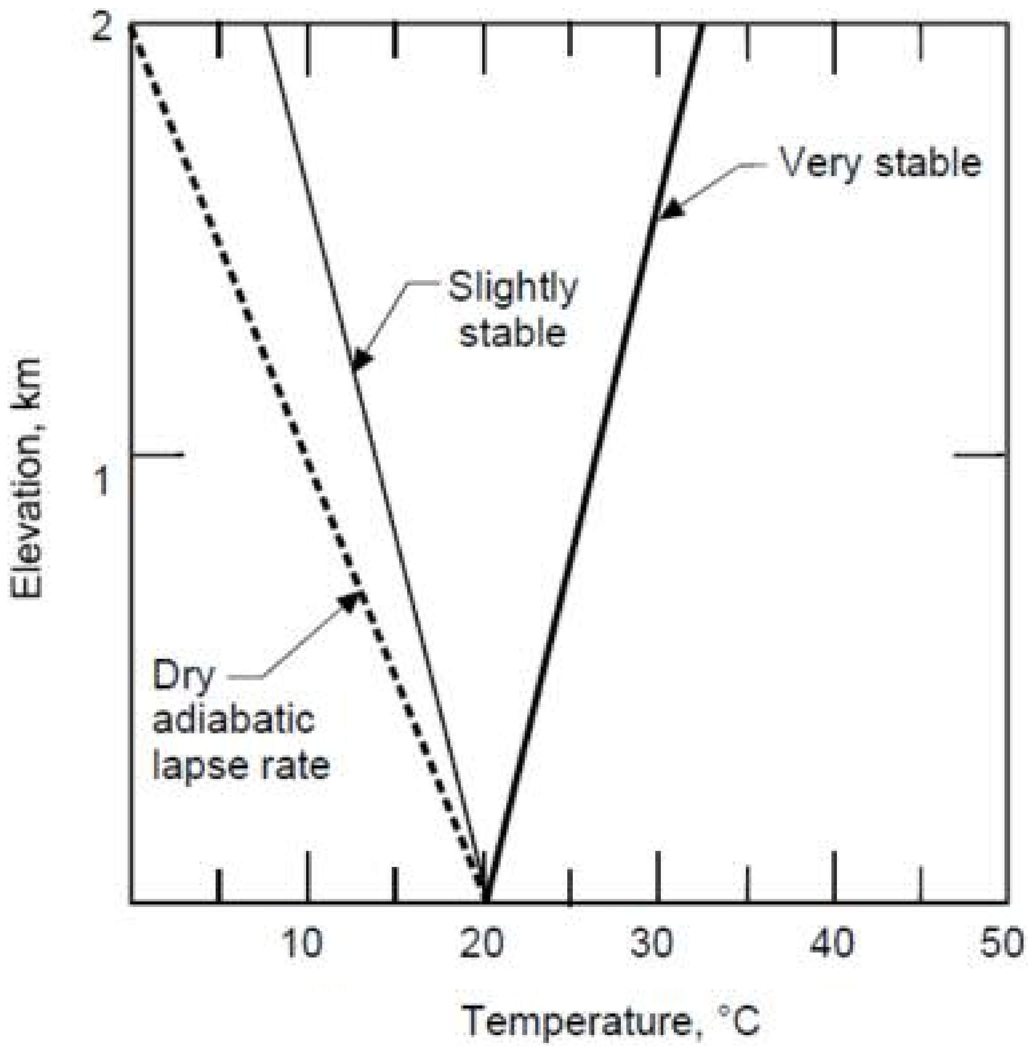


Stable Conditions

When the environmental lapse rate is less than the adiabatic lapse rate (cools at less than 9.8°C/1000 m), the air is stable and resists vertical motion. This is a **subadiabatic lapse** rate. Air that is lifted vertically will remain cooler, and therefore more dense than the surrounding air.

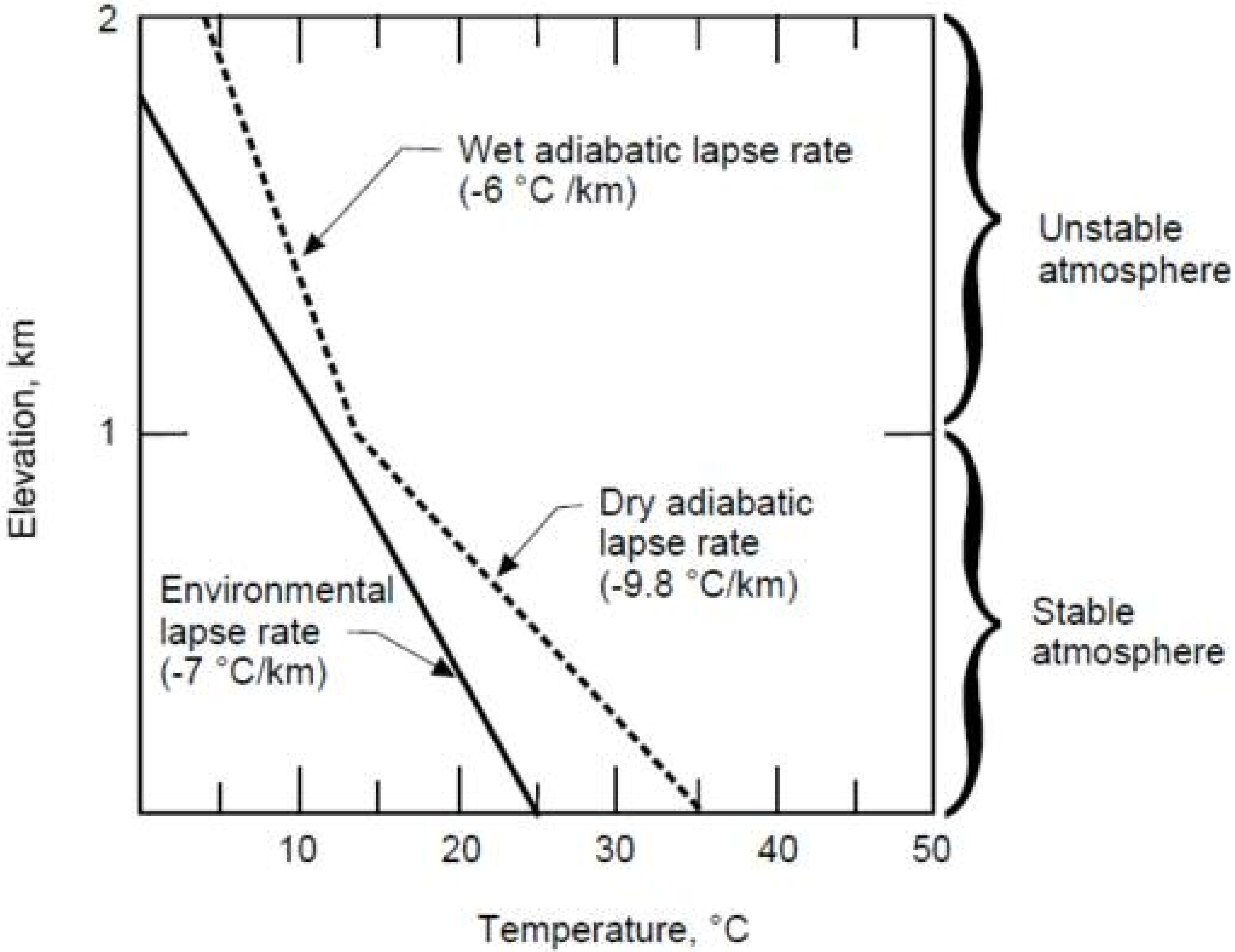
Once the lifting force is removed, the air that has been lifted will return to its original position.

Stable conditions occur at night when there is little or no wind.



Conditional Stability and Instability

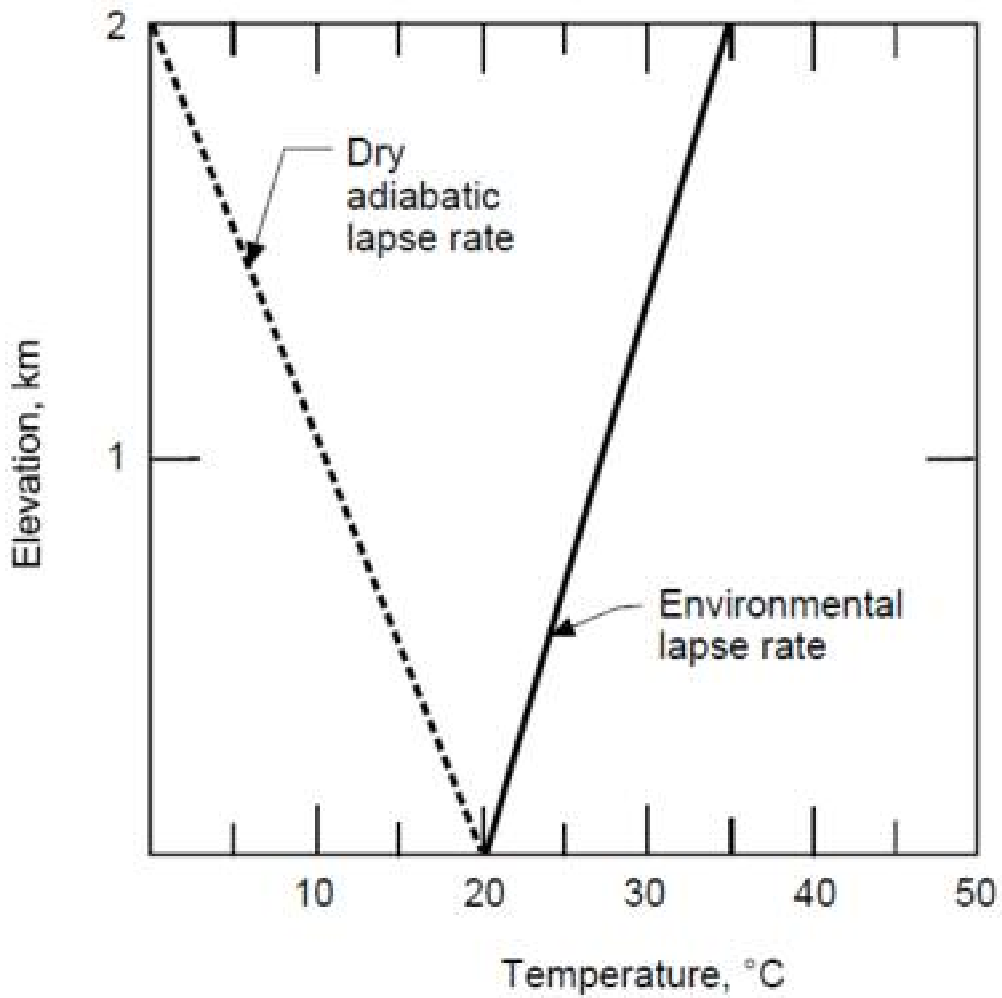
- ✓ Conditional instability occurs when the environmental lapse rate is greater than the wet adiabatic lapse rate but less than the dry rate.
- ✓ Stable conditions occur up to the condensation level and unstable conditions occur above it.



Inversions

An inversion occurs when air temperature increases with altitude. This situation occurs frequently but is generally confined to a relatively shallow layer.

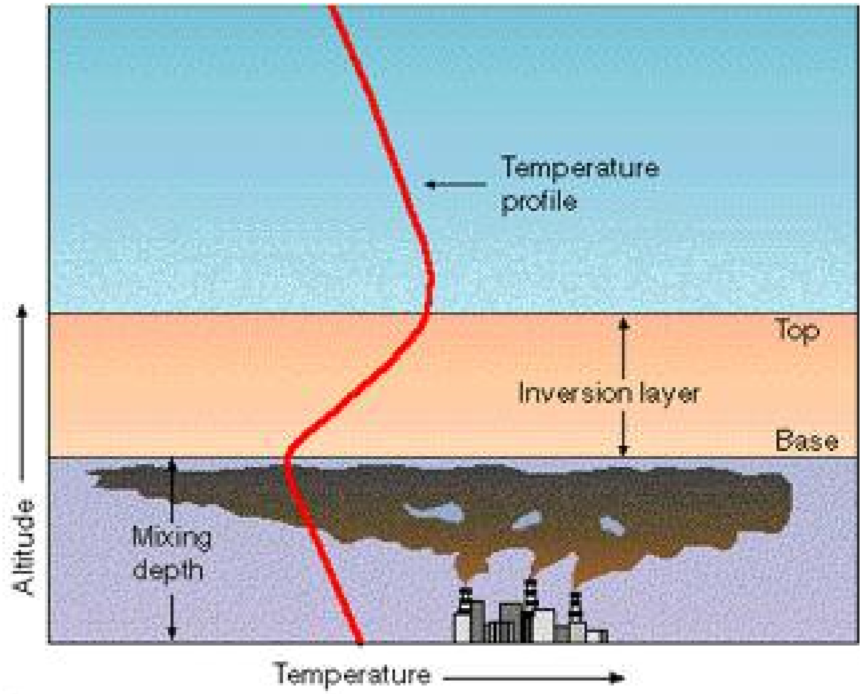
Plumes emitted into air layers that are experiencing an inversion (inverted layer) do not disperse very much as they are transported with the wind. Plumes that are emitted above or below an inverted layer do not penetrate that layer, rather these plumes are trapped either above or below that inverted layer.



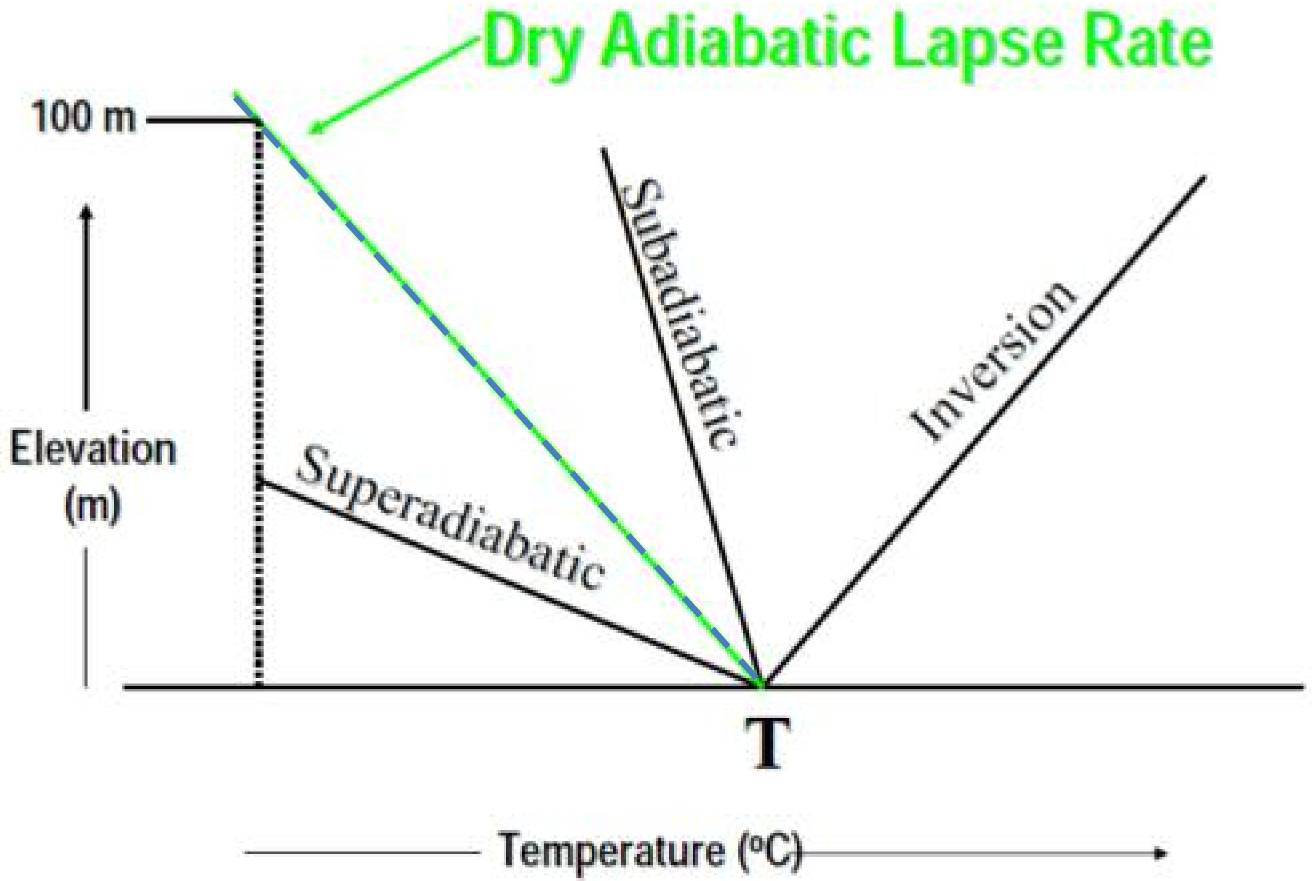
Winter inversion layer trapping smoke from home fires

www.ew.govt.nz/enviroinfo/air/weather.htm

www.co.mendocino.ca.us/aqmd/Inversions.htm



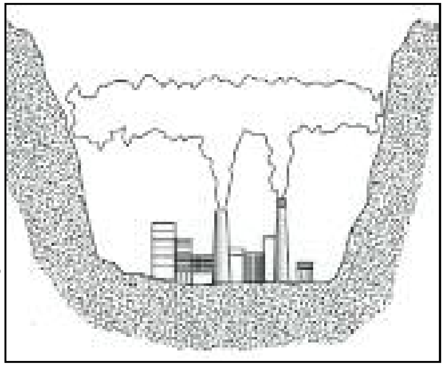
Summary



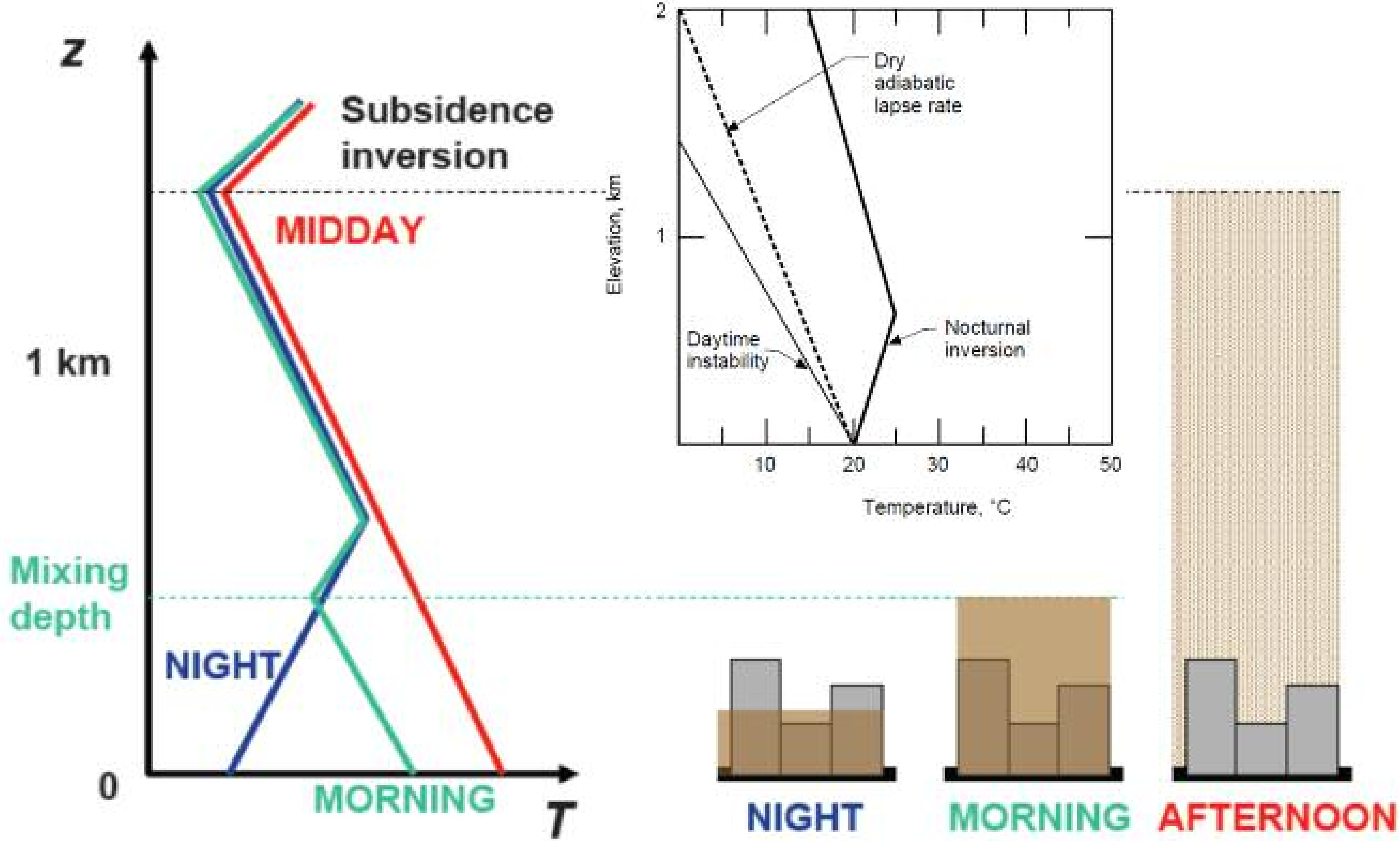
Dry Adiabatic Lapse Rate
100 m
Subadiabatic
Inversion
Elevation (m)
Superadiabatic
T
Temperature (ºC)

Radiation

- The **radiation inversion** is the most common form of surface inversion and occurs when the earth's surface cools rapidly. As the earth cools, so does the layer of air close to the surface. If this air cools to a temperature below that of the air above, it becomes very stable, and the layer of warmer air impedes any vertical motion.
- Radiation inversions usually occur in the late evening through the early morning under clear skies with calm winds, when the cooling effect is greatest.
- The effects of radiation inversions are often short-lived. Pollutants trapped by the inversions are dispersed by vigorous vertical mixing after the inversion breaks down shortly after sunrise.
- This situation is most likely to occur in an enclosed valley, where cool, downslope air movement can reinforce a radiation inversion and encourage fog formation.



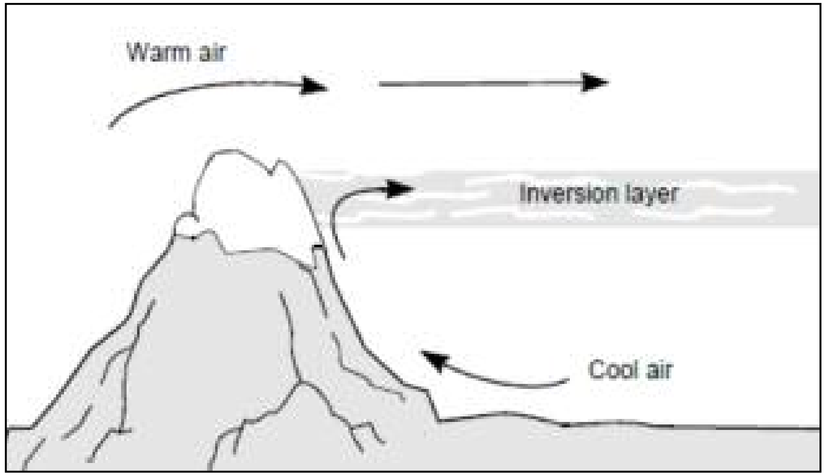
Diurnal Cycle of Surface Heating /Cooling

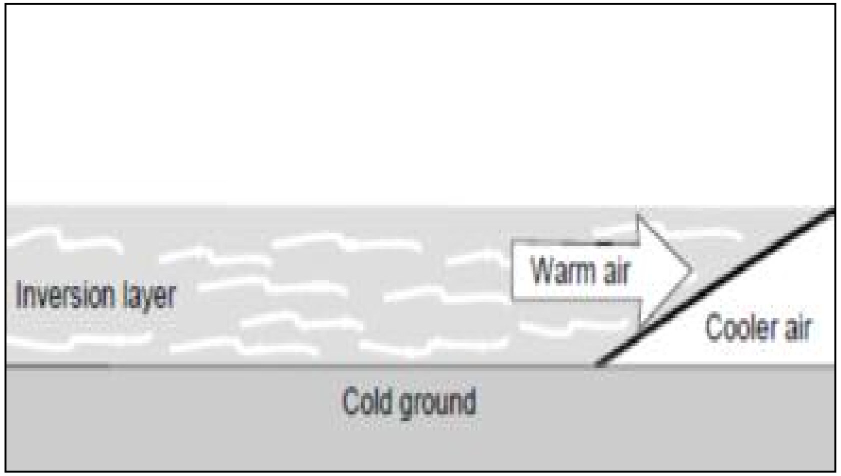


Advection

- Advection inversions are associated with the horizontal flow of warm air. When warm air moves over a cold surface, conduction and convection cools the air closest 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.



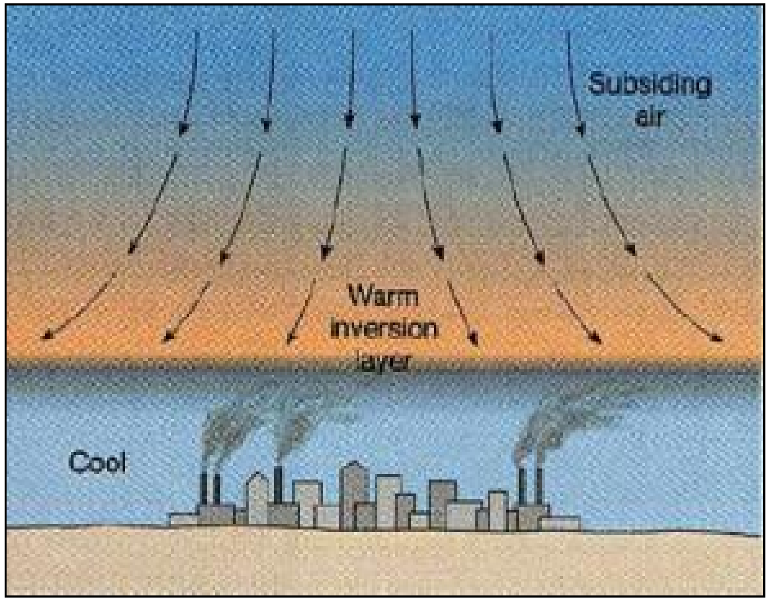


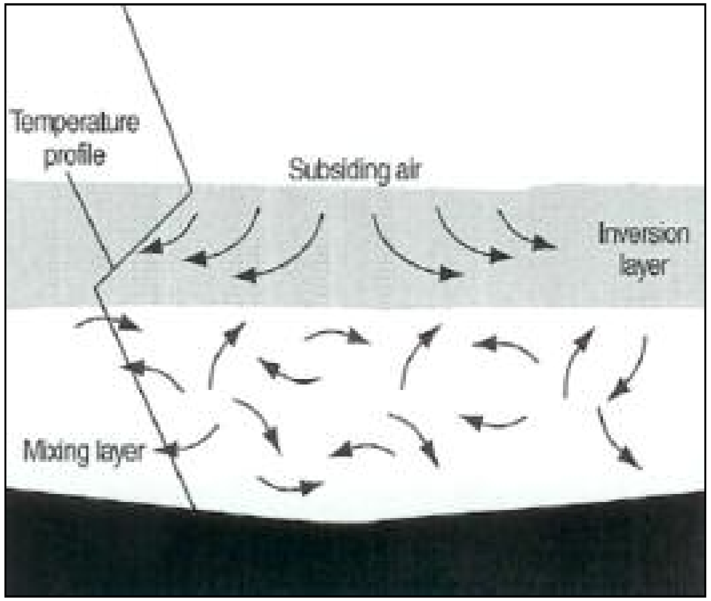
Subsidence Inversion

- Associated with atmospheric high-pressure systems (anticyclones). Where air in an anticyclone descends and flows outward in a clockwise rotation

➢ As the air descends, the higher pressure at lower altitudes compresses and warms it at the dry adiabatic lapse rate. Often this warming occurs at a rate faster than the environmental lapse rate. The inversion layer thus formed is often elevated several hundred meters above the surface during the day. At night, because of the surface air cooling, the base of a subsidence inversion often descends perhaps to the ground.

- Persists for days





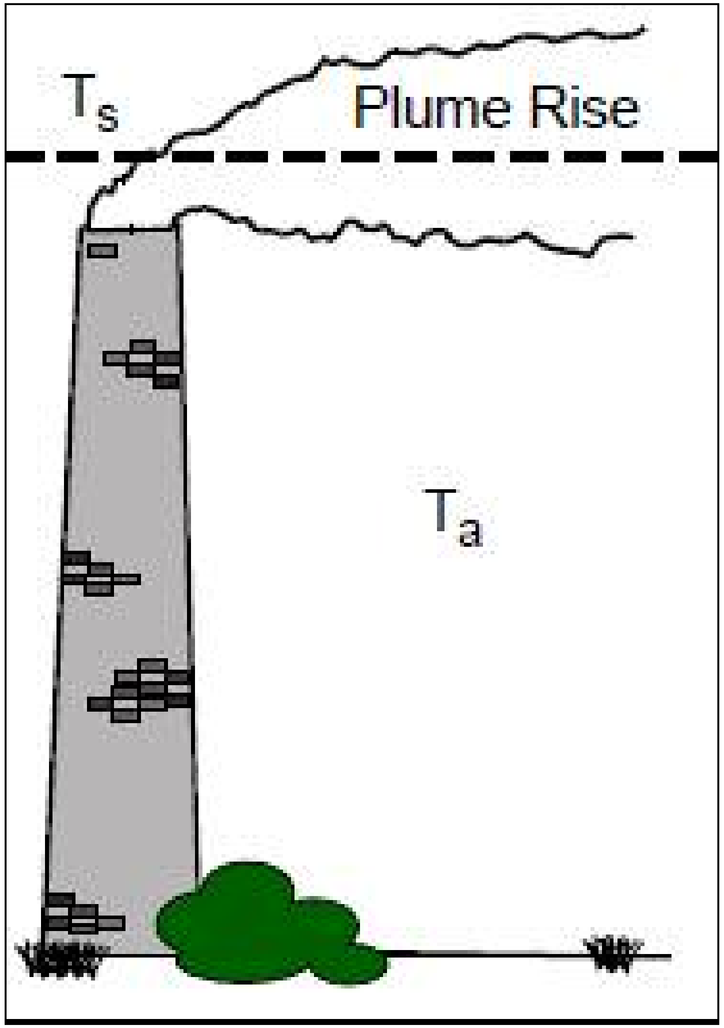
Stability and Plume Behavior

- The degree of atmospheric stability and the resulting mixing height have a large effect on pollutant concentrations in the ambient air. Although the discussion of vertical mixing did not include a discussion of horizontal air movement, or wind, you should be aware that horizontal motion does occur under inversion conditions. Pollutants that cannot be dispersed upward may be dispersed horizontally by surface winds.

- The combination of vertical air movement and horizontal air flow influences the behavior of plumes from point sources (stacks).

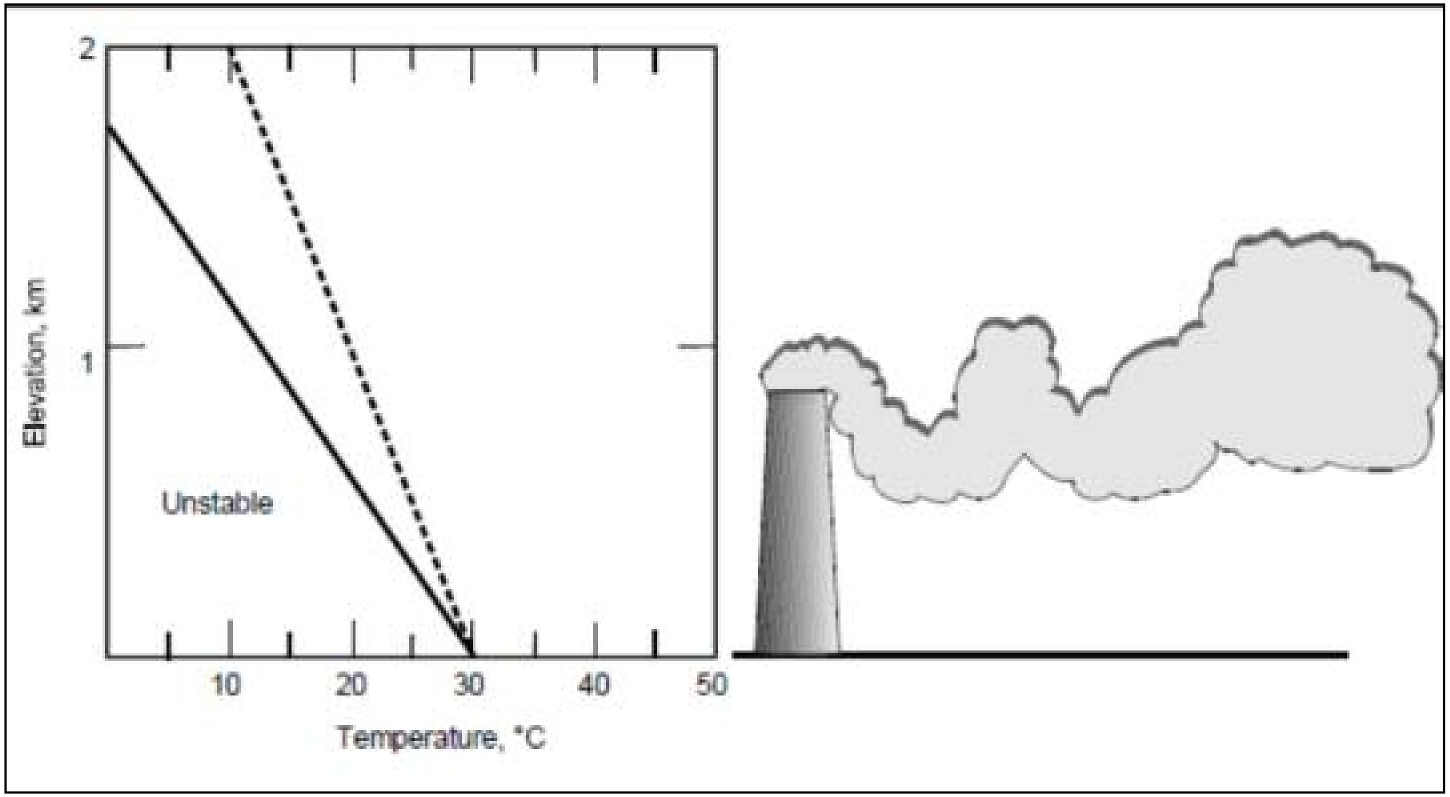
Plume Rise

- The distance that the plume rises above the stack is called *plume rise.*
- It is actually calculated as the distance to the imaginary centerline of the plume rather than to the upper or lower edge of the plume.
- The Plume rise, Δh, depends on the stack's physical characteristics. For example, the effluent characteristic of stack temperature in relation to the surrounding air temperature is more important than the stack characteristic of height. The difference in temperature between the stack gas (T_S) and the ambient air (T_a) determine plume density and that density affects plume rise.



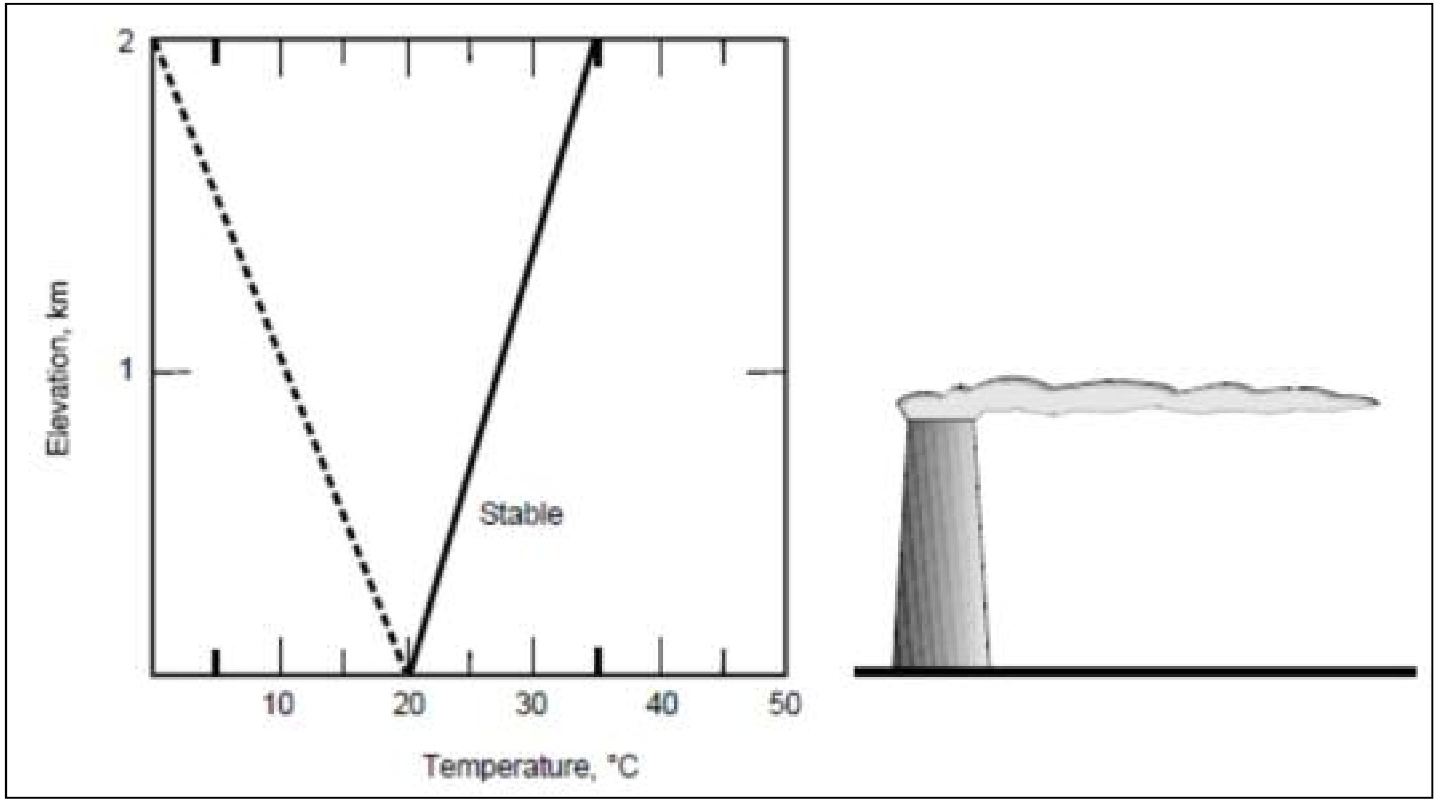
The looping plume

- It occurs in highly unstable conditions and results from turbulence caused by the rapid overturning of air. While unstable conditions are generally favorable for pollutant dispersion, momentarily high ground-level concentrations can occur if the plume loops downward to the surface.



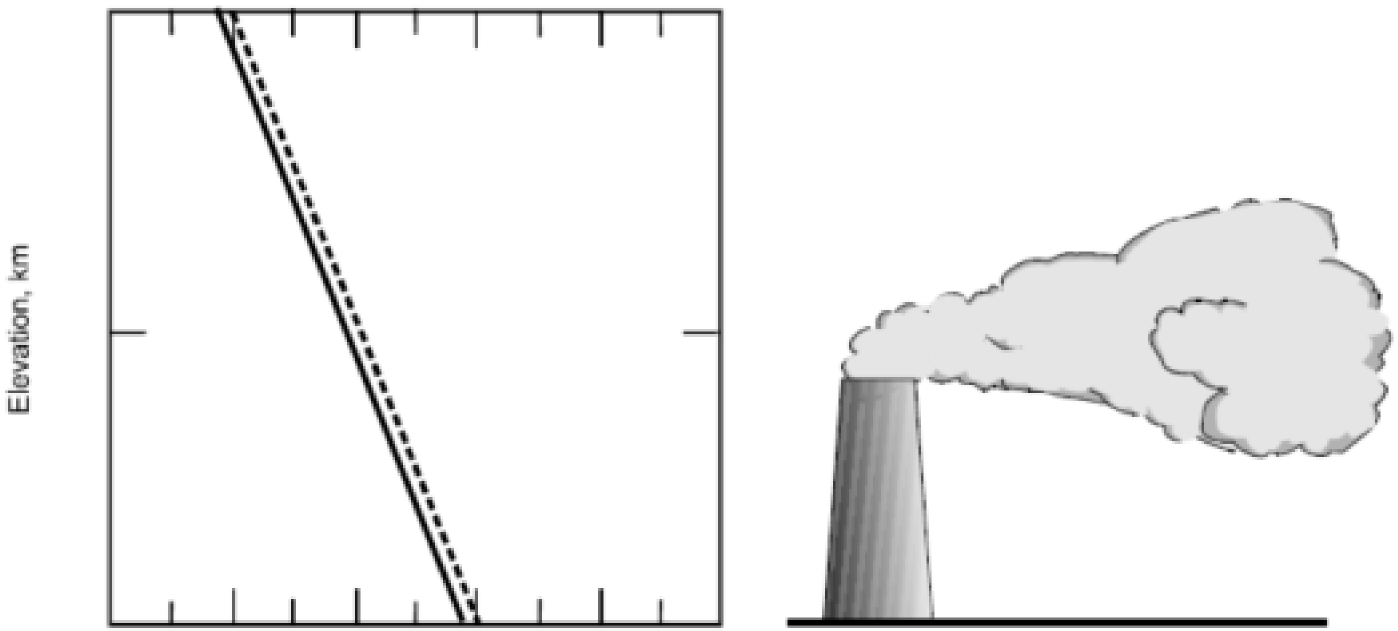
The fanning plume

- It occurs in stable conditions. The inversion lapse rate discourages vertical motion without prohibiting horizontal motion, and the plume may extend downwind from the source for a long distance. Fanning plumes often occur in the early morning during a radiation inversion



The coning plume

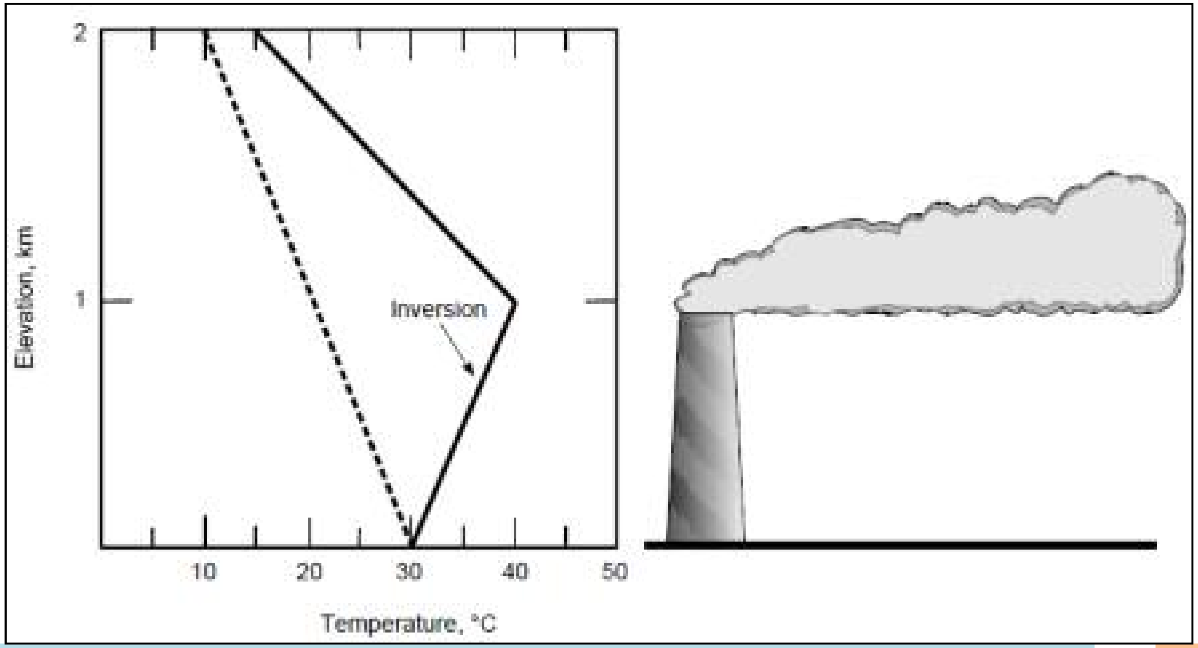
- It is characteristic of neutral conditions or slightly stable conditions. It is likely to occur on cloudy days or on sunny days between the breakup of a radiation inversion and the development of unstable daytime conditions



The Lofting plume

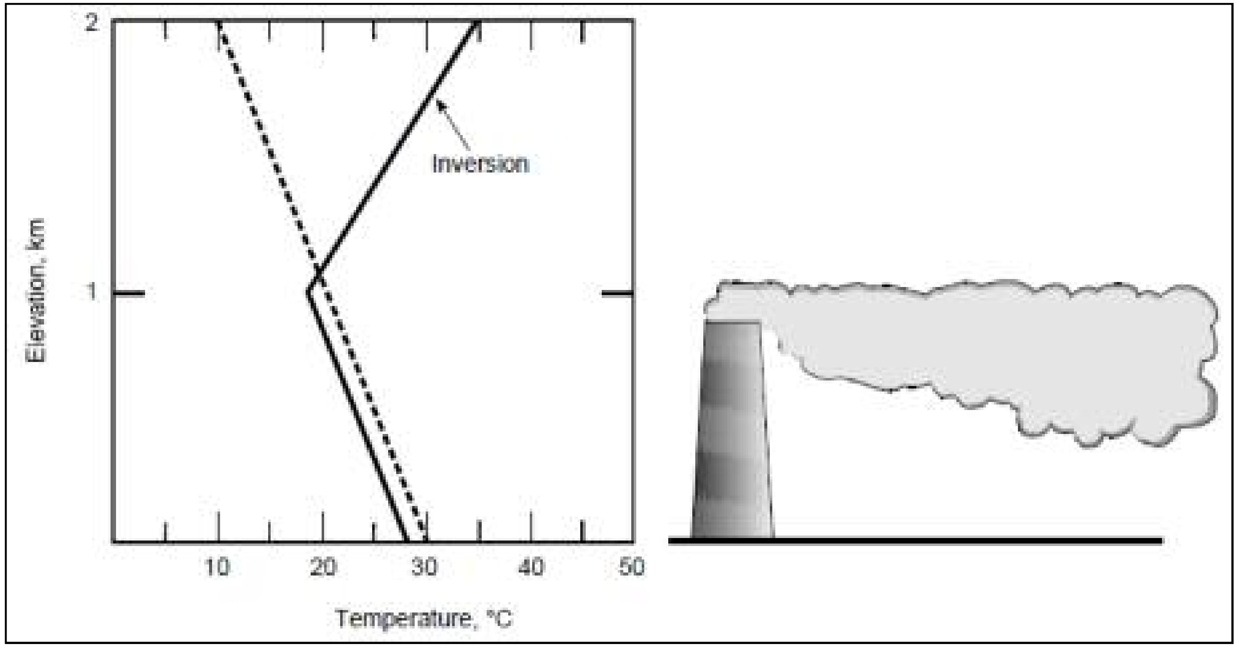
- Obviously a major problem for pollutant dispersion is an inversion layer, which acts as a barrier to vertical mixing. The height of a stack in relation to the height of the inversion layer may often influence ground-level pollutant concentrations during an inversion.

- When conditions are unstable above an inversion, the release of a plume above the inversion results in effective dispersion without noticeable effects on ground level concentrations around the source. This condition is known as **lofting**.



The Fumigation plume

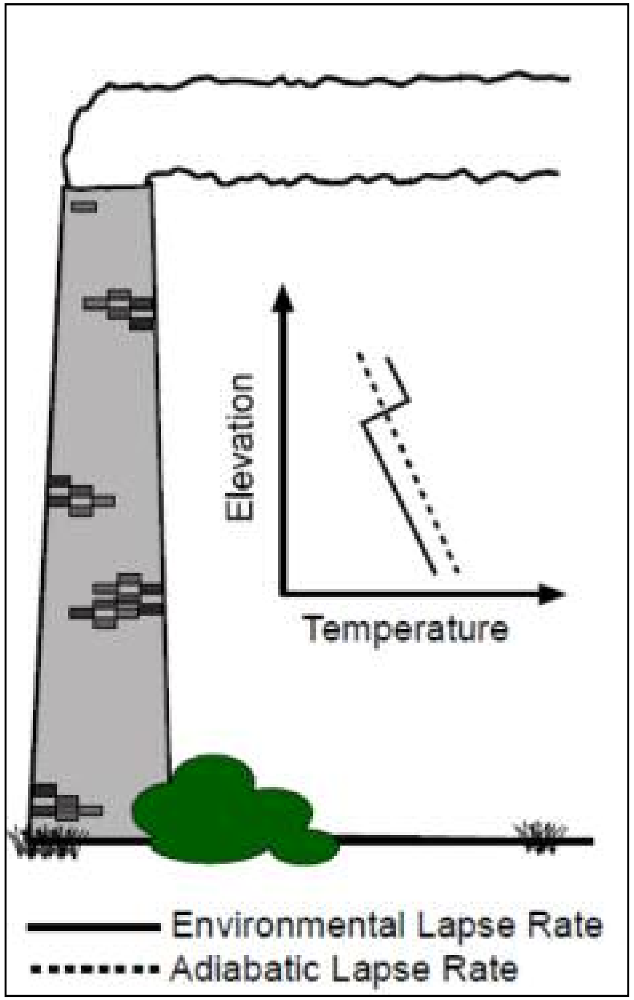
- If the plume is released just under an inversion layer, a serious air pollution situation could develop. As the ground warms in the morning, air below an inversion layer becomes unstable. When the instability reaches the level of the plume that is still trapped below the inversion layer, the pollutants can be rapidly transported down toward the ground. This is known as **fumigation**. Ground-level pollutant concentrations can be very high when fumigation occurs. Sufficiently tall stacks can prevent fumigation in most cases.



The Trapping plume

- A trapped plume is the result of an *unstable* air mass that creates an inversion layer both above and below the plume. A trapped plume, in contrasted with a fumigating plume, is one of the most favorable types of plume for pollutant dispersion. Temperature inversions, both above and below the plume, protect ground sources from potential exposure while winds at altitude disperse and dilute the pollutant.

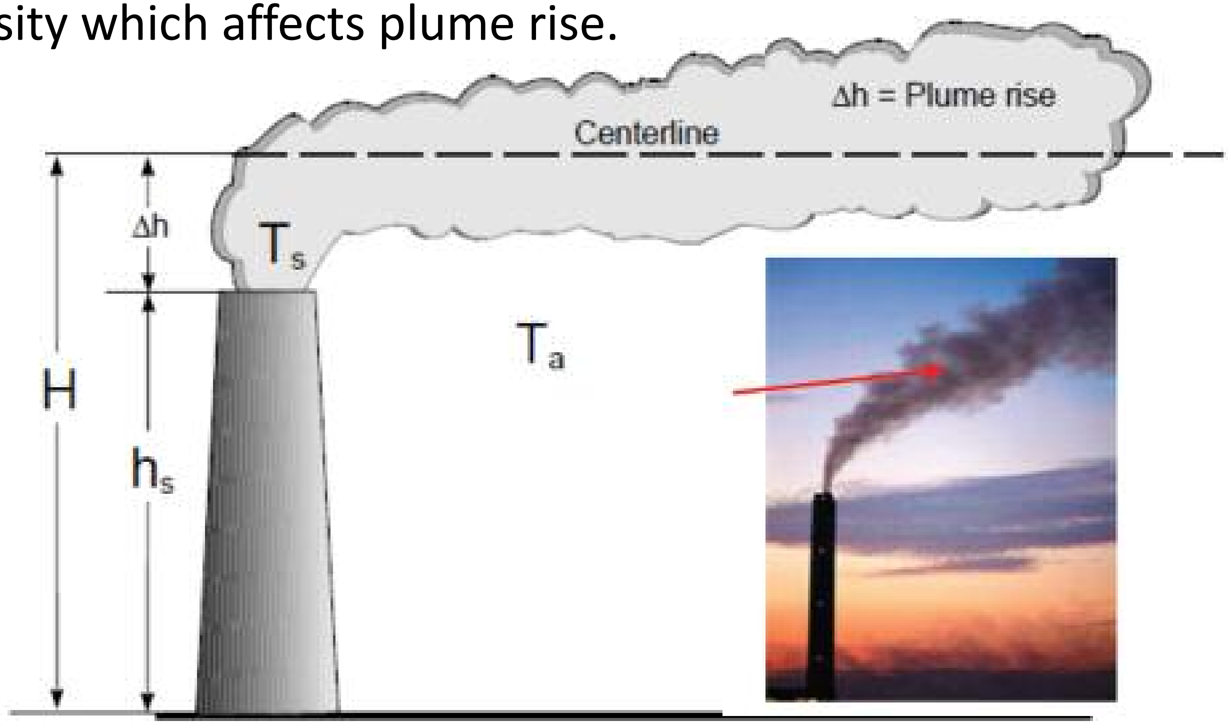
- A trapped plume is produced on clear, sunny days or clear nights with light winds.



Plume Rise: Momentum and Buoyancy

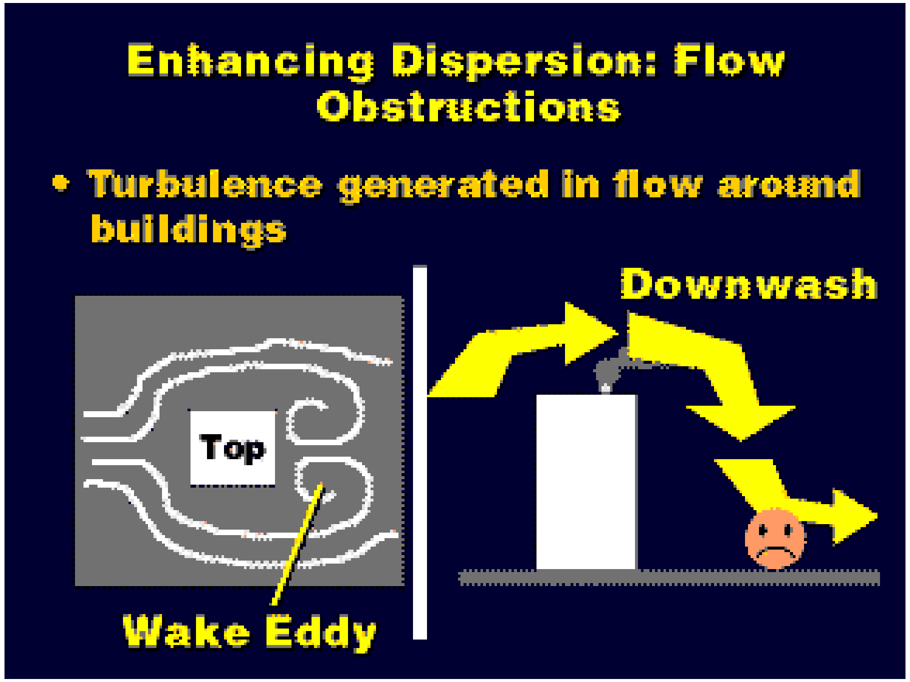
- The final height of the plume, referred to as the **effective stack height** (H), is the sum of the physical stack height (h_s) and the plume rise (Δh).
- Plume rise is actually calculated as the distance to the imaginary centerline of the plume rather than to the upper or lower edge of the plume
- The difference in temperature between the stack gas (Ts) and ambient air (Ta) determines the plume density which affects plume rise.

✓ The velocity of the stack gases which is a function of the stack diameter and the volumetric flow rate of the exhaust gases determines the plume's momentum



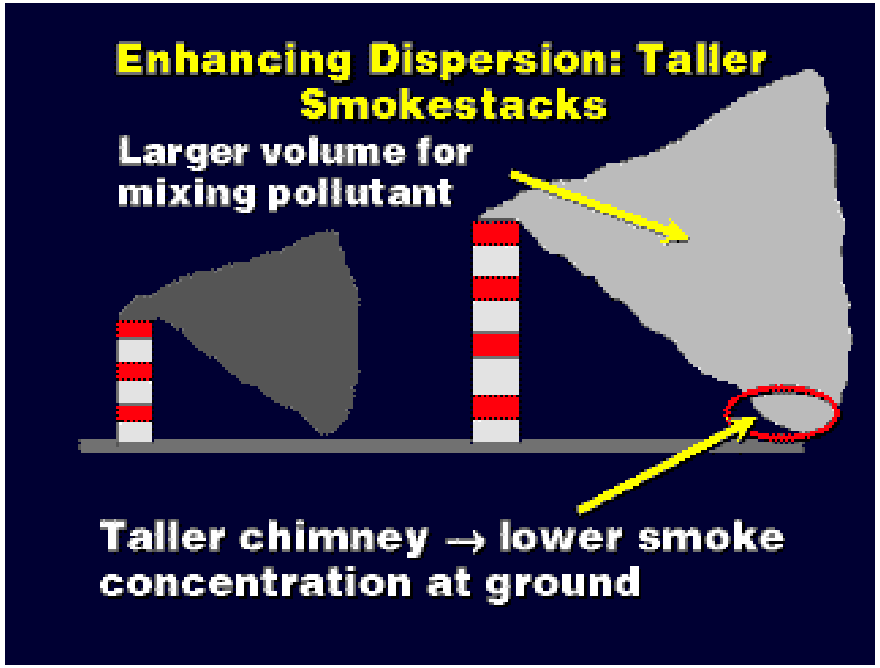
Enhancing Dispersion: Flow Obstructions

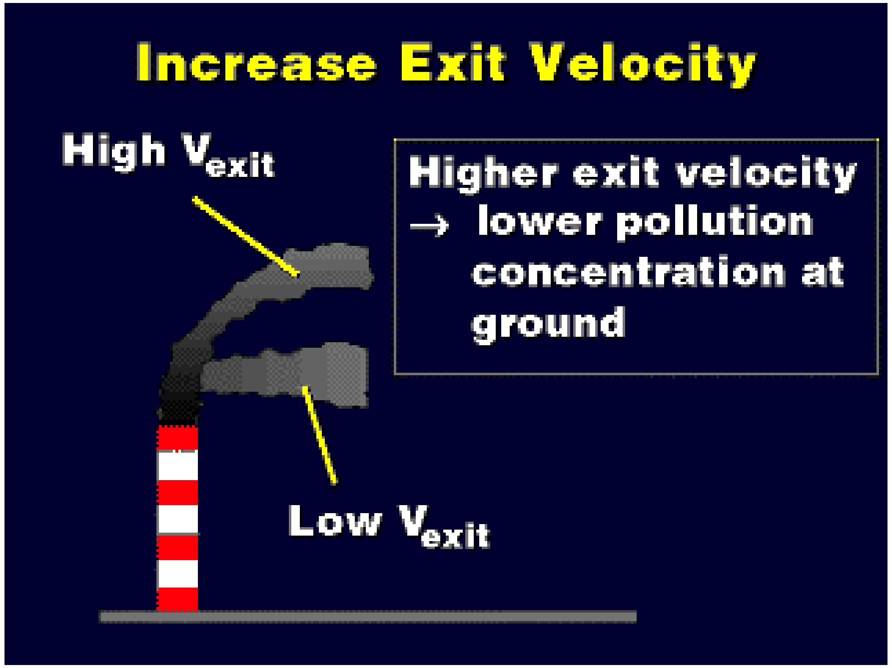
- The turbulent wake behind a building helps mix pollutants to the ground that might not have been there normally, in a stable atmosphere.
- Downwash is especially bad when there are pollution sources on the top of the building.
- It is important to get the pollution emitted high enough above the building so that it does not get caught in the downwash and get carried down to the ground



Enhancing Dispersion with Smokestacks

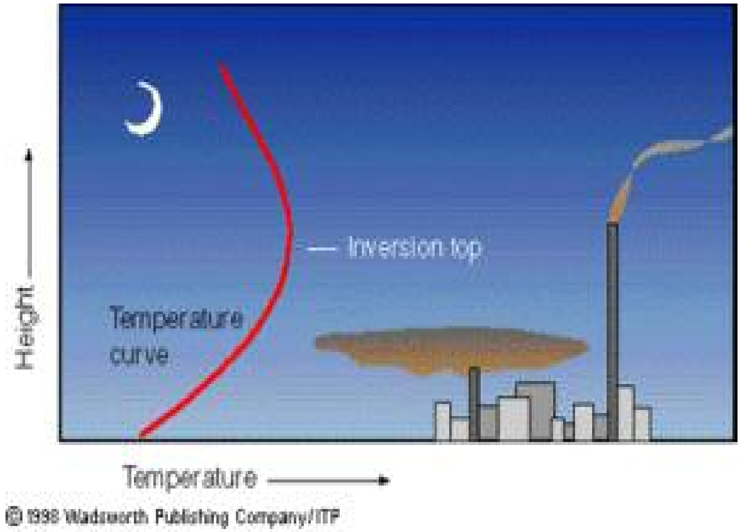
- Pollution emitted from a taller stack has to travel a longer distance to get to the ground, so it will become more dilute.
- The faster the smoke gushes out, the more momentum it has, and the higher it will fly before it levels out and disperses toward the ground.

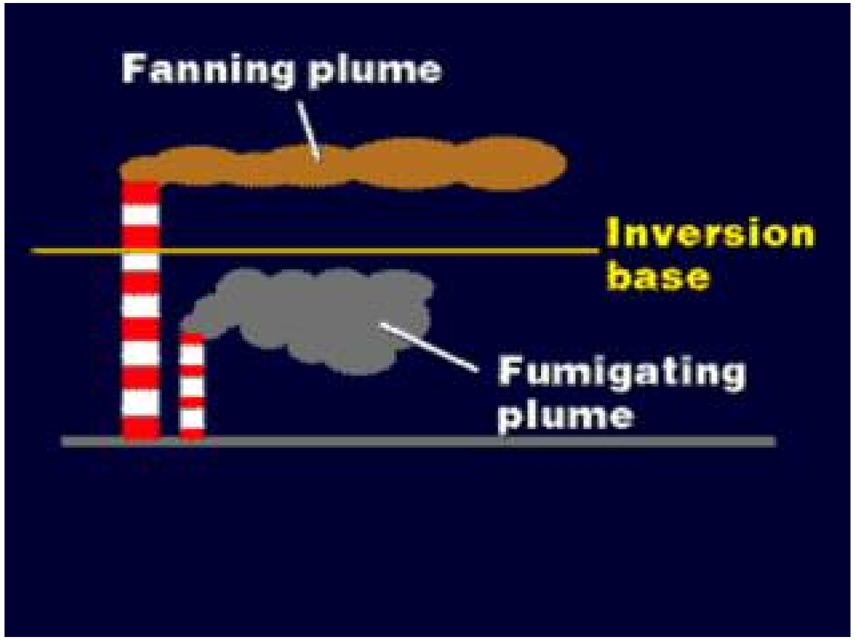




Tall and Short Smoke Stacks

- With a tall enough smokestack, pollution is emitted within the inversion aloft, forming a fanning plume that does not pollute the area near the smokestack. If it's not tall enough, it will fumigate the countryside.
- Switching the layers so that the inversion is at the ground, we need the smokestack tall enough to be above the ground inversion, so that a lofting plume is formed. Architects will need to know the average depth of the nocturnal radiation inversion in order to know how tall to build the smokestack.





Exit Temperature

- The higher the temperature, the greater the positive buoyancy in smoke streaming out of the smokestack.

- The smoke has to rise higher before it has adiabatically cooled to a neutral buoyancy temperature