Environmental Transport and Fate

Chapter 8

Introduction to Air Pollution

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### Types of air pollution

<table>
<thead>
<tr>
<th>Type</th>
<th>Example</th>
<th>Scales</th>
<th>Physics involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>Plume from industrial</td>
<td>~1 km horizontally ~10’s m in</td>
<td>near-ground air layer subject to surface roughness and</td>
</tr>
<tr>
<td></td>
<td>smokestack</td>
<td>vertical fraction of 1 hour</td>
<td>convection</td>
</tr>
<tr>
<td>Urban</td>
<td>Smog over</td>
<td>~10 km horizontally</td>
<td>local winds, atmospheric</td>
</tr>
<tr>
<td></td>
<td>Los Angeles</td>
<td>~100-1000m in vertical</td>
<td>boundary layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>several hours to days</td>
<td>hills and mountains</td>
</tr>
<tr>
<td>Regional</td>
<td>Acid rain</td>
<td>~100 km horizontally several km</td>
<td>weather patterns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in vertical several days</td>
<td>cloud formation</td>
</tr>
<tr>
<td>Continental</td>
<td>1986 Chernobyl</td>
<td>size of continent or ocean</td>
<td>prevailing winds</td>
</tr>
<tr>
<td></td>
<td>2011 Fukushima</td>
<td>troposphere</td>
<td>weather patterns</td>
</tr>
<tr>
<td></td>
<td>radioactive fallout</td>
<td>days to weeks</td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>Climate change</td>
<td>size of planet</td>
<td>hydrological cycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>troposphere and stratosphere</td>
<td>prevailing winds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>decades and beyond</td>
<td>equator-to-pole gradients</td>
</tr>
</tbody>
</table>

There is a strong correlation between time scale, length scale and chemical species.
Deadly air-pollution episode in London on 5–9 December 1952, during which SO₂ concentration (from stagnating combustion smoke) rose to a peak of 1.34 ppm.

For comparison, the US EPA standard for 1 day is 0.14 ppm.

Surge in number of deaths correlates with peak in SO₂ concentration. Several thousand deaths were blamed on this pollution episode (4000 in the first two weeks and up to 12000 over a longer period).

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### U.S. National Ambient Air Quality Standards (NAAQS)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Exposure duration</th>
<th>Standard</th>
<th>Cause for concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1 hour</td>
<td>35 ppm</td>
<td>headaches, asphyxiation</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>8 hours</td>
<td>9 ppm</td>
<td>decreased exercise tolerance</td>
</tr>
<tr>
<td>NO₂</td>
<td>1 year</td>
<td>0.053 ppm</td>
<td>aggravation of respiratory disease</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td>3 hours</td>
<td>0.50 ppm</td>
<td>shortness of breath</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>1 day</td>
<td>0.14 ppm</td>
<td>wheezing, odor</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>0.03 ppm</td>
<td>acid precipitation</td>
</tr>
<tr>
<td>O₃</td>
<td>1 hour</td>
<td>0.12 ppm</td>
<td>eye irritation</td>
</tr>
<tr>
<td>Ozone</td>
<td>8 hours</td>
<td>0.08 ppm</td>
<td>interference with breathing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>damage to materials and plants</td>
</tr>
<tr>
<td>Pb</td>
<td>3 months</td>
<td>1.5 µg/m³</td>
<td>blood poisoning</td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td></td>
<td>impaired infant development</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>24 hours</td>
<td>65 µg/m³</td>
<td>lung damage</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>15 µg/m³</td>
<td></td>
</tr>
<tr>
<td>PM₁₀</td>
<td>24 hours</td>
<td>150 µg/m³</td>
<td>visibility</td>
</tr>
<tr>
<td></td>
<td>1 year</td>
<td>50 µg/m³</td>
<td>respiratory disease</td>
</tr>
</tbody>
</table>
Question: Why does the temperature drop with height above ground?

A parcel of air in hydrostatic equilibrium

Balance of vertical forces:

- Pressure from above + weight = pressure from below

\[ p(z + dz) A + mg = p(z) A \]

\[ [p(z + dz) - p(z)] A + \rho V g = 0 \]

\[ \frac{p(z + dz) - p(z)}{dz} = -\rho g \]

since mass \( m = \rho \times \text{volume} \)

volume \( V = \text{area} A \times \text{height} dz. \)
Compressibility of air

1) Air is an ideal gas: \( p = R \rho T \) with \( T = \text{absolute temperature} = ^\circ\text{C} + 273.15 \)
\[ R = 287 \text{ m}^2/\text{s}^2.\text{K} \]
Take \( z \)-derivative \[ \frac{dp}{dz} = R \frac{d\rho}{dz} T + R \rho \frac{dT}{dz} \]

2) Consider a change in height
(de)compression work is compensated by a change in internal energy:

\[ \text{Internal energy} = E = m C_v T \]
with \( C_v = 718 \text{ m}^2/\text{s}^2.\text{K} \)

\[ \text{Work performed} = -pdV \]

Since this energy-work exchange is performed in the absence of heat exchange, it is called an \textit{adiabatic} exchange.

An atmosphere with interchangeable air parcels

descent, \( z \downarrow \)
compression
pressure increases \( p \uparrow \)
volume shrinks \( V \downarrow \) \( dV < 0 \)
pressure squeezes the parcel
parcel receives work
parcel gains energy
temperature increases \( T \uparrow \)
ascent, \( z \uparrow \)
expansion
pressure decreases \( p \downarrow \)
volume expands \( V \uparrow \) \( dV > 0 \)
parcel uses its pressure to push air out of the way
parcel performs work
parcel loses energy
temperature decreases \( T \downarrow \)

This explains why temperature normally drops with altitude.
Combining hydrostatic equilibrium with ideal-gas compressibility & adiabatic change:

- Hydrostatic equilibrium \( \frac{dp}{dz} = -\rho g \)
- Ideal gas \( \frac{dp}{dz} = R\frac{d\rho}{dz} T + R\rho \frac{dT}{dz} \)
- Adiabatic change \( C_v \frac{dT}{dz} = \frac{p}{\rho^2} \frac{d\rho}{dz} \)

Eliminate \( \frac{dp}{dz} \) to get:

\[-\rho g = R\frac{d\rho}{dz} T + R\rho \frac{dT}{dz} \]

Now eliminate \( \frac{d\rho}{dz} \) to have an equation solely for \( \frac{dT}{dz} \):

\[-\rho g = R\frac{C_v}{p} \frac{dT}{dz} + R\rho \frac{dT}{dz} \]

Use \( p = R\rho T \) here

And we are left with:

\[-g = (C_v + R) \frac{dT}{dz} \]

\[-g = (C_v + R) \frac{dT}{dz} \]

can be recast as

\[ \frac{dT}{dz} = -\frac{g}{C_p} \]

with \( C_p = C_v + R = 718 + 287 = 1005 \text{ m}^2/\text{s}^2/\text{K} \)

We note that in such equilibrium atmosphere, the temperature \( T \) decreases monotonically with altitude \( z \). The rate of decrease is:

\[ \frac{g}{C_p} = \frac{9.81 \text{ m/s}^2}{1005 \text{ m}^2/\text{s}^2/\text{K}} = 0.00976 \frac{\text{K}}{\text{m}} \]

about 1°C per 100m of elevation.

\[ \Gamma = \frac{g}{C_p} \]

is called the adiabatic lapse rate.

It describes the thermal structure of the atmosphere when it is in equilibrium.
The atmosphere can be in any of four possible cases:

1) \[ \frac{dT}{dz} < -\frac{g}{C_p} \]

Temperature drops too fast with height. Air is top heavy and unstable. Convection ensues to remove this instability.

2) \[ \frac{dT}{dz} = \frac{g}{C_p} \]

Atmosphere is in equilibrium. It state is said to be neutral. Vertical motions are not created but not impaired either.

3) \[ -\frac{g}{C_p} < \frac{dT}{dz} < 0 \]

Temperature does not drop fast enough with height. Higher air is warmer and floats on top. Lower air is colder and lies at the bottom. Thermal stratification is impairing vertical exchanges. Atmosphere is said to be stable.

4) \[ 0 < \frac{dT}{dz} \]

Atmosphere is strongly stratified. It state is qualified as very stable. The situation is called an inversion.

stable
Stagnation, unhealthy

unstable
well ventilated, healthy

neutral
somewhat mixed, healthy
Correction to take into account humidity in the air

Layers of gravitational stability and instability in a compound temperature profile

This leads to the concept of *mixing height*.

The mixing height is the thickness of the atmosphere over which overturns when a layer becomes unstable.

The mixing height is usually longer than the thickness of the original unstable layer because mixing engulfs a portion of the stable layer.
The lower atmosphere over the course of the diurnal cycle

Mixing height = thickness of zone of instability.

Note the suppression of mixing near ground at night and the gradual increase in mixing depth over the course of the day.

Diurnal cycle of the Atmospheric Boundary Layer (ABL)

NBL = Nocturnal Boundary layer
An example of mixing depth variation over the course of the day (Schenectady, New York, in a summer day of 1994)

This mixing height is on the large side.

A typical mixing height is on the order of 1000m to 1500m.

Reasons for inversion

High-pressure weather disturbance (anticyclone)

Clear winter night

FIGURE 7.40  Decreasing air temperature causes subsidence inversion. (d) During the day, air under the inversion may be unstable due to solar warming of the surface (b). Radiation inversions may form under the subsidence inversion when nights are clear, especially in winter (c).
Examples of the effect of an atmospheric inversion

[Image: www.stuffintheair.com/weather-inversions.html]

[Image: www.flickr.com/photos/clombardi/255319115/]

Scorer, 1997, page 416