EVE 402/502
Air Pollution Generation and Control

Lecture #1 (Ch. 1)

Effects and Sources of Air Pollutants

Air quality around the world


Calgary, Alberta, Canada


Urban China


El Cercado, Dom. Rep.


Rural India

Introduction

- Air pollution is a WASTE…a by-product of how we live our lives
  - Production of goods
  - Transportation
  - Energy generation
- At the root…COMBUSTION

$$\text{Fuel} + O_2 \rightarrow CO_2 + H_2O + \underbrace{CO + SO_2 + NO + NO_2 + \text{particles} + \ldots}_{\text{Pollutants}}$$

Introduction, continued

- Air pollution is NOT a recent phenomenon
  - 1272: King Edward I banned "sea coal" in an effort to clear smoky London air
  - 1377-1422: Kings Richard II and Henry V restricted the use of coal
  - 1661: A royal pamphlet was published that outlined some air/smoke remedies
  - The Great Smoky Mountains were "smoky" before there were people around to see it

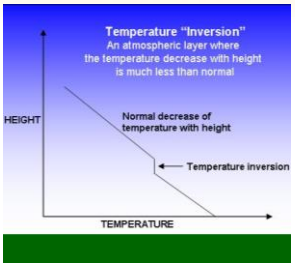
(In)famous Air Pollution Episodes

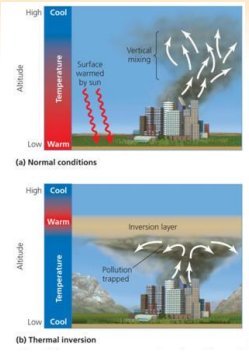
- 1930: Meuse Valley, Belgium (December)
  - Dense population, heavily industrialized area
  - High industrial emissions (SO_2) coupled with a "temperature inversion" led to a severe 3-day fog
    - Hundreds became ill
    - 60 "excess" deaths
- 1952: London, UK (December)
  - Similar scenario as above, except many more people
  - Results: 4000 excess deaths in ~15 day period
  - Most of the dead had histories of respiratory and/or cardiac problems ("susceptible" groups)

More (in)famous AP Episodes

- 1956: London, UK (January)
  - 1000 excess deaths
  - Clean Air Act passed in Parliament
- Current problems (although not as serious as the aforementioned) in
  - Los Angeles
  - Mexico City: smog can burn your eyes
  - Beijing: 2008 Olympics
  - Houston, Atlanta, Philadelphia, etc.

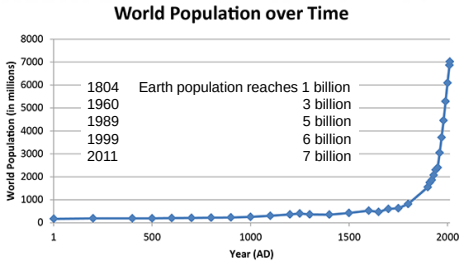
A Temperature Inversion





General Nature of Air Pollution

- There's a relationship with population



General Nature of AP, cont.

- There is a relationship to GDP

Country	GDP [$/capita]	Energy cons. [MBtu/capita]
Dem. Rep. of Congo	180	2
Chile	2500	34
Saudi Arabia	5800	168
France	18300	104
United States	19500	273

- Since 1950, we have consumed more resources than in all of previous history combined

General Nature of AP, cont.

- Four basic assumptions of AP control
  - *Air is in the public domain*: it is a problem both for those who discharge and those who may suffer
  - *AP is an inevitable consequence of modern life*: our economic concerns and physical well-being conflict
  - *Mitigation techniques must not worsen the situation elsewhere*
  - *We don't know everything*

Definition of Air Pollution

"…the presence in the outdoor and/or indoor atmosphere of one or more contaminants or combinations thereof in such quantities and of such duration as may be or may tend to be injurious to human, plant, or animal life, or property; or which unreasonably interferes with the comfortable enjoyment of life or property or the conduct of business."

Composition of Dry Atmospheric Air

In order to define polluted, what's "clean" (or "normal")?

Substance	Volume %
N_2	78%
O_2	20.9%
Argon	~1%
CO_2	0.033%
Other	Trace amts.

→ 79% N_2
→ 21% O_2

Typically used in Engineering Calculation

Broad Categories of AP

- *Ambient air pollution*: refers to AP in the outdoor environment (regulatory authority lies within the US EPA)
- *Indoor air pollution*: AP in buildings, homes, cars, planes, etc. (no regulatory authority)
- *Occupational air pollution*: refers to workplace exposures (OSHA is the regulatory authority)
- *Personal exposure*: cigarette smoking, etc.

Expressing Pollutant Concentrations

- Concentration on a volumetric basis

$$1\text{ppm} = \frac{1\text{ volume of gaseous pollutant}}{10^6\text{ volumes air}} = 0.0001\%\text{ by vol.}$$

- Concentration on a mass basis

$$\frac{\mu g}{m^3} = \frac{\text{micrograms}}{\text{cubic meter}}$$

Volumetric-Mass Relationship

- A general expression of concentration

$$\frac{m_{pol}}{V_{air}} = \frac{\rho_{pol} V_{pol}}{V_{air}} = \frac{V_{pol}}{V_{air}} \times \frac{P(MW)_{pol}}{RT}$$

- Assuming IGL with P = 1 atm, T = 25°C
  - MW_{pol} = the pollutant's molecular weight
  - R = 0.08208 atm·m³/kg·mol·K

$$\frac{m_{pol}}{V_{air}}\left[\frac{kg}{m^3}\right] = \frac{V_{pol}}{V_{air}} \times \frac{(MW)_{pol}}{24.5}$$

Volume-Mass Relationship, cont.

- Multiplication of LHS by 10^9 converts mass to μg
- Division by 10^6 converts (V_{pol}/V_{air}) to ppm
- Final result at 25°C and 1 atm:

$$\frac{\mu g}{m^3} = \frac{ppm \times MW_{pol}}{24.5} \times 10^3$$

Examples

- Car exhaust contains 1.5% CO by volume. What is the [CO] in μg/m³ at 25°C and 1 atm?

- The average daily concentration of SO_2 is observed to be 415 μg/m³ at 25°C and 1 atm at a given location. What is the [SO_2] in ppm?

Air Pollutant Classification

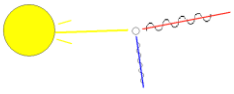
- *Anthropogenic* (man-made) vs. *biogenic* (natural)
  - Examples:
- *Primary* (directly emitted) vs. *secondary* (formed via reactions of primary pollutants)
  - Examples:
- *Particulate* vs. *gas* vs. *aerosol*
  - Examples:

Particulate Matter (PM)

- Particulate: dispersed airborne solid and liquid particles
  - Generally, larger than 0.0002 μm in diameter
  - Generally, smaller than 500 μm in diameter
  - The smallest sizes undergo Brownian motion
  - The largest sizes undergo gravitational settling

Characteristics of PM

- Visibility reduction
  - Scattering: a ray is deflected from its straight path



  - Absorption: light wave energy is "taken up" by matter

PM: Visibility Reduction

- Let the light passing through an incremental distance *dx* be reduced by absorption and scattering by an amount *dI* which is proportional to the intensity *I*

$$dI = -\sigma_{ext} I dx,$$

- Where the proportionality constant (σ_{ext}) is called the extinction coefficient
- Integration over the path length from 0 to d gives

$$I = I_o exp(-\sigma_{ext} d)$$

Where I = the intensity at d and I_o is the original intensity at x = 0

PM: Visibility Reduction (2)

- The extinction coefficient (σ_{ext}) includes the effects of both scattering and absorption

$$\sigma_{ext} = \sigma_{Rayleigh} + \sigma_{abs\text{-}gas} + \sigma_{abs\text{-}part} + \sigma_{scat\text{-}part}$$

- So, ultimately, σ_{ext} is a function of
  - Wavelength (λ) of incident light
  - Concentration of air molecules
  - Concentration of absorbing gases
  - Particle size and shape

PM: Visibility Reduction (3)

- Lower limit of visibility (L_v, a distance) occurs when light intensity is reduced to 2-5% of unattenuated
  - So, with $I/I_o = 0.02$, we can show analytically that

$$L_v = \frac{3.9}{\sigma_{ext}}$$

  - Further, we've shown empirically that

$$L_v = \frac{1.2 \times 10^3}{C}$$

C[μg/m^3], L_v[km]

PM: Effects on Materials, Vegetation, and Animals

- Particles will soil surfaces, clothing, and curtains by settling on them
- Particles may corrode metals
- Particles impact crop yields
- Some particulate contains toxics
  - Fluorosis: ingestion of fluoride-containing PM
  - Arsenic poisoning: ingesting of As-containing PM

PM: Effects on Human Health

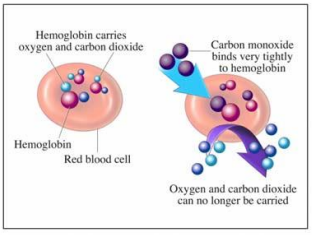
- PM poses a very serious health hazard
- Two mechanisms:
  - The PM may be of a certain size that efficiently penetrates deep lung tissue
  - The PM may be toxic due to physical and/or chemical characteristics
- Health effects:
  - Upper respiratory infections, cardiac disease, bronchitis, asthma, pneumonia, emphysema, and cancer

Carbon Monoxide (CO)

- CO is colorless, odorless, and very stable in atm (2-4 month lifetime)
- Biogenic and anthropogenic sources
- 1-2% annual increase globally over last few decades
- Global background concentration of 50-120 ppb (higher in winter)
- No harmful effects on plant life (to date)

CO: Effects on Human Health

- High [CO] causes physiological and neurological changes and even death
- CO is an asphyxiant



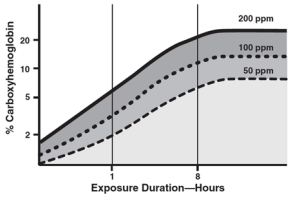
CO: Effects on Human Health (2)

- Exposure to CO leads to equilibrium concentrations of COHb and O_2Hb given by:

$$\frac{COHb}{O_2Hb} = M\frac{P_{CO}}{P_{O_2}}$$

- Where P_{CO} and P_{O_2} are partial pressures of the inhaled gases, and M is 240 for human blood (Hb has an affinity for CO that is 240 times greater than for O_2)

CO: Effects on Human Health (3)

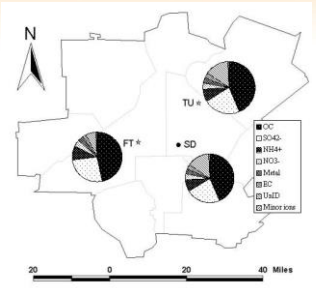


COHb%	Effects
< 1	No apparent effect
1 – 2	Some impact on behavioral performance
3 – 6	Reduced exercise duration
7 – 10	Impaired vision, motor performance, hearing
> 10	Headaches, dizziness, death (long exp. time)

Sulfur Oxides (SO_x)

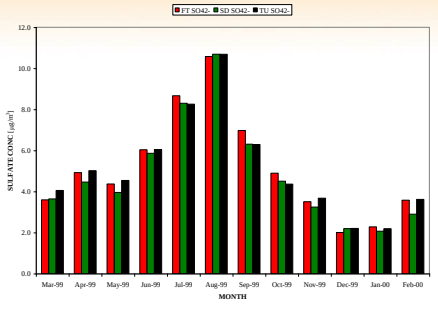
- SO_2 and SO_3 are dominant forms in atm.
- SO_2 is colorless and nonflammable; a pungent odor above 3.0 ppm
- Some SO_2 converts to SO_3 in atm
  - The SO_3 quickly converts to H_2SO_4
- Some SO_2 converts directly to H_2SO_4
- SO_X (gas and particle phase) produce some of the most damaging effects attributable to air pollution

Urban abundance of SO_x aerosol



5-25% of aerosol in urban areas has sulfur

SO_x aerosol temporal trend

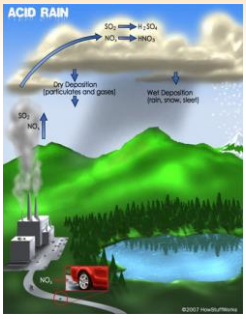


SO_x: Effects on Visibility and Materials

- Sizeable contribution to visibility reduction (up to 70%, or more)
- High [SO_2] increases paint drying time and decreases surface durability
- SO_2 accelerates metal corrosion, decreases tensile strength of Al, and weakens nylon

SO_x: Acid Deposition

- Acid precipitation from rain, snow, or cloud water droplets, or as solid acidic particles
  - What's a neutral pH?
  - What's "normal" for rain?
  - What's typical for acid rain?



SO_x: Acid Deposition(2)

- The chemistry is heterogeneous (gaseous SO_2 is adsorbed onto an aqueous droplet)

$$SO_2(g) \leftrightarrow SO_2(aq)$$
$$SO_2(aq) + H_2O \leftrightarrow HSO_3^- + H^+$$
$$HSO_3^- \leftrightarrow SO_3^{2-} + H^+$$
$$SO_3^{2-} + H_2O \leftrightarrow SO_4^{2-} + 2H^+$$

- 60-70% of acidity in the eastern US is due to sulfuric acid
- Species may be carried FAR from source

SO_x: Acid Deposition Effects

- Acidification of natural waters
  - Reproduction in many fish fails with pH ≤ 5.5
    - But natural rainwater has pH ≈ 5.6. What's going on?
  - Trout and salmon especially sensitive
- Nutrients leached from soil
  - Demineralization reduces crop yields
  - Implicated as a major contributor to the die off of forests

SO_x: Human Health Effects

- Hard to distinguish effects from those of other air pollutants
- Short-term (acute) response is reasonably clear
  - Pungent, suffocating bronchoconstriction at $[SO_2] \geq 5$ ppm
- Long-term (chronic) response is more difficult to assess

Other Important Pollutants

- Hydrocarbons (PAHs, terpene, isoprene)
  - Play a major role in tropospheric O_3 prod.
- Oxides of Nitrogen (NO, NO_2, others)
  - Important for O_3, acid deposition
- Photochemical Oxidants (O_3, PAN H_2O_2, others)
  - Secondary pollutants
  - Corrosive (materials), and toxic (health) effects

One more thing…

- Never lose sight of the various SOURCES
  - Transportation, combustion, industrial
  - Volcanoes, forest fires, swamps, bacterial action
- Obviously, different pollutants have different sources
  - And therefore, different control technologies and strategies
- Mexico City News Report

Discussion Questions

1. What are the causes of air pollution?
2. What are the effects of PM on health?
3. What are the effects of gas-phase pollutants on health?
4. What are the important non-health effects of air pollution?