

CE 213A

Introduction to Environmental Science

Module D

Air Pollution

Dr. Anubha Goel

FB 308, anubha@iitk.ac.in, x 7027

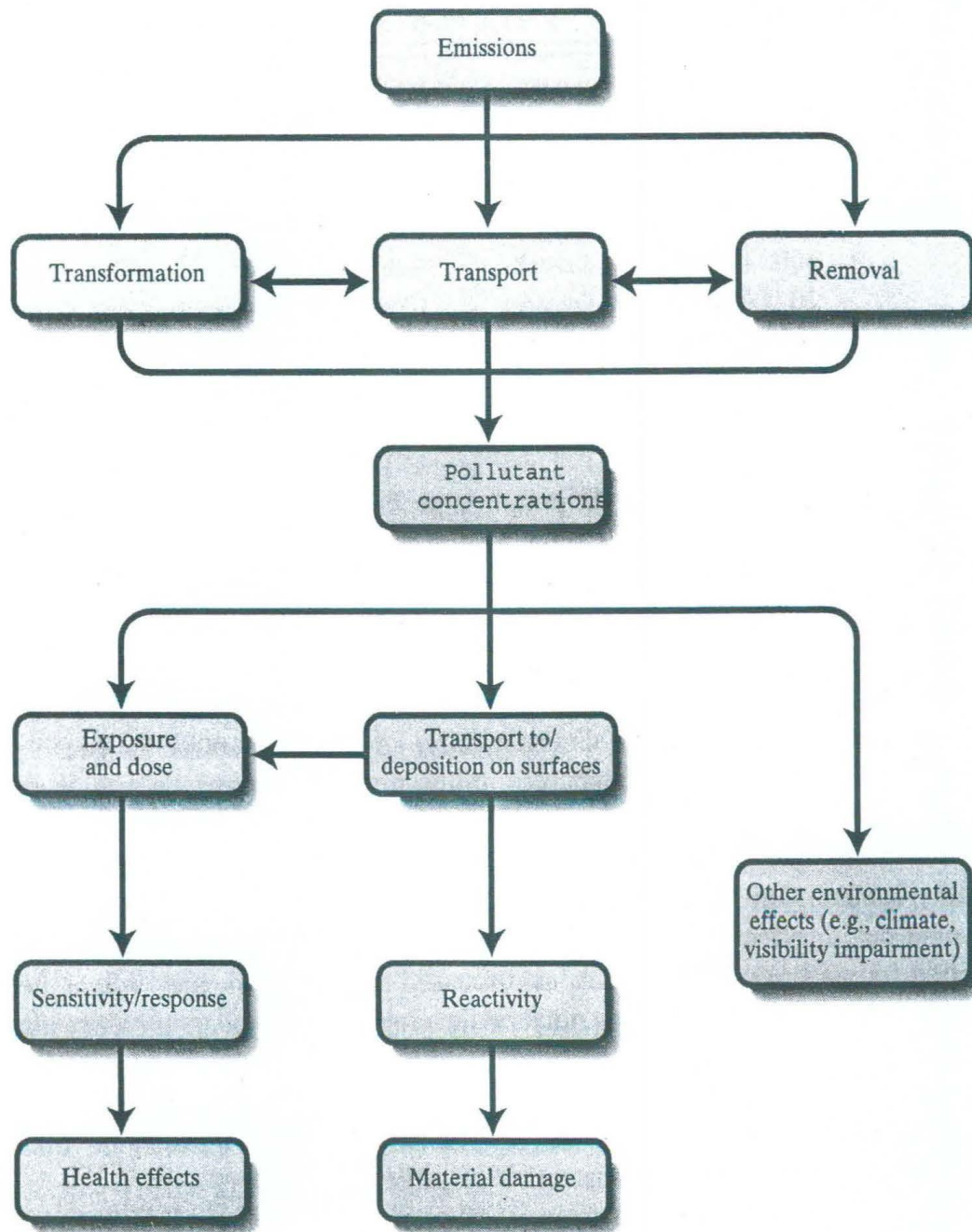


Figure 7.A.1 Framework for understanding air pollution problems.

Key Concepts

- Structure and composition of the atmosphere
- Types and sources of outdoor air pollution
- Indoor Air Pollution
- Sources and effects of acid deposition
- Types, formation, and effects of smog
- Effects of air pollution
- Prevention and control of air pollution

Content

- Nature of Air Pollution Problems
 - Air Quality parameters
- Global warming and International Initiative
- Air Pollutant Emissions
- Measurement of air quality - AQMS
- Transport phenomenon
 - Advection, Dispersion, Plumes
 - Gaussian plume modeling, dispersion modeling, inversion
- Air pollution control devices
 - Overview - Cyclones, bag houses, venture scrubbers, spray towers
- Air Quality Models

A. Nature of Air Pollution Problems

A1. Outdoor Air Pollution

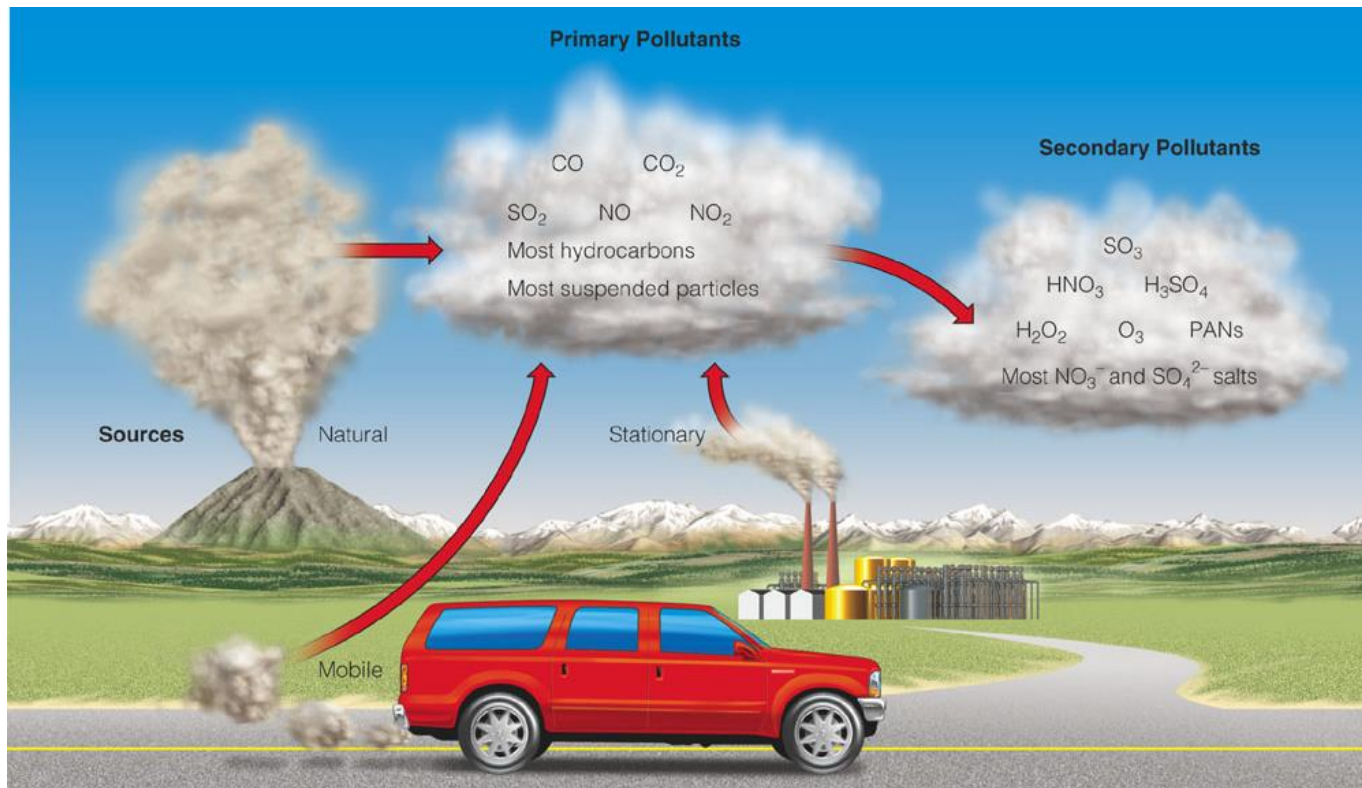
- Primary and Secondary pollutants
- NAAQS and Air Quality Parameters
 - Criteria Pollutants
 - Hazardous Air Pollutants
 - Monitoring of Ambient Air Quality in India
- Acid Deposition
 - Problems associated, solutions
- Photochemical Smog
- Global Change

A2. Indoor Air Quality

- Control of Air Pollution

A1. Outdoor Air Pollution

- Primary - Released directly from planet's surface.
 - Dust, smoke particles, Nitrogen, Carbon etc.
- Secondary - Formed when primary pollutants react or combine with one another, or basic elements.



Primary Air Pollutants

Carbon Monoxide—Produced when organic materials are incompletely burned.

- Single largest source is the automobile.
- Not a persistent pollutant.
- Binds to hemoglobin in blood and makes the hemoglobin less able to carry oxygen.
- Most dangerous in enclosed spaces.
- Cigarette smoking an important source.

Secondary Air Pollutants

- Ozone (O₃)
- PANs (Peroxyacetyl nitrate)
- Aldehydes

all three formed by interaction between NO_x and VOCs.

Note: - Ozone is a pollutant in the troposphere, but natural and beneficial in the stratosphere.

Source	Necessary conditions	Reactions take place in atmosphere	Products
Primarily automobiles	volatile organic compounds (VOC) present	$\text{VOC} + \text{O}^* \text{ or } \text{O}_3 \rightarrow \text{highly reactive organic radicals} + \text{NO}_2$	Peroxyacetyl nitrates Aldehydes
Primarily automobiles	Nitrogen monoxide (NO) present	$\text{NO} + \text{organic radicals} \rightarrow \text{NO}_2$	
From automobiles and formed from NO	Nitrogen dioxide (NO ₂) present	$\text{NO}_2 \xrightarrow{\text{sunlight}} \text{NO} + \text{O}^* \text{ (atomic oxygen)}$ $\text{O}^* + \text{O}_2 \rightarrow \text{O}_3 \text{ (ozone)}$	Ozone
Sun	Sunlight		
Sun (summer temperatures)	Heat	Reactions take place more rapidly at higher temperatures.	

NAAQS

National Ambient Air Quality Standards

Case study – USA

The Clean Air Act, which was last amended in 1990, requires EPA to set National Ambient Air Quality Standards (40 CFR part 50) for pollutants considered harmful to public health and the environment.

The Clean Air Act identifies two types of national ambient air quality standards. **Primary standards** provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. **Secondary standards** provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

Ambient air quality refers to the condition or quality of air surrounding us in the outdoors.

Criteria Air Pollutants

The EPA has set National Ambient Air Quality Standards for six principal pollutants, which are called "criteria" air pollutants.

- The six criteria pollutants are carbon monoxide (CO), nitrogen dioxide (NO₂), (O₃), sulfur dioxide (SO₂), particulate matter (PM), and lead (Pb).
- These six pollutants are not the only ones that have adverse health effects.

Periodically, the standards are reviewed and may be revised. Units of measure for the standards are parts per million (ppm) by volume, parts per billion (ppb) by volume, and micrograms per cubic meter of air ($\mu\text{g}/\text{m}^3$)

NATIONAL AMBIENT AIR QUALITY STANDARDS

S. No.	Pollutant	Time Weighted Average	Concentration in Ambient Air		
			Industrial, Residential, Rural and Other Area	Ecologically Sensitive Area (notified by Central Government)	Methods of Measurement
(1)	(2)	(3)	(4)	(5)	(6)
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual* 24 hours**	50 80	20 80	- Improved West and Gaeke - Ultraviolet fluorescence
2	Nitrogen Dioxide (NO ₂), µg/m ³	Annual* 24 hours**	40 80	30 80	- Modified Jacob & Hochheiser (Na-Arsenite) - Chemiluminescence
3	Particulate Matter (size less than 10µm) or PM ₁₀ µg/m ³	Annual* 24 hours**	60 100	60 100	- Gravimetric - TOEM - Beta attenuation
4	Particulate Matter (size less than 2.5µm) or PM _{2.5} µg/m ³	Annual* 24 hours**	40 60	40 60	- Gravimetric - TOEM - Beta attenuation
5	Ozone (O ₃) µg/m ³	8 hours** 1 hour**	100 180	100 180	- UV photometric - Chemiluminescence - Chemical Method
6	Lead (Pb) µg/m ³	Annual* 24 hours**	0.50 1.0	0.50 1.0	- AAS/ICP method after sampling on EPM 2000 or equivalent filter paper - ED-XRF using Teflon filter
7	Carbon Monoxide (CO) mg/m ³	8 hours** 1 hour**	02 04	02 04	- Non Dispersive Infra Red (NDIR) spectroscopy
8	Ammonia (NH ₃) µg/m ³	Annual* 24 hours**	100 400	100 400	- Chemiluminescence - Indophenol blue method

NAAQS – India:

- Ambient air quality refers to the condition or quality of air surrounding us in the outdoors.
- National Ambient Air Quality Standards are the standards for ambient air quality set by the [Central Pollution Control Board \(CPCB\)](#) that is applicable nationwide. The CPCB has been conferred this power by the Air (Prevention and Control of Pollution) Act, 1981.

(1)	(2)	(3)	(4)	(5)	(6)
9	Benzene (C ₆ H ₆) µg/m ³	Annual*	05	05	- Gas chromatography based continuous analyzer - Adsorption and Desorption followed by GC analysis
10	Benzo(a)Pyrene (BaP) - particulate phase only, ng/m ³	Annual*	01	01	- Solvent extraction followed by HPLC/GC analysis
11	Arsenic (As), ng/m ³	Annual*	06	06	- AAS /ICP method after sampling on EPM 2000 or equivalent filter paper
12	Nickel (Ni), ng/m ³	Annual*	20	20	- AAS /ICP method after sampling on EPM 2000 or equivalent filter paper

**Detail in Handout:
H5- Ambient Air Quality
Standards in India**

- Prior to the November 2009 standards, India had set Air Quality standards on 11 April 1994, and this was later revised on 14 October 1998.
- The 2009 standards further lowered the maximum permissible limits for pollutants and made the standards uniform across the nation.
- Earlier, less stringent standards were prescribed for industrial zones as compared to residential areas.

Hazardous Air Pollutants HAPs

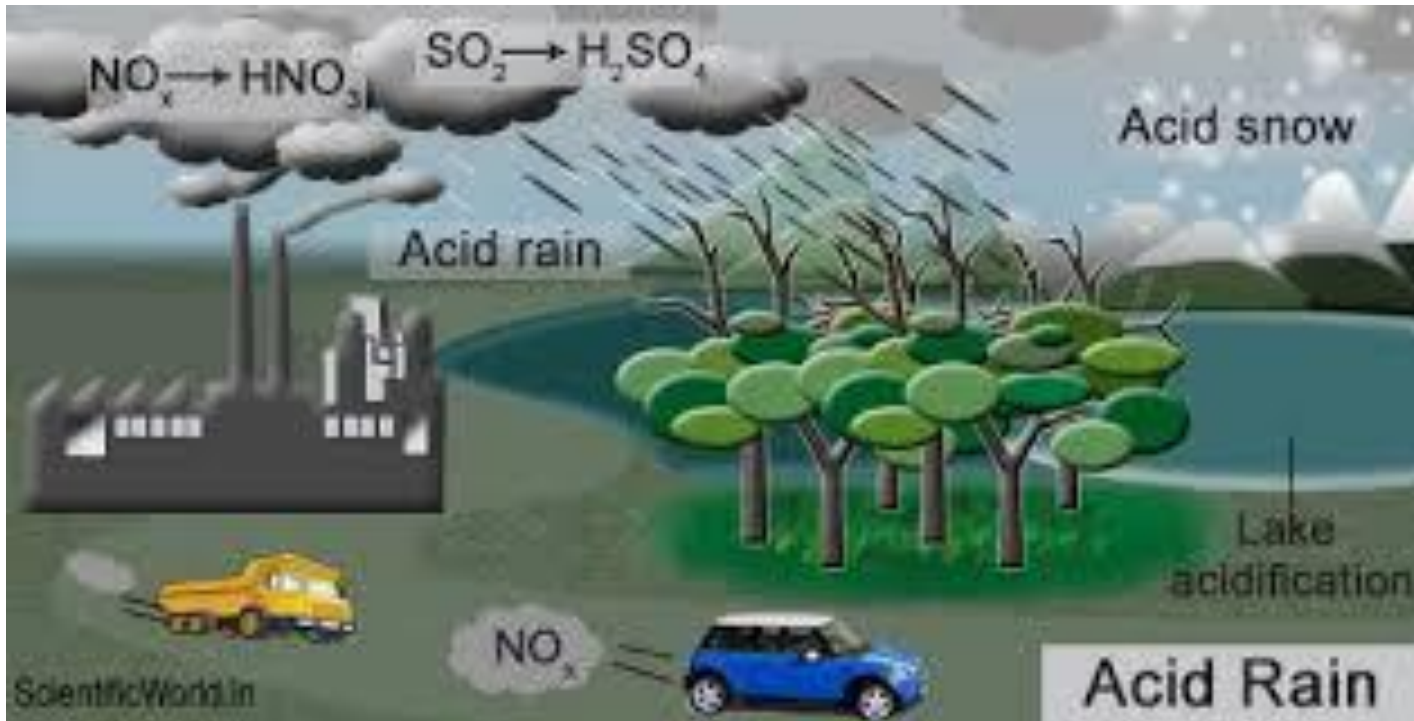
- Hazardous air pollutants (HAPs) are species that are known or suspected carcinogens, or that have been shown to cause other serious health effects, such as reproductive problems or birth defects.
- HAPs include metal compounds, hydrocarbons, halogenated organics, and pesticides
- Characterization and control of HAPs focus on major emission sources, which are usually associated with industrial processes.

Characteristics of Hazardous and Criteria Air Pollutants

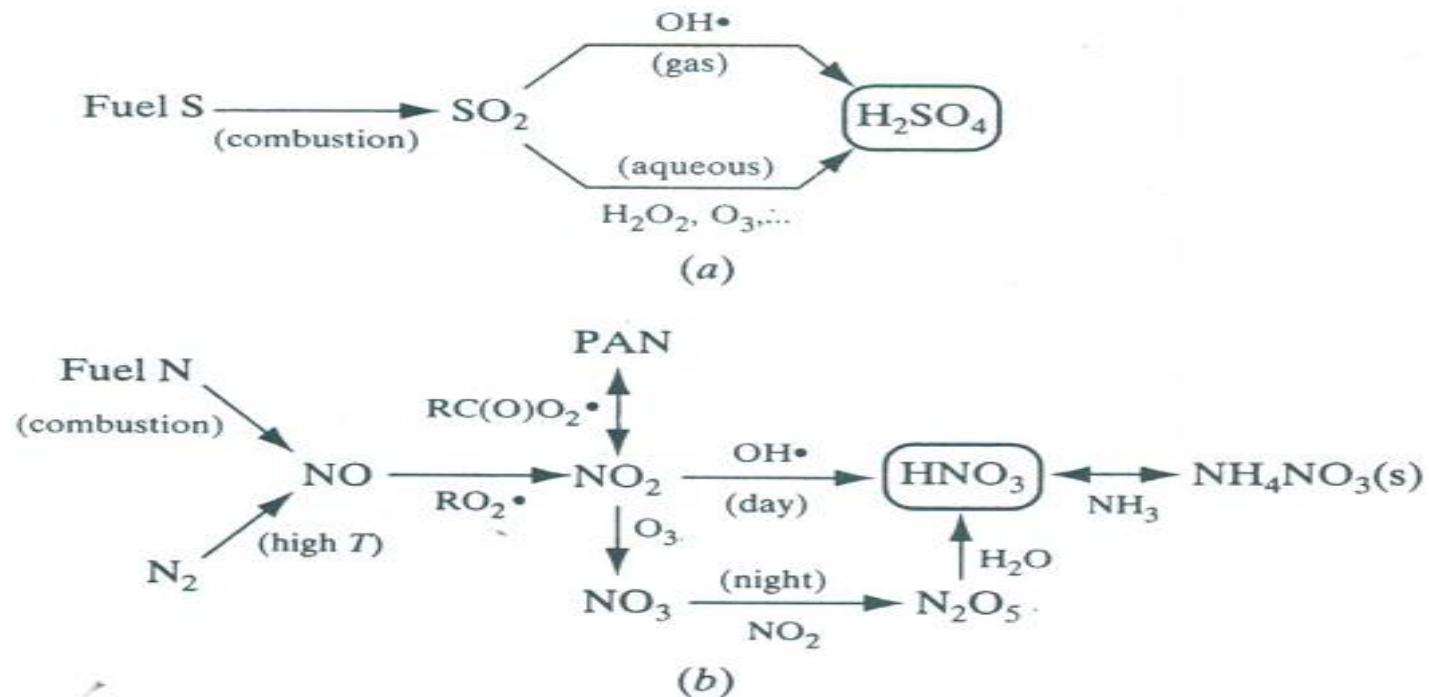
Characteristic	Hazardous air pollutants	Criteria pollutants
Number of species	Hundreds	Six
Ambient concentration data	Sparse	Extensive
Ambient concentrations	Often below detection limit	Relatively easily measured
Scale of problems	Localized (plume)	Dispersed (urban airshed or regional)
History of control effort	Limited, recent (years)	Extensive (decades)

Acid Deposition OR Acid Rain

- Some compounds emitted into the atmosphere can be converted to acidic species. The deposition of excessive amounts of these species can cause economic and ecosystem damage.



Transformation dynamics that produce atmospheric acids from (a) sulfur oxides and (b) nitrogen oxides.

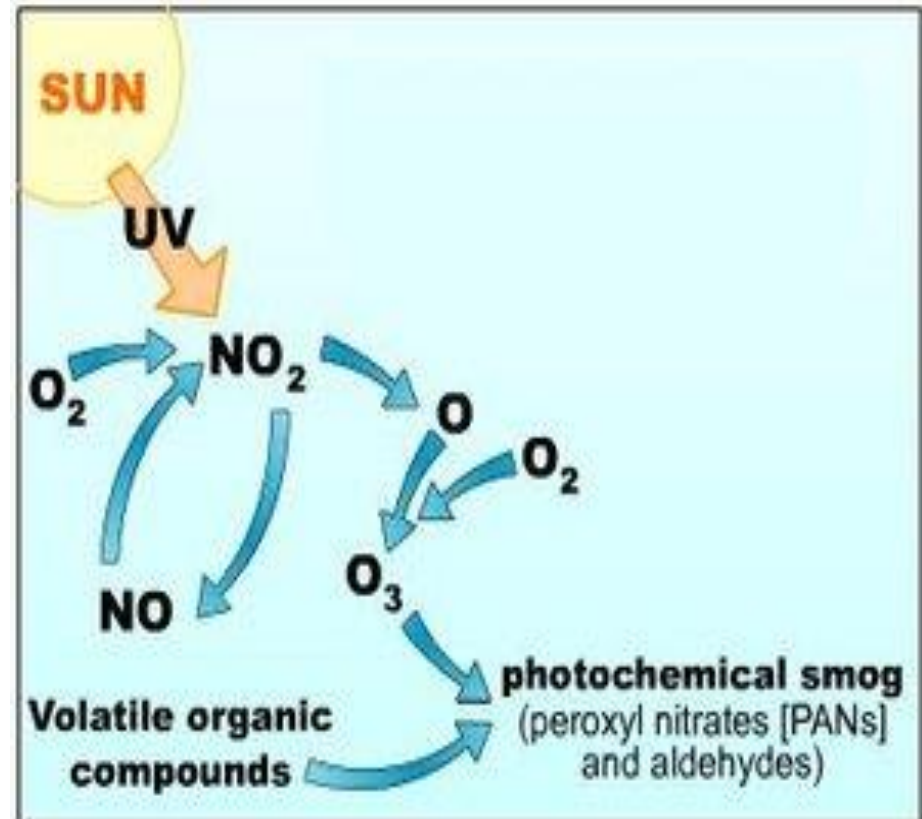


The arrows are labelled with the major reactant that is involved in the transformation process.

R denotes a hydrocarbon fragment such as CH₃
 PANs (Peroxyacetyl nitrate), a secondary pollutant

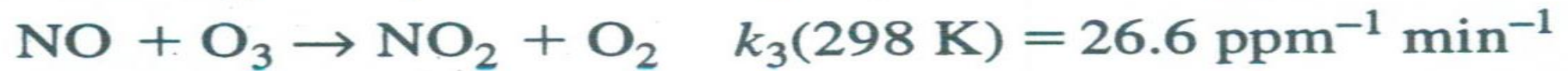
Photochemical Smog formation

- Brown-air smog
- Some primary pollutants react under the influence of sunlight (photochemical reaction), including NO_x , O_3 , PANs.
- Corrosive, irritating.
- Central to this system are transformation processes chemical kinetic reactions and phase changes that produce secondary pollutants whose effects are worse than the primary emissions.



FORMATION OF PHOTOCHEMICAL SMOG

Equations



In summary, tropospheric ozone is formed when a mixture of organic gases and nitrogen oxides is exposed to sunlight. The sunlight causes nitrogen dioxide to dissociate, liberating an oxygen radical that combines with an oxygen molecule to produce ozone.

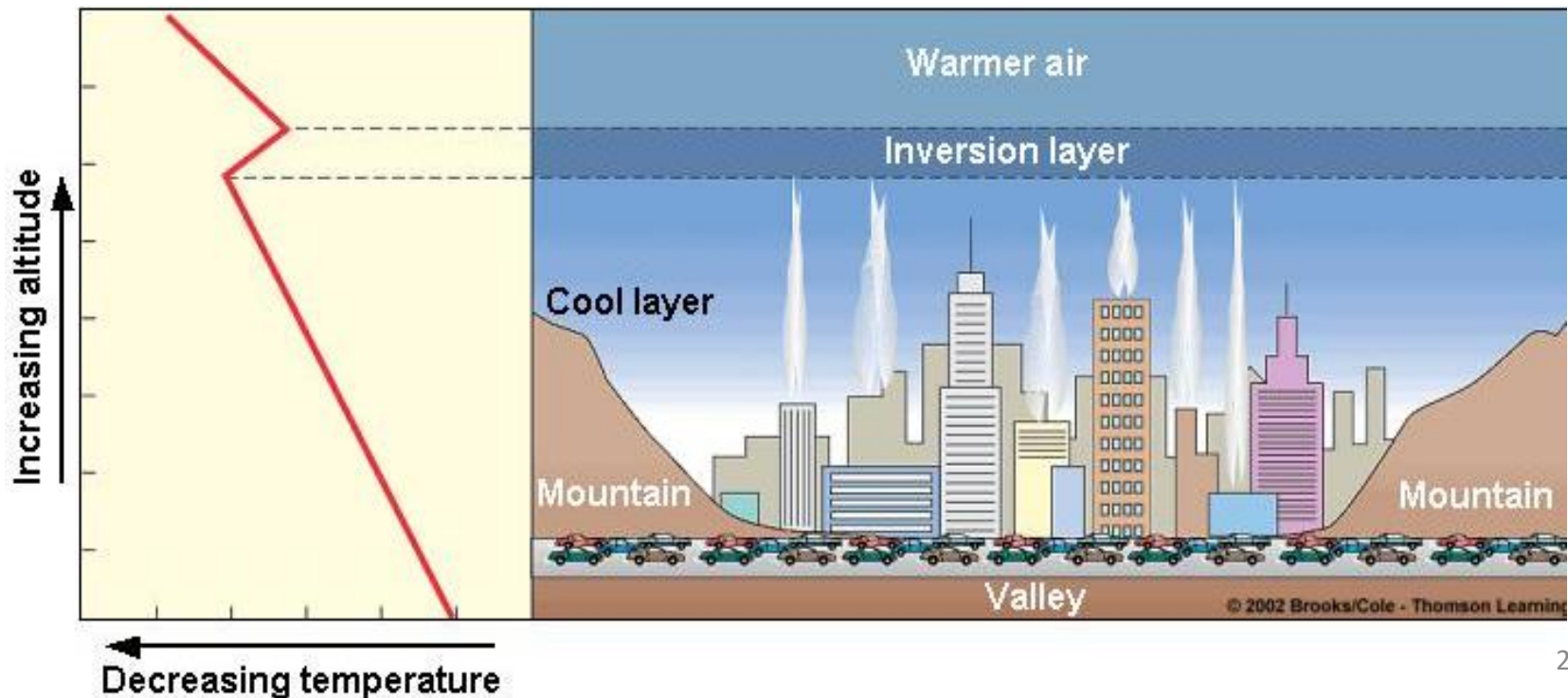
Industrial Smog

- Gray-air smog
- From burning coal and oil (particulates, sulfur dioxide, sulfuric acid).
- London was the smog capitol. In 1952, smog developed for days, no atmospheric mixing, 4,000 people died.
- Now mainly a problem in LDCs (*Least Developed Countries*) with developing industries and no pollution control laws.

The *least developed countries* (LDCs) are a group of *countries* that have been classified by the UN as "*least developed*" in terms of their low gross national income (GNI), their weak human assets and their high degree of economic vulnerability

Thermal inversion

- warm air normally near surface, pollutants disperse as air rises and mixes
- when cool air trapped under warm air, confined by mountains, pollutants do not disperse, intensify with time



A2. Indoor air pollution

- Indoor air pollution started with the use of fires in caves, but prehistoric peoples had many more pressing concerns than that health hazard.
- Concerns about indoor air quality focus on health risks such as disease, as well as other aspects of human well-being, such as odors and irritancy or allergic reactions to indoor air pollutants.
- For example, much attention is now being given to the “sick building syndrome” and its effects on workplace productivity.

Effects of Air Pollution on People

- Respiratory diseases
- Asthma
- Lung cancer
- Chronic bronchitis
- Emphysema
- Premature death

UNEP 2014 Report

Air Pollution: World's Worst Environmental Health Risk
(Handout 6)

Control of Air Pollution

- Industrial Activities
 - Scrubbers
 - Precipitators
 - Filters
- Sulfur Removal
 - Switch to low-sulfur fuel.
 - Remove sulfur from fuel before use.
 - Scrubbing gases emitted from smokestack.

Emission Reduction

Solutions

Stationary Source Air Pollution

Prevention

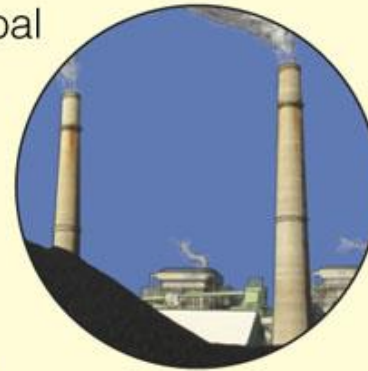
Dispersion or Cleanup

Burn low-sulfur coal

Remove sulfur from coal

Convert coal to a liquid or gaseous fuel

Shift to less polluting fuels



Disperse emissions above thermal inversion layer with tall smokestacks

Remove pollutants after combustion

Tax each unit of pollution produced

Reducing Motor Vehicle Air Pollution

Solutions

Motor Vehicle Air Pollution

Prevention

Cleanup

Mass transit

Bicycles and walking

Less polluting engines

Less polluting fuels

Improve fuel efficiency

Get older, polluting cars off the road

Give buyers large tax write-offs for buying low-polluting, energy-efficient vehicles

Restrict driving in polluted areas



Emission control devices

Car exhaust inspections twice a year

Stricter emission standards

Reducing Indoor Air Pollution

Solutions

Indoor Air Pollution

Prevention

Cover ceiling tiles and lining of AC ducts to prevent release of mineral fibers

Ban smoking or limit it to well-ventilated areas

Set stricter formaldehyde emissions standards for carpet, furniture, and building materials

Prevent radon infiltration

Use office machines in well-ventilated areas

Use less polluting substitutes for harmful cleaning agents, paints, and other products



Use adjustable fresh air vents for work spaces

Increase intake of outside air



Change air more frequently

Circulate a building's air through rooftop greenhouses



Use exhaust hoods for stoves and appliances burning natural gas



Install efficient chimneys for wood-burning stoves

Types of air pollutant sources

- Point Source
- Mobile Source
- Area Source
- Line source

1. Measurement : Air pollutant emissions from Point Sources

- **Stack emissions:**

- The principle of mass balance can be applied to determine the mass emission rate (g/sec).
- If the pollutant species is well mixed within the flue, then measure of the species concentration in the flue gas, C (g/m³) and multiply it by the rate at which gas is emitted, Q (m³ /s)

$$E = QC$$



2. Calculation of Emissions - Emission factors

- Measuring air pollutant emissions from sources can be an expensive and complex undertaking. The number of sources that emit pollutants is large, so it is not practical to measure emissions from every source. Furthermore, it is often necessary to predict emissions for planned sources in advance of their construction.
- In addressing these issues, emission factors are often used. An emission factor specifies the mass of pollutant emitted from an activity normalized by the intensity of the activity. For example, emission factors for carbon monoxide from a motor vehicle might be expressed in terms of grams of CO emitted per mile traveled or per gallon of gasoline consumed.

Determining Emissions from Overall Material Balance

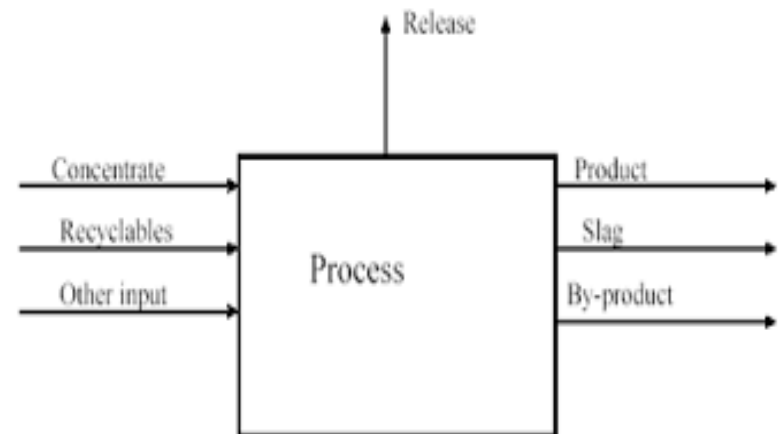
- Based on Knowledge of
 - material used and final end products
 - Stoichiometry
- Works well for combustion processes
 - Carbon monoxide, Carbon dioxide
 - Nitrogen oxides
 - Sulfur oxide

Material Balance

$$\left(\begin{array}{c} \text{Rate of} \\ \text{Accumulation of} \\ \text{mass in system} \end{array} \right) = \left(\begin{array}{c} \text{Mass} \\ \text{flow rate} \\ \text{into} \\ \text{system} \end{array} \right) - \left(\begin{array}{c} \text{Mass} \\ \text{flow rate} \\ \text{out of} \\ \text{system} \end{array} \right)$$

$$\frac{\left(\begin{array}{c} \text{mass at} \\ \text{time } t + \Delta t \end{array} \right) - \left(\begin{array}{c} \text{mass at} \\ \text{time } t \end{array} \right)}{\Delta t} = \frac{\left(\begin{array}{c} \text{mass} \\ \text{entering} \\ \text{from } t \text{ to} \\ t + \Delta t \end{array} \right)}{\Delta t} - \frac{\left(\begin{array}{c} \text{mass} \\ \text{exiting} \\ \text{from } t \text{ to} \\ t + \Delta t \end{array} \right)}{\Delta t} + \frac{\left(\begin{array}{c} \text{net} \\ \text{chemical} \\ \text{production} \\ \text{between } t \\ \text{and } t + \Delta t \end{array} \right)}{\Delta t} \quad (13)$$

$$\begin{aligned} \frac{dm}{dt} &= \dot{m}_{in} - \dot{m}_{out} + \dot{m}_{rxn} \\ V \frac{dC}{dt} &= QC_{in} - QC + 0, \text{ or} \\ \frac{dC}{dt} &= -(Q/V)(C - C_{in}) \end{aligned}$$



Tips for Solving Problems

1. Write the Given and Find statements
2. Draw a picture of the system labeling all Inputs and Outputs for each component.
3. Assign variables to the unknowns. Use symbols to describe the known parameters and list their values.
4. Determine whether the problem is a batch process or rate process .
5. Determine whether components are generated or consumed.
5. Write the conservation of mass for each component and for the entire system.
6. Use algebra to solve for the unknowns.
7. Check your work.

Models – Statistical, Deterministic

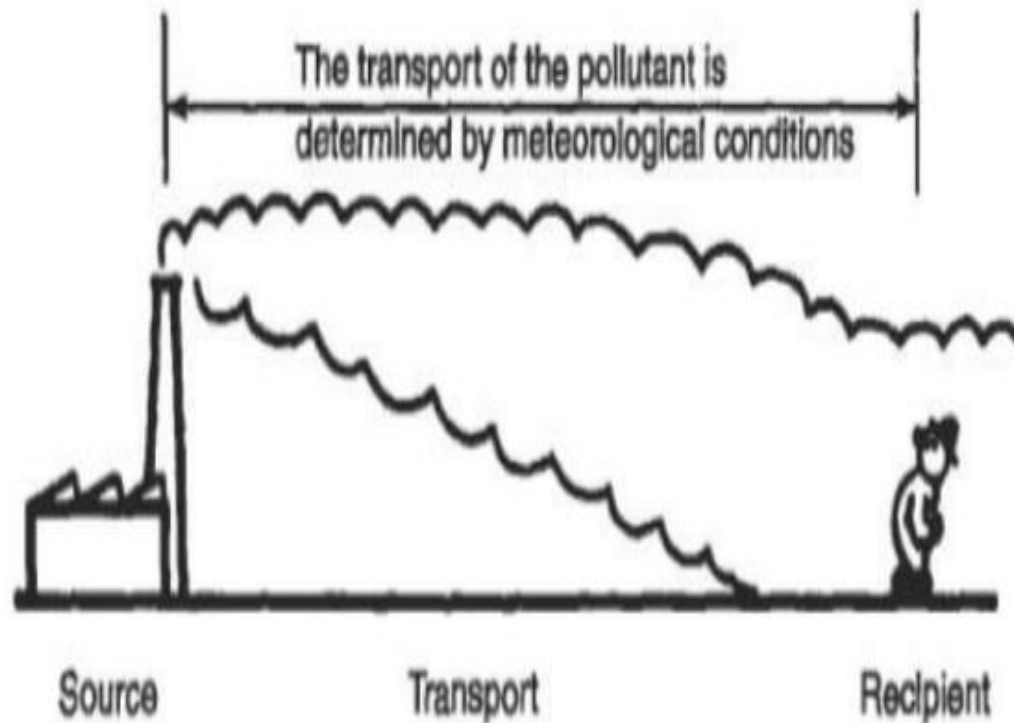
Atmospheric Physics basics- Stability, Lapse Rate, Inversion

Gaussian Plume Model

MODELING POLLUTANT TRANSPORT FROM POINT SOURCES

An air pollution problem involves three parts:

- The pollution source
- The movement or dispersion of the pollutant
- The recipient



Basic concepts and mechanisms of Transport phenomena

Flux

Advection, Diffusion and Dispersion

Ref. Nazaroff, Ch. 4

Contaminant flux:

Transport of both molecules and particles is commonly quantified in terms of flux density or simple flux.

- Flux is a vector quantity, comprising both a magnitude and a direction.
- The flux vector points in the direction of net contaminant motion, and the magnitude indicates the rate at which the contaminant is moving.

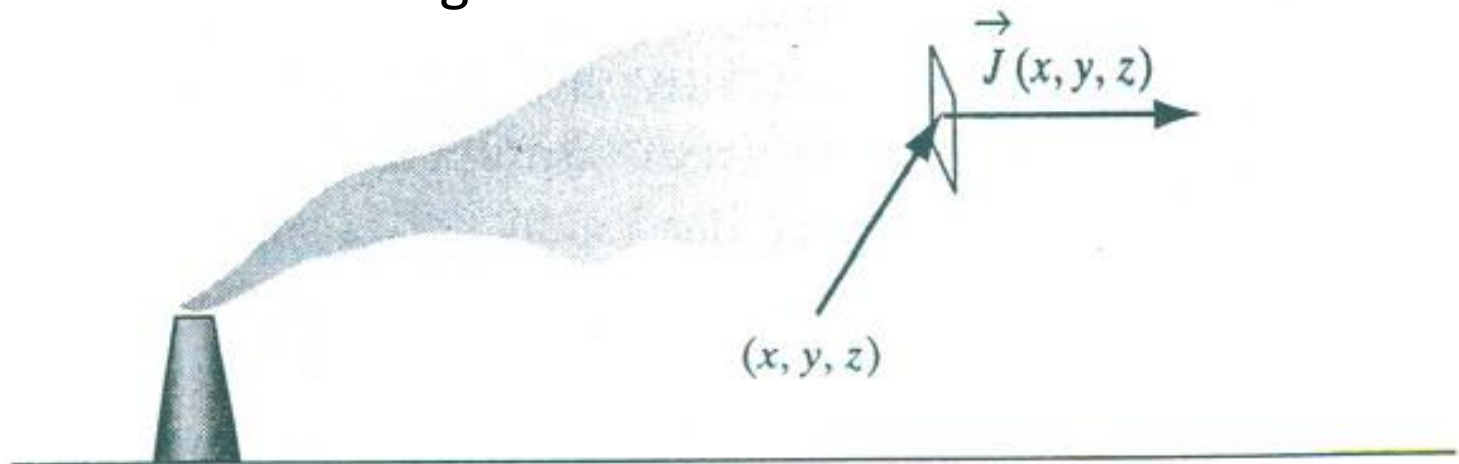


Figure 4.A.1 Flux, \vec{J} , is a vector quantity whose value varies with position (x, y, z) . The contaminant flux vector points in the direction of transport, and its magnitude is the quantity transported (usually

Advection, diffusion and dispersion

1. Advection

- transport of material caused by the net flow of the fluid in which that material is suspended.
- Whenever a fluid is in motion, all contaminants in the fluid, including both molecules and particles, are advected along with the fluid.

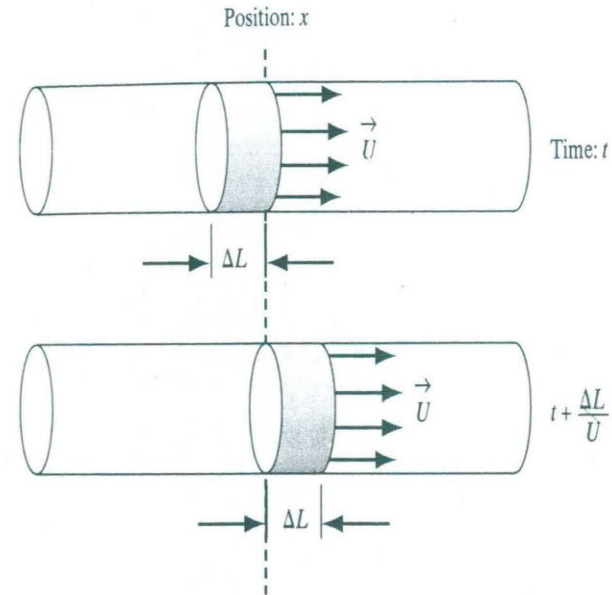


Figure 4.A.2 Advective flux of contaminant through a tube. The two pictures represent the same tube at two points in time, t and $t + \Delta t$, where $\Delta t = \Delta L / U$.

per time:

$$J_a = \frac{C \times \Delta L \times A}{A(\Delta L / U)} = CU \quad (4.A.1)$$

In general, the three-dimensional advective flux vector is the product of the contaminant concentration and the fluid velocity:

$$\vec{J}_a(x, y, z) = C(x, y, z) \times \vec{U}(x, y, z) \quad (4.A.2)$$

2. Molecular diffusion

The random motion of fluids causes a net movement of species from regions of high concentration to regions of low concentration this phenomenon is known as molecular diffusion

Fick's law for molecular diffusion

$$J_d \propto -\frac{\Delta C}{\Delta x} \quad (4.A.3)$$

where J_d is the diffusive flux density (moles per cross-sectional area of the tube per time), ΔC is the change in concentration of ethylbenzene molecules across the tube, and Δx is the tube length. The minus sign appears in this relationship to remind us that the diffusive flux proceeds in the direction of decreasing concentration.

By introducing the proportionality constant, D , this expression can be converted to an equation:

$$J_d = -D \frac{\Delta C}{\Delta x} \quad (4.A.4)$$

The constant, D , is called the *diffusion coefficient*, or *diffusivity*. It is a property of the diffusing species (ethylbenzene in this case), the fluid through which it is diffusing

3. Dispersion

In complex flow fields, it is impossible (or at least impractical) to describe fluid velocity exactly as a function of space and time. Without this information, dispersion cannot be accurately described in terms of the fundamental mechanisms of advection and molecular diffusion. As an alternative, dispersion can be treated as a random process, analogous to molecular diffusion, by applying Fick's first law of diffusion with the molecular diffusion coefficient replaced by a dispersion coefficient. So in one dimension, we would write

$$J_{\text{dispersion}} = -\varepsilon \frac{dC}{dx} \quad (4.A.10)$$

where ε is a *dispersion coefficient*, obtained through a combination of empirical data and theoretical equations.

Several types of dispersion phenomena are encountered in environmental engineering. In this section, two common types are introduced: *shear-flow dispersion* and *turbulent diffusion*.

For the situation depicted in Figure 4.A.6, the contaminant flux in the direction of flow can be described as the sum of two components: (1) advection, which transports the overall pulse through the tube, and (2) shear-flow dispersion, which causes the pulse to become stretched as it travels. The flux in the direction of flow caused by shear-flow dispersion is written as

$$J_s = -\varepsilon_s \frac{dC(x)}{dx} \quad (4.A.11)$$

where ε_s is the shear-flow dispersivity and $C(x)$ represents the contaminant concentration averaged over a cross-section of the tube at position x .

Shear-flow dispersion is most commonly applied to predict the transport of contaminants in systems in which the flow is confined. In addition to pipe or tube flow, shear-flow dispersion is applied to study pollutant transport in rivers and in estuarine environments influenced by tides.

Particle Motion

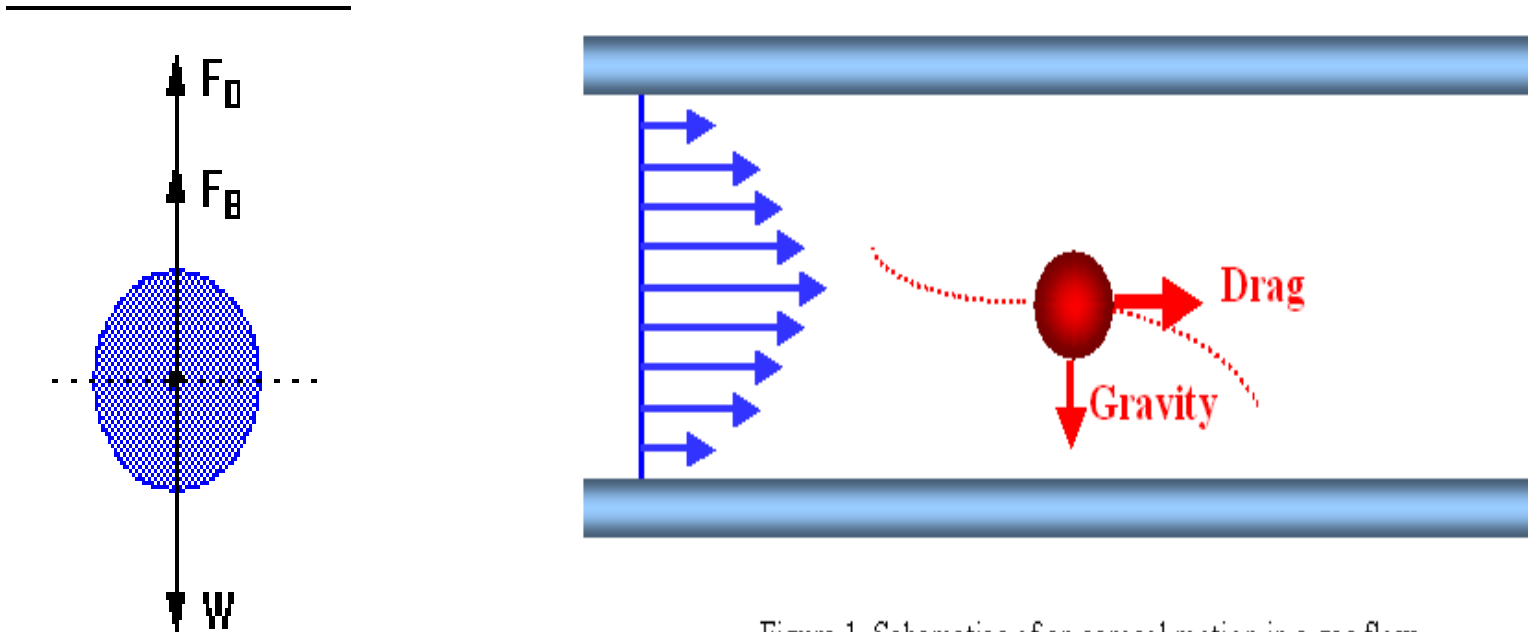
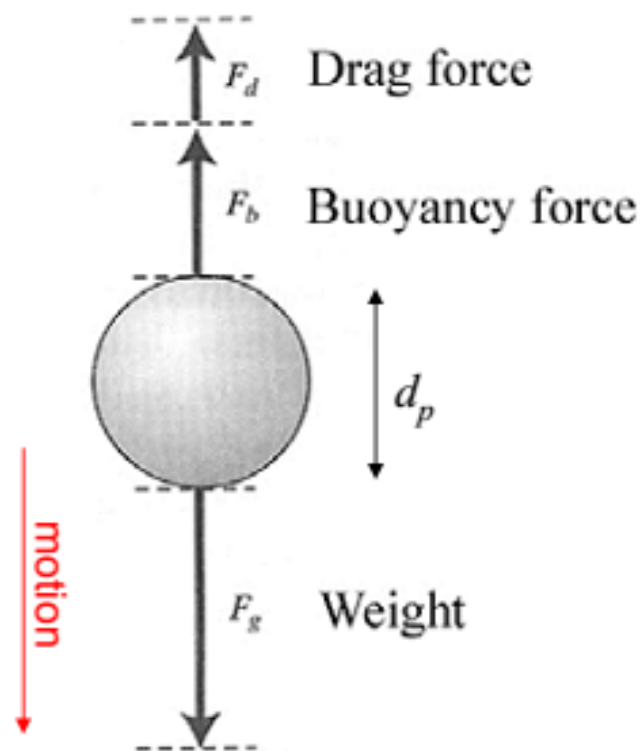


Figure 1. Schematics of an aerosol motion in a gas flow.

Gravitational settling

(Nazaroff & Alvarez-Cohen, Section 4.B.2)



When moving relatively to a fluid, a particle is subject to 3 forces:

- its own weight
- a buoyancy force
- a drag force.

After a brief period of acceleration, A terminal velocity is reached, and a balance is achieved between these 3 forces:

$$F_g = F_b + F_d$$

weight of particle: $F_g = m_{\text{particle}} g = \rho_p \frac{\pi d_p^3}{6} g$

buoyancy force: $F_b = m_{\text{displaced fluid}} g = \rho_f \frac{\pi d_p^3}{6} g$

drag force: $F_d = C_d \frac{\pi}{4} d_p^2 \frac{1}{2} \rho_f V_p^2$

Note the difference: ρ_p = density of material making up the particle, ρ_f = fluid density.