Chapter 3. Circulation and dispersion of pollutants

The discharge of pollutants into the environment is a complex phenomenon that cannot be limited to the seemingly local aspect of a sewer outlet flowing into a river or a factory's smoke rising into the air. None of the substances released by humans into the biosphere remain in place; in most cases, they travel far from their point of emission.

3.1. Structure of the atmosphere and composition of air

The Earth's atmosphere is composed of a complex gaseous mixture called air, extending from the ground up to an altitude of about 150 km. Based on the vertical temperature structure of the atmosphere, four layers are conventionally distinguished, in which pressure gradually decreases:

a) The Troposphere: From the ground to about 10 km. The air temperature decreases with altitude; at its top (the tropopause), the temperature is around -60°C. Most meteorological phenomena occur in this region.

b) The Stratosphere: From 10 to 50 km. The air temperature increases due to the absorption of solar radiation by ozone; at 50 km altitude, the pressure is about 1 mb (millibar).

c) The Mesosphere: From 50 to 80 km. The air temperature decreases again with altitude.

d) The Thermosphere: Above 80 km, the temperature increases continuously; at 150 km, the pressure is about 0.00005 mb.

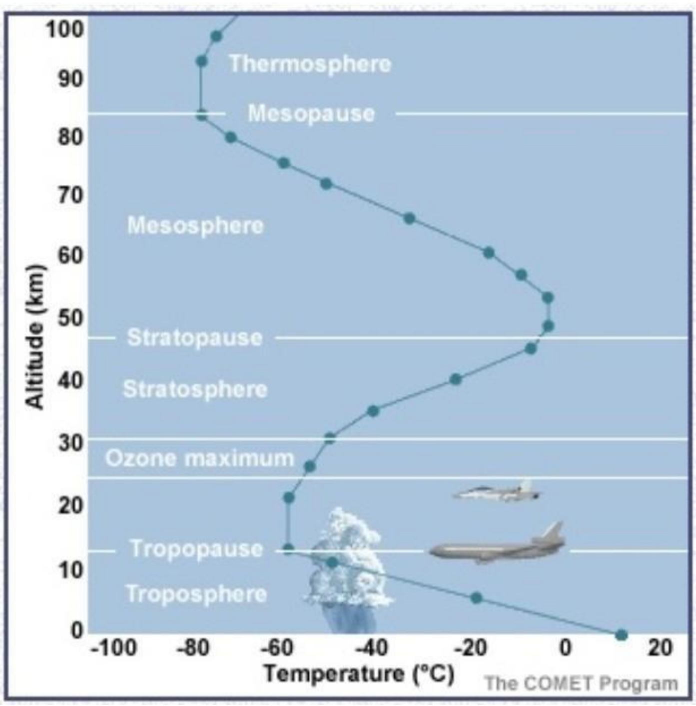

Figure 11. Vertical Structure of the Atmospher.

Atmospheric air is a complex mixture of gases and suspended liquid and solid particles. Nitrogen and oxygen are the major components: 78% by volume for nitrogen and 21% for oxygen. The remaining 1% includes “rare” gases (helium, argon, neon, krypton, radon), water vapor, carbon dioxide, hydrogen, ozone, suspended solid and liquid particles (liquid or solid water, fine dust, salt crystals, pollen), and atmospheric pollutants. It is generally accepted that the overall composition of dry air varies very little up to 80 km altitude; this region is called the **homosphere**.

3.2. Origin and nature of atmospheric pollutants

A pollutant is a substance present in the atmosphere at a concentration higher than its usual one -often zero -except for carbon dioxide, nitrogen oxides, ozone, and ammonia, which are normal components of unpolluted air (Paul et *al*., 1974).

The nature of pollutants is directly linked to the types of emissions into the atmosphere. There are **natural sources** (rock erosion, volcanoes, sea spray, etc.) and **anthropogenic sources** (industry, transport, agriculture and livestock, domestic activity). These various sources emit numerous substances, including:

- **Gases and vapors** of various mineral or organic compounds such as sulfur oxides (mainly sulfur dioxide SO_2), nitrogen oxides (NO_x, including NO and NO_2), carbon monoxide (CO), ozone (O_3), lead (Pb), hydrocarbons (aliphatic and aromatic), acids, phenols, etc.
- **Solid particles or liquid droplets** forming aerosols ranging from 0.05 µm (the finest, remaining suspended) to 20 µm or more (eventually settling to the ground).

3.3. Atmospheric circulation of pollutants

Atmospheric movements play a fundamental role in the distribution of pollutants. Updrafts and winds disperse them vertically and latitudinally, ensuring their circulation. This contamination does not occur randomly but follows well-defined mechanisms governed by meteorological parameters. These mechanisms have been clarified through research using high-performance weather balloons and, more recently, meteorological satellites.

A dominant **westerly wind** blowing at the tropopause level in the Northern Hemisphere, with an average speed of 35 m/s, allows for circumterrestrial transit of substances at that altitude in about twelve (12) days. This explains the global dispersion of particles emitted by nuclear or volcanic explosions.

These horizontal currents are associated with vertical air movements that enable circulation from north to south. The combination of west-east winds with upward drift at low altitudes creates an atmospheric circulation type called the **Hadley cell**, which exchanges air masses between hemispheres at tropical troposphere levels.

The different cells are arranged in latitudinal bands, forming a zonal organization. The general circulation model includes six convection cells: two **Hadley cells** (direct circulation), two **Ferrel cells** (reverse circulation), and two **Polar cells** (direct circulation again).

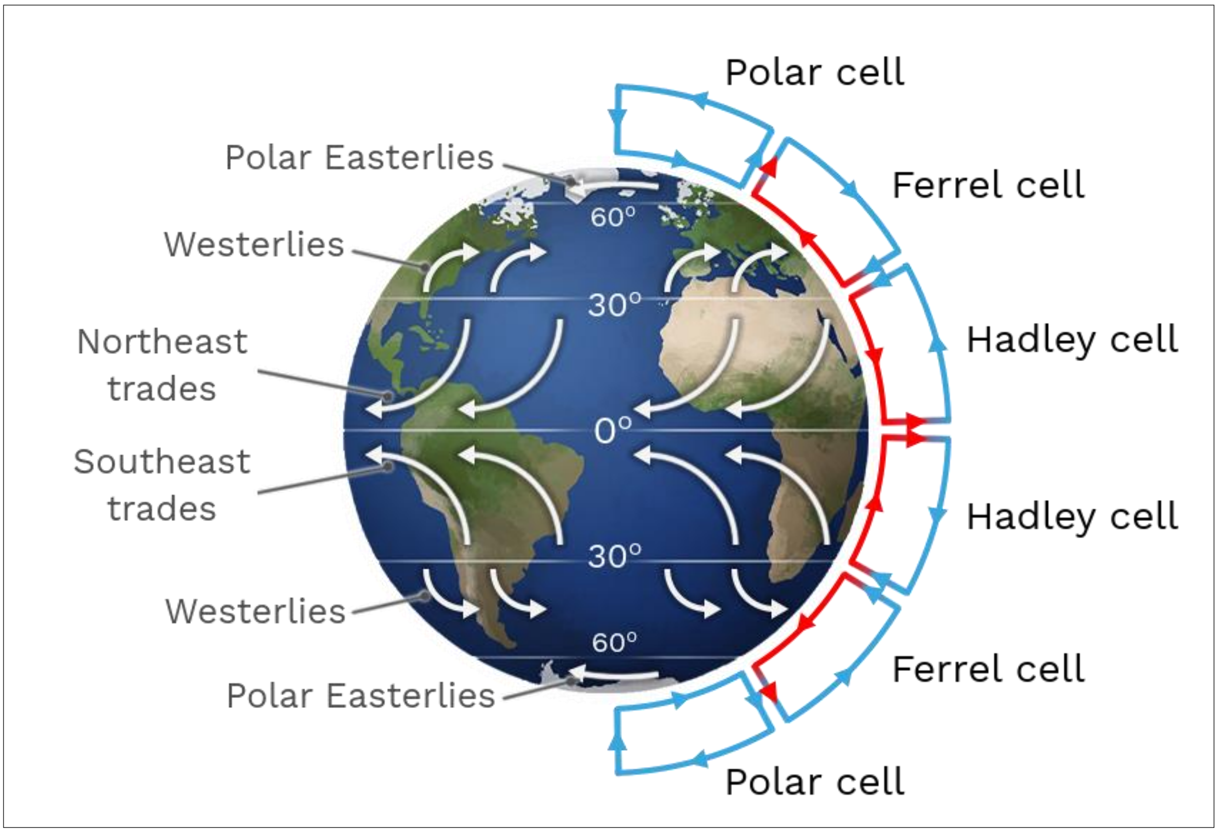

Figure 12. Model of General Atmospheric Circulation

3.4. Dispersion of pollutants in the atmosphere

The concentrations of primary pollutants in ambient air are highest near emission sources and decrease with distance.
Major influencing factors include emission characteristics (flux, altitude, temperature), site topography (relief), climatology (temperature, humidity, wind speed, pressure), and particle size (for dust and aerosols).

• Atmospheric Turbulence:

Small-scale air movements mix the air mass and allow dilution of pollutants. The stronger the turbulence, the greater the dispersion.

• Wind:

There is a clear relationship between wind speed and pollutant concentration. Dispersion increases with wind speed and turbulence; weak winds promote accumulation. Wind speed also increases with altitude.

• Temperature:

Temperature affects pollutant chemistry: cold reduces the volatility of some gases, while summer heat promotes photochemical ozone formation.

• Atmospheric Stability and Instability:

These are key factors in dispersion. A stable atmosphere resists mixing; an unstable one promotes it.

If an air parcel lifted upward becomes cooler and heavier than its surroundings, it descends again—indicating **stability**. If it remains warmer and lighter, it continues to rise—indicating **instability**.

- **Unsaturated air:**
  - Decrease faster than -1°C/100 m → instability
  - Decrease slower than -1°C/100 m → stability
- **Saturated air:**
  - Decrease faster than -0.65°C/100 m → instability
  - Decrease slower than -0.65°C/100 m → stability

• Thermal Inversion:

Normally, temperature decreases with altitude, allowing pollutants to disperse. During **thermal inversion**, the ground cools significantly (e.g., at night), and the air above becomes warmer, trapping pollutants under a “thermal lid.” Without wind, pollutant concentrations can rise sharply.

• Local Topography:

- **Sea Breezes:** Caused by temperature contrasts between land and sea. During the day, breezes blow from sea to land, possibly bringing marine pollutants inland; at night, breezes reverse.
- **Valleys:** Daytime upslope winds disperse pollutants; nighttime downslope winds trap them at valley bottoms.

3.5. Residence time of pollutants in the atmosphere

The residence time of pollutants depends on their ability to deposit via dry or wet processes (washing or dissolution) or to undergo chemical transformation.

Wet deposition includes pollutants incorporated into precipitation (rain, snow, fog). Raindrops remove particles depending on their size, fall speed, and density.

Dry deposition occurs without precipitation, through diffusion, turbulence, or gravity. Residence time varies greatly depending on the pollutant's physico-chemical properties.

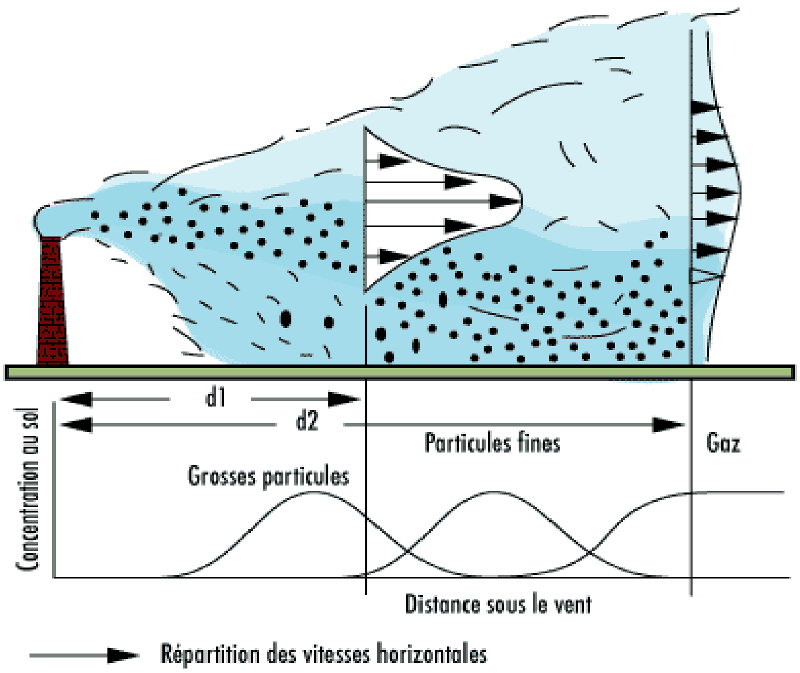

Figure 13. Dispersion of pollutants as a function of particle size.

3.6. Transfer of pollutants from the atmosphere to water and soil

Fortunately (with few exceptions), atmospheric pollutants do not remain indefinitely suspended. Precipitation and dry deposition return them to the soil and hydrosphere. Solid particles are transported mechanically or by dissolution; gaseous substances dissolve in rainwater. These deposition mechanisms purify the atmosphere of undegraded pollutants.

The fundamental role of the **water cycle** and **general atmospheric circulation** in pollutant transfer was first demonstrated in the 1950s during studies of radioactive fallout from nuclear tests.

Numerous analytical chemistry studies confirmed that the combination of atmospheric circulation and precipitation can transport pollutants far from their emission zones.

Acid rain is a clear example of long-distance atmospheric pollutant transfer, capable of affecting vast areas.

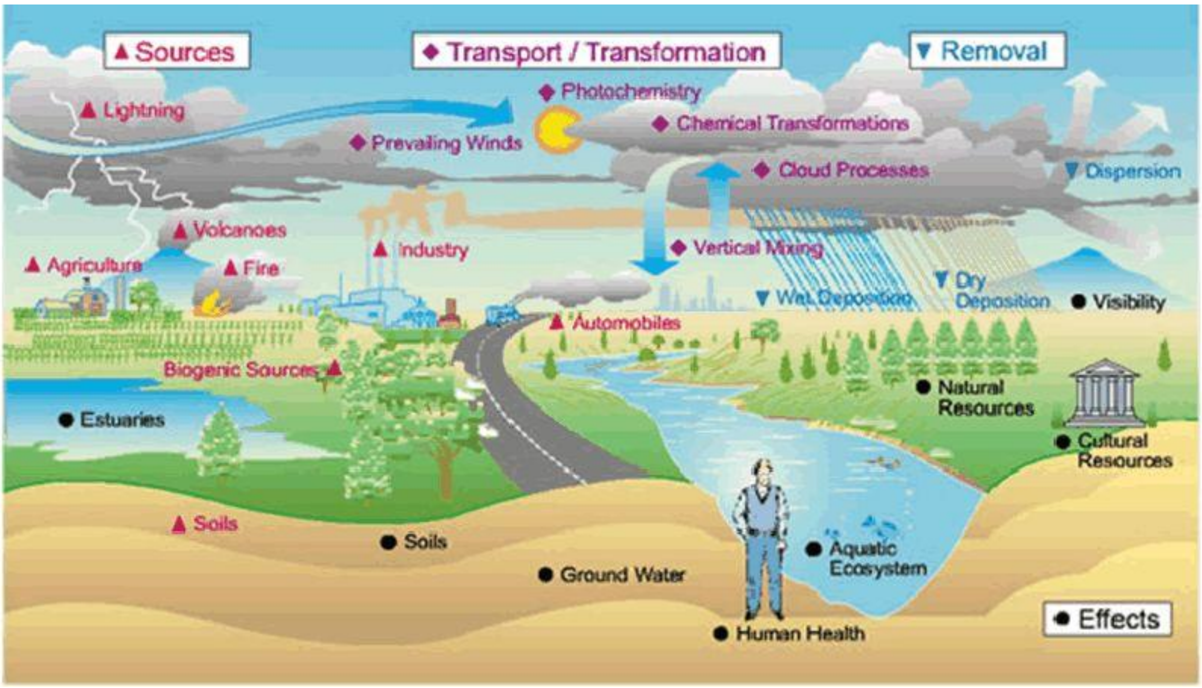

Figure 14. Transfer of Pollutants into the Biosphere

3.7. Transfer of pollutants into biomass and contamination of food webs

The distribution and dispersion of pollutants in the biosphere are influenced not only by abiotic factors (air and water circulation) but also by biological processes. Any substance contaminating the environment can be absorbed by living organisms through metabolic processes, entering trophic networks, integrating into matter cycles, and harming numerous plant and animal species.

3.8. Concentration by living organisms: bioconcentration and bioaccumulation

The final phase of pollutant circulation in the biosphere involves contamination of organisms and sometimes **bioaccumulation** within them.

Bioconcentration refers to the direct increase in pollutant concentration as it moves from water into aquatic organisms. It also applies to terrestrial organisms (uptake from air or soil via leaves or roots, or inhalation in animals).

Bioaccumulation is the sum of direct and dietary pollutant absorption by animals. Some species can accumulate substances thousands of times more concentrated than in soil or water. For example, **Fucus** and **Laminaria** algae concentrate iodine and bromine from seawater and are used industrially for their extraction.

This process also applies to human-made pollutants: **plutonium**, for example, can be concentrated up to 3,000 times by phytoplankton and 1,200 times by benthic algae compared to seawater levels.

The **concentration factor (Fc)** is defined as the ratio of pollutant concentration in an organism to that in its environment.

Many organisms can accumulate poorly degradable substances. **Earthworms**, for instance, can bioconcentrate **DDT** or **lead** tens of times higher than soil levels. This leads to **biomagnification** an increase in pollutant concentration along trophic chains. Higher-trophic organisms exhibit the greatest concentrations, especially for persistent compounds and long food chains. Thus, aquatic ecosystems often show higher concentration factors than terrestrial ones.

Table 2. Concentration of Dieldrin in a Trophic Chain

Trophic Level	Organism	Dieldrin Concentration (ppm)
I	Phytoplankton	10^{-3}
II	Zooplankton	$1.5–2\times10^{-2}$
III	Crustaceans, microphagous fish	3×10^{-2}
IV	Predatory fish, terns, kittiwakes	$1–2\times10^{-1}$
V	Cormorants	1.6 (liver), 1.2 (eggs)