Air Pollution

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The thin shell called the atmosphere

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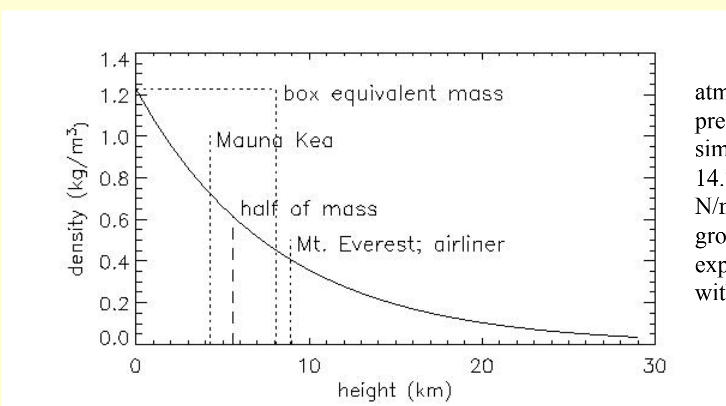
- Most of the atmosphere is below 20,000 feet in elevation
  - 38% is below Mauna Kea, at about 14,000 ft
  - this is like a layer of paint on a basketball
  - sums up to one millionth of earth's total mass
  - follows exponential density, but would all fit in 8 km layer if compressed to sea-level pressure



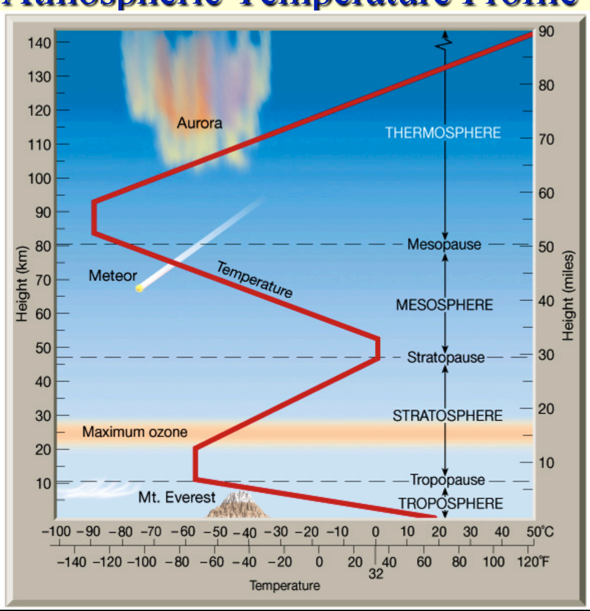
atmospheric pressure has similar shape: 14.7 psi (10^5 N/m^2) at the ground, falling exponentially with height

Constituency of the Atmosphere

Element	Symbol	percent by volume
Nitrogen	N_2	78.1
Oxygen	O_2	21.0
Argon	Ar	0.93
Carbon Dioxide	CO_2	0.036*
Neon	Ne	0.002

- •current value: pre-industrial carbon dioxide was 0.028%
- •Also, Water, H_2O, varies over a wide range, typically < 0.03

Atmospheric Temperature Profile



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Notes on the Temperature Profile

- Near the ground, temperature decreases with altitude
  - typically about 3ºF per 1000 feet, or 6ºC per km
  - inherently unstable: cold on top of hot→mixing
- At top of troposphere, get a temperature inversion in the stratosphere
  - inherently stable: hot air on top of cold air
  - other crazy things happening at higher altitude

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On Stability

- Hot air is less dense than cold air (at same pressure), and will therefore rise when encapsulated by cooler air
- As this parcel of air rises, it moves into air at lower pressure, meanwhile expanding and cooling
  - cools at 10ºC/km if dry, 3.5ºC/km if wet; 6.5ºC/km is typical
  - Equal to roughly 3^0 F/1000 ft
  - this is called the *adiabatic lapse rate*, or ALR
- If surrounding air has steeper temperature profile than the ALR, then rising air gets hotter relative to surroundings, and rises faster → **unstable air**
- If surrounding air has slow profile, rising air cools faster, and will soon cease to climb → **stable air**

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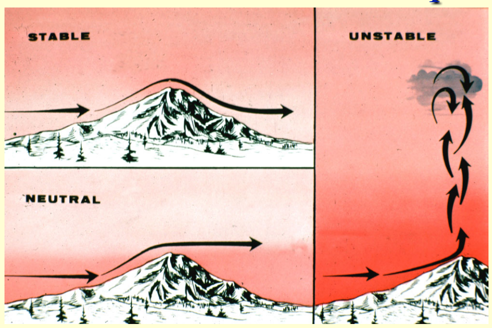
Terrain Interface Example



- Stable air suppresses mixing, interface with terrain undramatic
- Unstable air will promote runaway vertical rise, often to top of troposphere
  - keep your eyes open for tall towers of clouds over mountains

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Towering Cumulonimbus

- Unstable air promotes the formation of towering "thunderheads"
- Top is often anvil-shaped as cloud reaches top of troposphere and gets "pushed over" by the high winds (e.g., jet stream)
- This runaway process often produces lightning/ thunder/rain/hail

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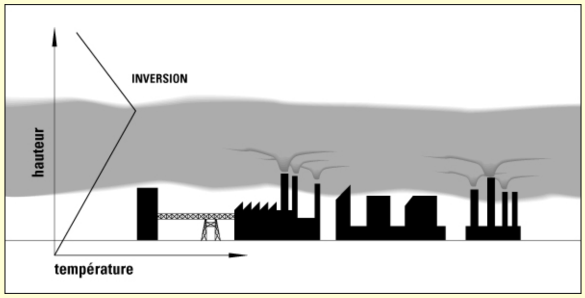
Inversion Profiles



- When the temperature profile switches direction, it creates a layer of stable air that traps emissions
- Frequent condition in Los Angeles
- Also source of ground fog (“Thule fog”)

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Thermal inversions and smog

- L.A., Denver, Mexico City typically get thermal inversions; this is why they are smoggy
- London, 1952
  - Burned coal sulfur dioxide and particulates trapped within 150 ft of ground
  - After 12 hours people started coughing
  - Over next 4 days, 4000 people died (mostly older people)
- L.A. and Mexico smog is photochemical smog.

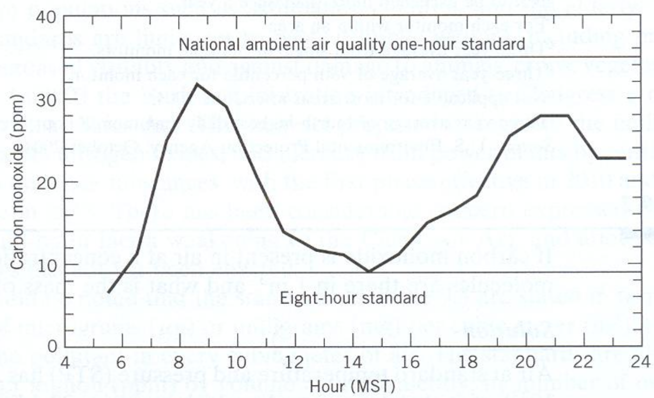

Figure 9.4 Carbon monoxide concentrations averaged over a one-hour period during a weekday at a downtown location in Denver, Colorado. The standard shown of 35 ppm is also for a one-hour averaging time. (*Source:* State of Colorado, Department of Health.)

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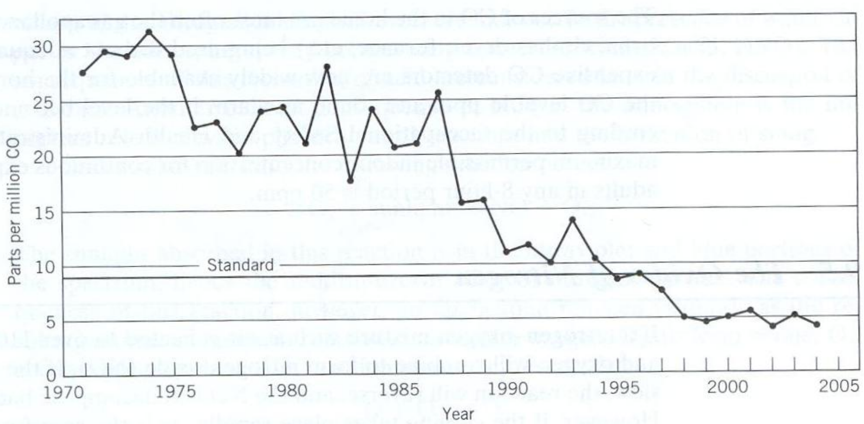

Figure 9.5 The second 8-hour maximum concentration of carbon monoxide observed each year in Denver from 1970 to 2004. There have been no violations of the NAAQS carbon monoxide standard for the past decade, owing to the success of air quality control programs. (*Source:* Colorado Air Quality Control Commission, Report to the Public, 2003–2004.)

Pollutants: CO

- CO: carbon monoxide from incomplete combustion of hydrocarbons
  - blocks oxygen intake of blood; headaches
  - converts to CO_2 in tropopause with "half-life" of 0.2 yr
  - 100 ppm for 10 hours => headaches and reduced ability to think
  - 360 ppm for 10 hours => nausea and loss of consciousness
  - 600 ppm for 10 hours => death
  - 1000 ppm for 1 hour => loss of consciousness, death after 4 hours
  - Why there is SMOG checks on cars!
  - National Ambient air quality standards: < 35ppm for any hour, < 9ppm for 8 hours; frequently exceeded in L.A., Denver, Cincinnati, and Detroit
  - CO is local problem; "easy" to solve: public transportation using electric vehicles, pollution controls, smog checks, electric/ Hydrogen cars, etc.
  - CO also comes from gas appliances:

Pollutants

- NO_x: nitrous oxides formed in combustion chamber out of atmospheric constituents
  - NO_2 is reddish brown, smelly, eye/lung irritant
  - together with sunlight begets ozone (O_3)
  - ozone is smelly, affects respiratory system, lungs
- Unburned hydrocarbons: eye irritant

More pollutants

- SO_2: Sulfur dioxide
  - mainly from coal plants: 0.5% to few-% sulfur, by mass
  - lung cancer and bronchitis
  - melting ruins and statues of historical importance
  - acid rain
- Particulates
  - Much more from natural causes than humans
  - Gives great sunsets, offsets global warming
  - Kills people: 4 deaths per year per million people per microgram/m^3 (Rural average 25ug/m^3, cities 100)
  - Similar effects to sulfur dioxide
  - Particulates offset global warming!
  - Great sunsets

Table 9.4 U.S. Emissions, 2001

Pollutant	All Sources (10^6 tons/yr)	Transportation (10^6 tons/yr)	Percent
CO	120.76	99.50	82
NO_x	22.35	12.41	55
VOC[a]	17.96	7.50	42
PM2.5[b]	7.38	0.45	6
PM10[b]	24.10	0.53	2
SO_2	15.97	0.70	4

[a]Volatile organic compounds.
[b]PM2.5 designates particulate matter smaller than 2.5 microns; PM10 designates particulate matter smaller than 10 microns.
Source: Transportation Energy Data Book, Edition 24, ORNL-6973, December 2004.

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Some pollution successes

- 1963 Clean Air Act (CAA), amended in 1970, has held pollution at 1960 levels despite almost 50% population growth
- Lead has been virtually eliminated (unleaded gas)
- Los Angeles much better today than a few decades ago
- See progress, Fig. 9.13 of book, or:
  - www.epa.gov/ttn/chief/trends/trends98/execsum.pdf

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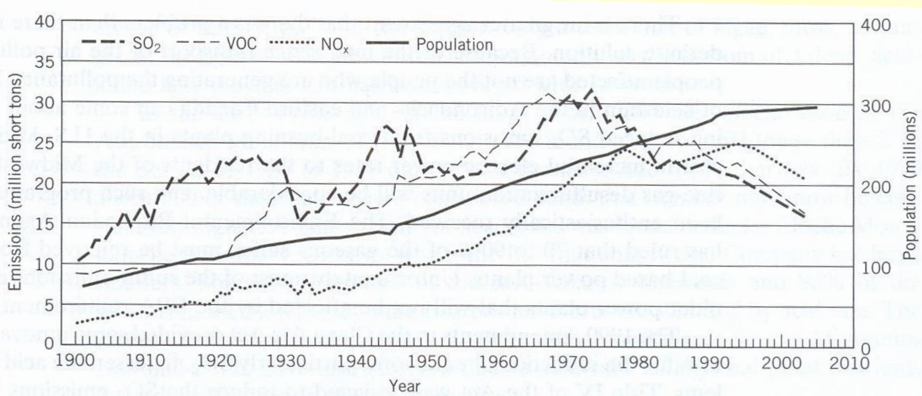

Figure 9.13 A century-long record of annual air pollution emissions compared to the population of the United States. (*Sources:* Trends in National Emissions, United States Environmental Protection Agency, Office of Air Quality Planning and Standards, October 1995, September 2004; U.S. Census Bureau, *Statistical Abstracts of the United States*, 2003. For NO_x, these three sources do not show exact agreement in the years following 1970, and some averaging is shown here.)

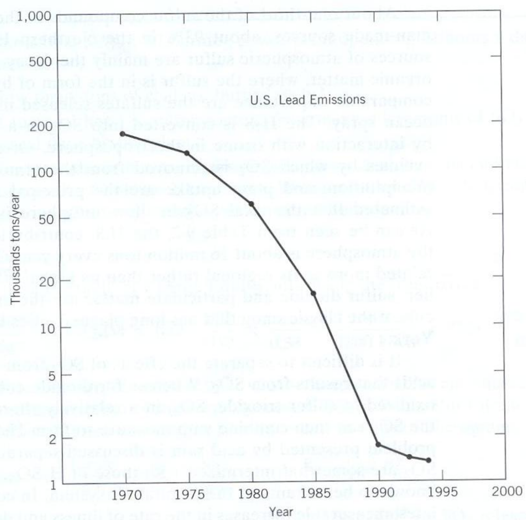

Figure 9.8 Lead emissions into the environment from highway vehicles in the United States. From 1970 to 1994 these emissions were reduced from 200,000 tons/year to less than 2,000 tons/year. By 1997 they were essentially down to zero. (*Source: Transportation Energy Data Book*, Edition 16, 1996. Stacy C. Davis and David N. McFarlin, ORNL-6898. Oak Ridge National Laboratory.)

The hole in the ozone:

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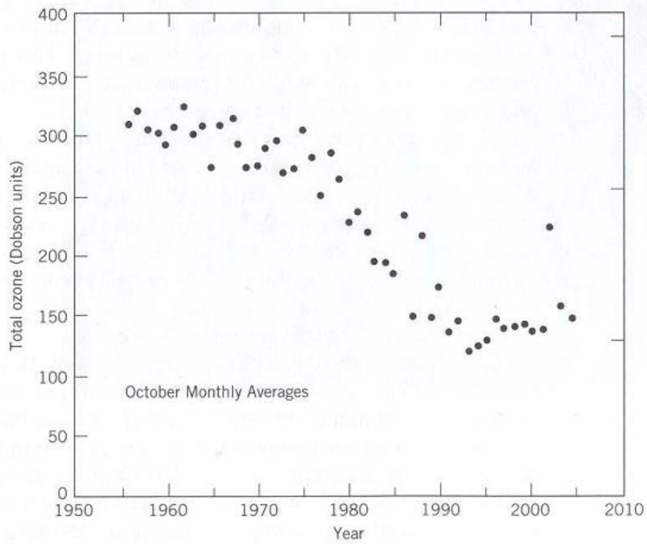

Figure 10.1 The observed downward trend in statospheric ozone from 1956 to 2004 over the Antarctic. These measurements are for the springtime total ozone over Halley Bay, Antarctica. (*Source:* British Antarctic Survey, April 2005.)

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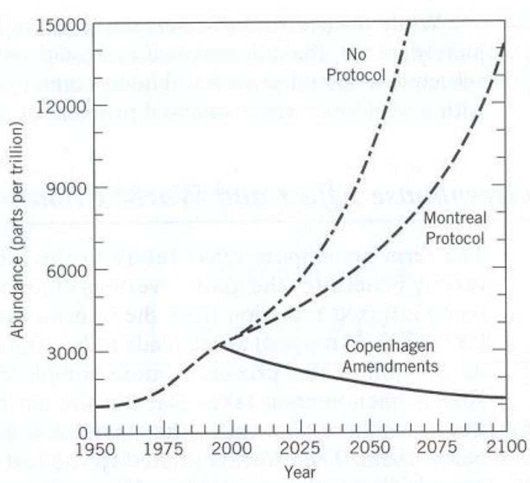

Figure 10.2 Expected stratospheric abundances of chlorine and bromine assuming no Protocol, the Montreal Protocol, and the Montreal Protocol with the Copenhagen Amendments. (*Source:* Scientific Assessment of Ozone Depletion: 1994. World Meteorological Organization Global Ozone Research and Monitoring Project—Report No. 37, Executive Summary, February 1995.)

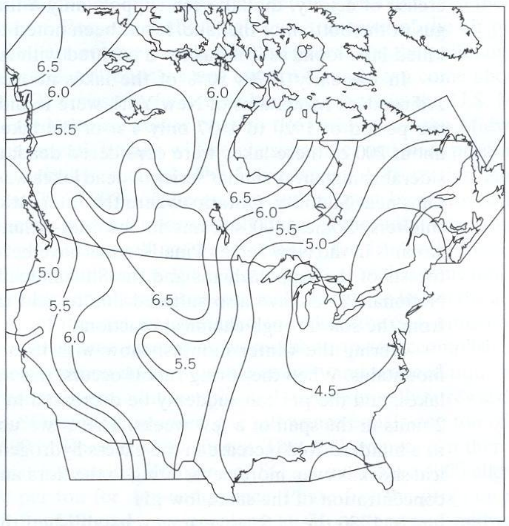

Figure 9.12 Approximate pH values measured in the spring of the year in the surface waters of various regions of the United States and Canada.

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Table 9.2 Major U.S. Air Pollutants (10^6 tons/yr) in 2003[a]

	CO	SO_2	NO_x	VOC[b]	PM2.5[c]	PM10[c]
Fuel combustion, electric utilities	0.53	10.93	4.46	0.05	0.14	0.68
Industrial fuel combustion	1.38	2.22	2.78	0.17	0.15	0.31
Other fuel combustion	3.00	0.60	0.73	0.88	0.43	0.46
Chemical and allied product manufacturing	0.33	0.33	0.10	0.22	0.02	0.05
Metals processing	1.42	0.29	0.09	0.07	0.03	0.14
Petroleum and related industries	0.77	0.75	0.64	0.80	0.20	0.45
Waste disposal and recycling	1.85	0.03	0.14	0.43	0.36	0.39
Highway vehicles	58.81	0.26	7.38	4.43	0.13	0.19
Off-highway	24.45	0.44	4.10	2.57	0.28	0.31
Miscellaneous	14.35	0.12	0.31	6.44	4.45	20.06
Total	**106.89**	**15.97**	**20.73**	**16.06**	**6.19**	**23.04**

[a]Adapted from data from U.S. Environmental Protection Agency.
[b]VOC stands for volatile organic compounds. Their main source is solvent utilization, included under miscellaneous.
[c]PM2.5 designates particulates smaller than 2.5 microns; PM10 designates particulates smaller than 10 microns.

Table 9.3 National Ambient Air Quality Standards

Pollutant	Averaging Time	Concentration
Carbon monoxide (CO)		
Primary	1 hour[a]	35 ppm (40 mg/m^3)
Primary	8 hour[a]	9 ppm (10 mg/m^3)
Nitrogen dioxide (NO_2), Primary and Secondary	Annual arith. mean	0.053 ppm (100 μg/m^3)
Sulfur Oxides		
Primary	Annual arith. mean	0.03 ppm (80 μg/m^3)
Primary	24-hour[a]	0.14 ppm (365 μg/m^3)
Secondary	3-hour[a]	0.5 ppm (1300 μg/m^3)
Particulates (PM10)		
Primary and Secondary	Annual arith. mean[b]	50 μg/m^3
Primary	24-hour[a]	150 μg/m^3
Particulates (PM2.5)		
Primary and Secondary	Annual arith. mean[c]	15 μg/m^3
Primary	24-hour[d]	65 μg/m^3
Ozone (O_3), Primary and Secondary	1-hour[e]	0.12 ppm (245 μg/m^3)
	8-hour[f]	0.08 ppm (163 μg/m^3)
Lead, Primary and Secondary	Calendar quarter	1.5 μg/m^3

[a]Not to be exceeded more than once a year.
[b]For each monitor within an area.
[c]Three-year average from single or multiple monitors.
[d]Three-year average of 98th percentile for each monitor.
[e]Not applicable for most areas after June 2004.
[f]Three-year average of fourth-highest daily maximum 8-hour average at each monitor.
Source: U.S. Environmental Protection Agency, October 2004.

Table 9.5 National Average Emission Factors

Fuel Type	Percent of Generation[a]	CO_2[a] (lb/MWh$_e$)	NO_x[b] (lb/MWh$_e$)	SO_2[b] (lb/MWh$_e$)
Coal	51.0%	2100	8.8	17[c]
Fuel oil	3.2%	2000	4.2	12
Natural gas	15.2%	1300	4.6	0
Other[d]	30.6%	0	0	0

[a]U.S. Energy Information Administration, July 2000.
[b]Energy Efficiency and Renewable Energy—Opportunities, from Title IV of the Clean Air Act, EPA 430-R-94-001, February 1994.
[c]Emission rate for coal is an average of the 1990 value of 22 lb/MWh$_e$ and a projected value for 2000 of 12 lb/MWh$_e$.
[d]Other includes nuclear and hydroelectric and other renewable energy sources.

Hydrocarbon Emissions and Photochemical Smog 303

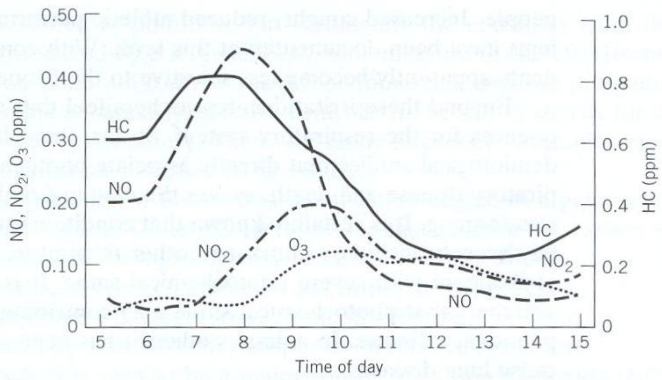

Figure 9.6 Concentrations of total hydrocarbons (HC), nitrogen oxides (NO and NO_2), and ozone (O_3) measured at a downtown location in Los Angeles for different hours of the day.

On Stability

- Hot air is less dense than cold air (at same pressure), and will therefore rise when encapsulated by cooler air
- As this parcel of air rises, it moves into air at lower pressure, meanwhile expanding and cooling
  - both happen: $PV = nRT$, but $P \cdot V^{5/3}$ is constant
    - V doesn't increase enough to cover decreasing P, so T also must drop
  - cools at 10ºC/km if dry, 3.5ºC/km if wet; 6.5ºC/km is typical
  - this is called the *adiabatic lapse rate*, or ALR
- If surrounding air has steeper temperature profile than the ALR, then rising air gets hotter relative to surroundings, and rises faster → **unstable air**
- If surrounding air has slow profile, rising air cools faster, and will soon cease to climb → **stable air**