PHYS 4520: Physics in Meteorology

Introduction to the Earth's atmosphere

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Atmospheric science: weather forecast

- atmospheric models

  based on physical principles from fluid dynamics, thermodynamics,...etc

- parameterization

  represents phenomena at the unresolved scales of the model

- observational systems

  acquire various weather variables (e.g. temperature, pressure) using radar, satellite, GPS

- data assimilation:

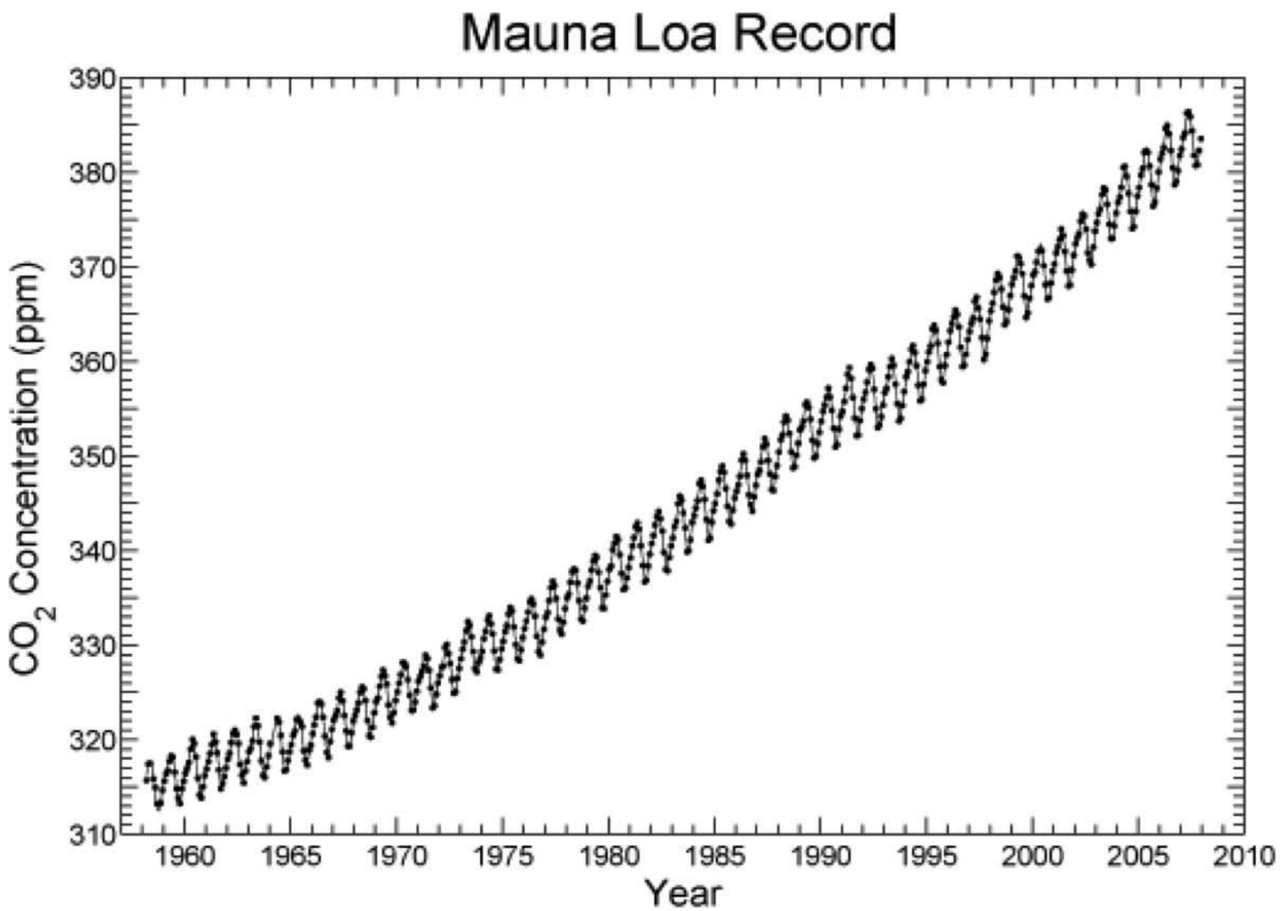
  combines information from current data (based on imperfect observation) and from a short-term forecast (based on a model) to produce a current state estimate.

Atmospheric science: atmospheric chemistry

- Ozone depletion
  - ozone absorbs UV radiation from the Sun
  - 1974: Crutzen, Rowland and Molina proposed CFCs may reduce ozone concentration in the atmosphere
  - CFC dissociated by UV light releasing Cl atom which is a catalyst of the destruction of ozone
  - 1985: Antarctic ozone hole discovered by Farman, Gardiner and Shanklin
  - Montreal Protocol
    - 1987: specified a 50% reduction in CFCs production
    - 1990: complete phase out of CFCs by early 21st century
  - 1995: Crutzen, Molina, and Rowland were awarded the Nobel Prize in Chemistry

Atmospheric science: climate dynamics

- Greenhouse warming
  - human-induced warming due to the buildup of greenhouse gases (e.g. CO_2) in the atmosphere
  - Keeling curve (*Scripps Institution of Oceanography*, http://scrippsco2.ucsd.edu)

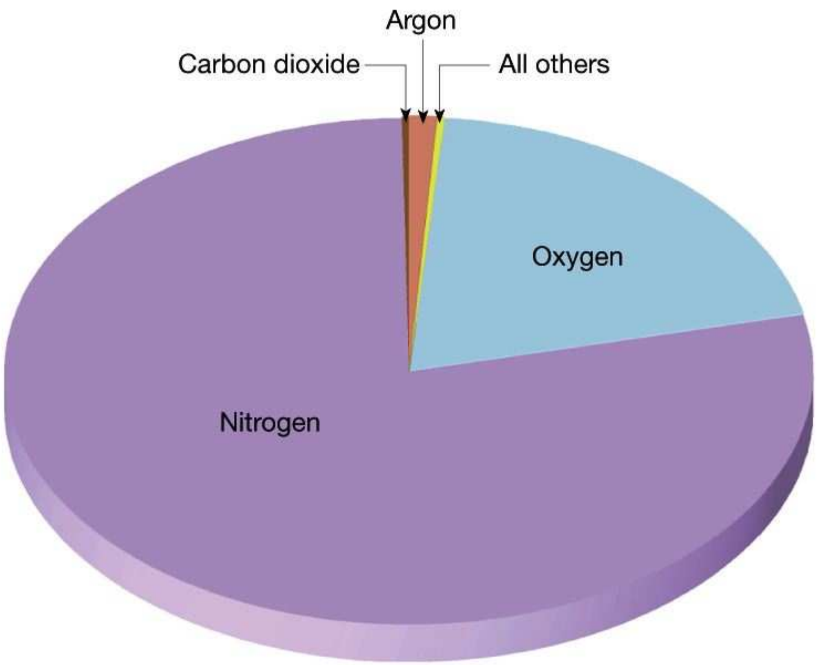


Composition of the atmosphere

Constituent	Fractional concentration by volume
Nitrogen (N_2)	78.08%
Oxygen (O_2)	20.95%
Argon (Ar)	0.93%
Water vapor (H_2O)	0 – 5%
Carbon dioxide (CO_2)	380 ppm
Neon (Ne)	18 ppm
Helium (He)	5 ppm
Methane (CH_4)	1.75 ppm
Krypton (Kr)	1 ppm
Hydrogen (H_2)	0.5 ppm
Nitrous oxide (N_2O)	0.3 ppm
Ozone (O_3)	0 – 0.1 ppm

ppm: parts per million = 0.0001%

(Atmospheric Science, Wallace & Hobbs)



(The Atmosphere, Lutgens & Tarbuck)

Composition of the atmosphere

- Nitrogen and Oxygen (~ 99%)

  of little or no importance in affecting weather phenomena

- Water vapor (highly variable, up to 5%)

  significantly affects our weather and climate: cloud, fog, thunderstorm, tropical cyclone, tornado, hail

- Carbon dioxide (~ 0.038%)

  significantly affects our climate through the greenhouse effect

- Ozone (~ 0.0000005%, layered 25km from surface)

  protect living things on Earth from ultraviolet radiation from the Sun

Vertical structure of the atmosphere

- a thin layer of gas surrounding the Earth

  "thickness" of the atmosphere, $h \sim 50$ km

  radius of the Earth, $R \approx 6400$ km

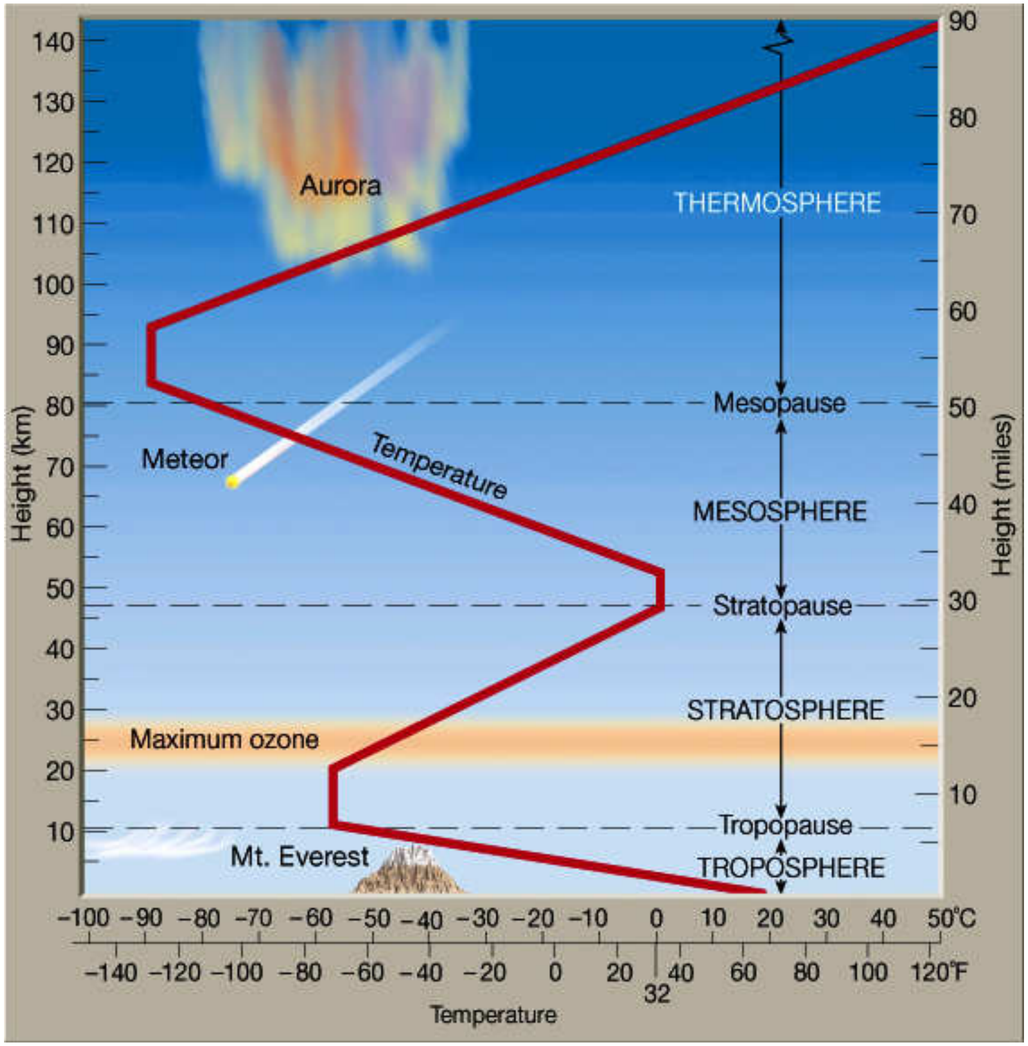
  $$h \ll R \quad \Rightarrow \quad \text{thin}$$

- variation with height z of thermodynamic properties: temperature (T), pressure (p) and density (ρ)

Vertical profile of atmospheric temperature

Troposphere and Tropopause
(0 – 20 km)

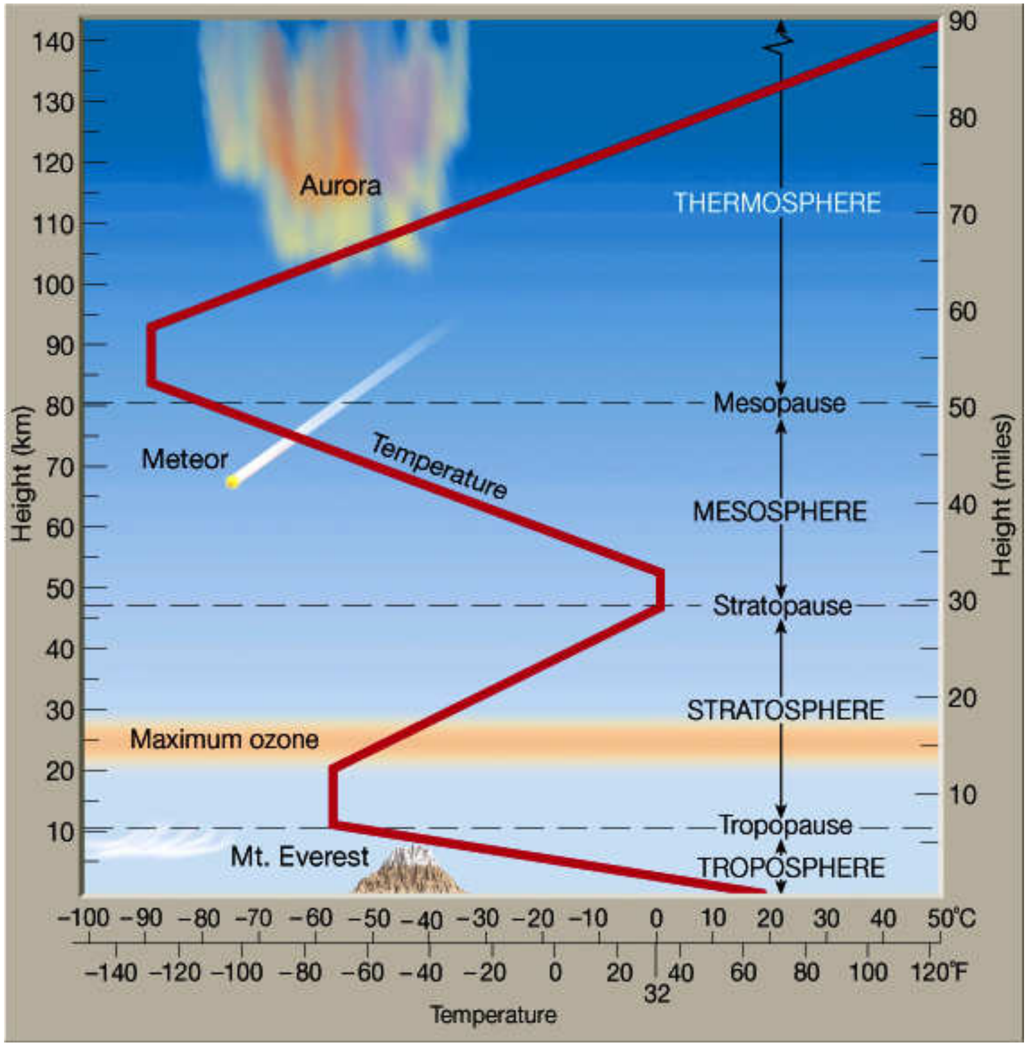
- contained about 80% of the mass of the atmosphere
- heated from below by the Earth's surface
- lapse rate $\Gamma \equiv \frac{\partial T}{\partial z} \approx -7°\mathrm{C/km}$
- temperature inversion: embedded layer with $\Gamma > 0$
- contains nearly all the atmospheric water vapor, the moving weather systems and the associated clouds are almost entirely confined to this layer
- large-scale turbulence and mixing



Vertical profile of atmospheric temperature

Stratosphere and Stratopause
(20 – 50 km)

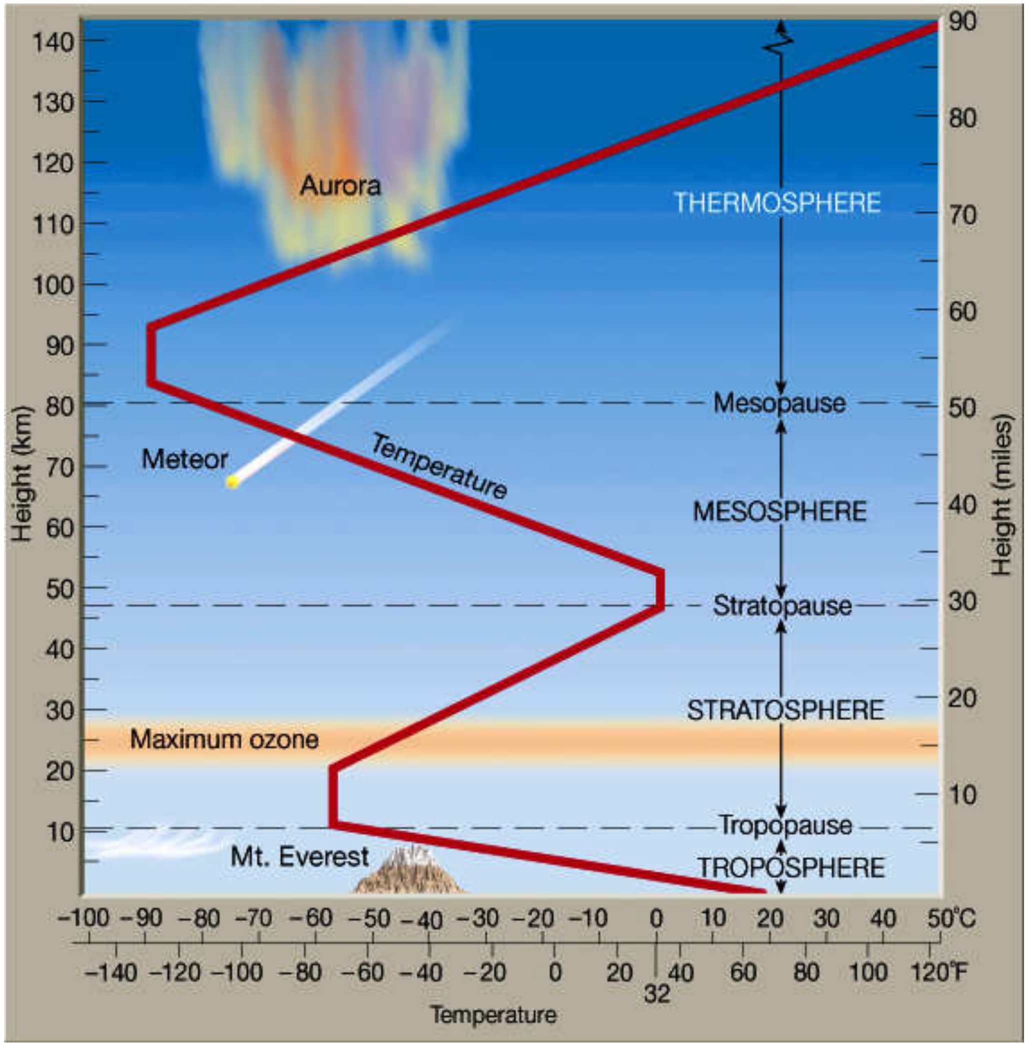
- temperature increases slowly with height up to about 30 km, above which it rises rapidly
- free from cloud and weather phenomena, vertical mixing is inhibited by the stratification of temperature
- ozone layer formed here because there is sufficient UV radiation to break O_2 into O atom and enough O_2 molecules to react with the O atom to form O_3
- ozone absorbs UV radiation and releases heat, less UV radiation reaches the lower stratosphere, hence the lower temperature there



Vertical profile of atmospheric temperature

Mesosphere and Mesopause
(50 – 80 km)

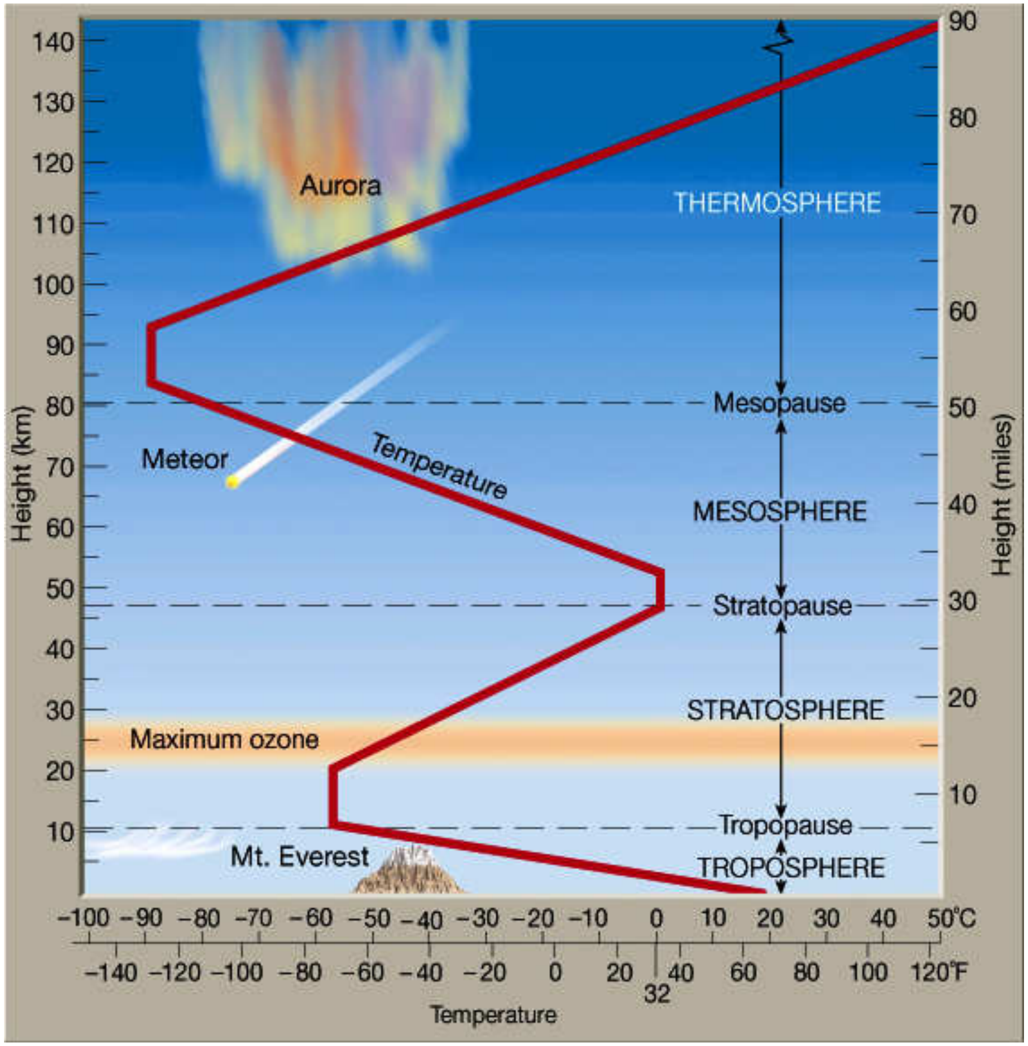
- temperature decreases with height and approaches a minimum of about –90°C at around 80 km
- most meteors enter the atmosphere melt or vaporize here



Vertical profile of atmospheric temperature

Thermosphere
(80 – 550 km)

- temperature increases with height due to the photodissociation of nitrogen and oxygen molecules and photoionization of their atoms
- temperature in the outer thermosphere varies widely in response to the Sun's activities
- temperature can be over 1000°C, **but…**
- density is extremely low, so one won't feel warm here since there is not enough contact with the few high-speed gas particles to transfer the energy
- Aurora occurs here due the presence of ions

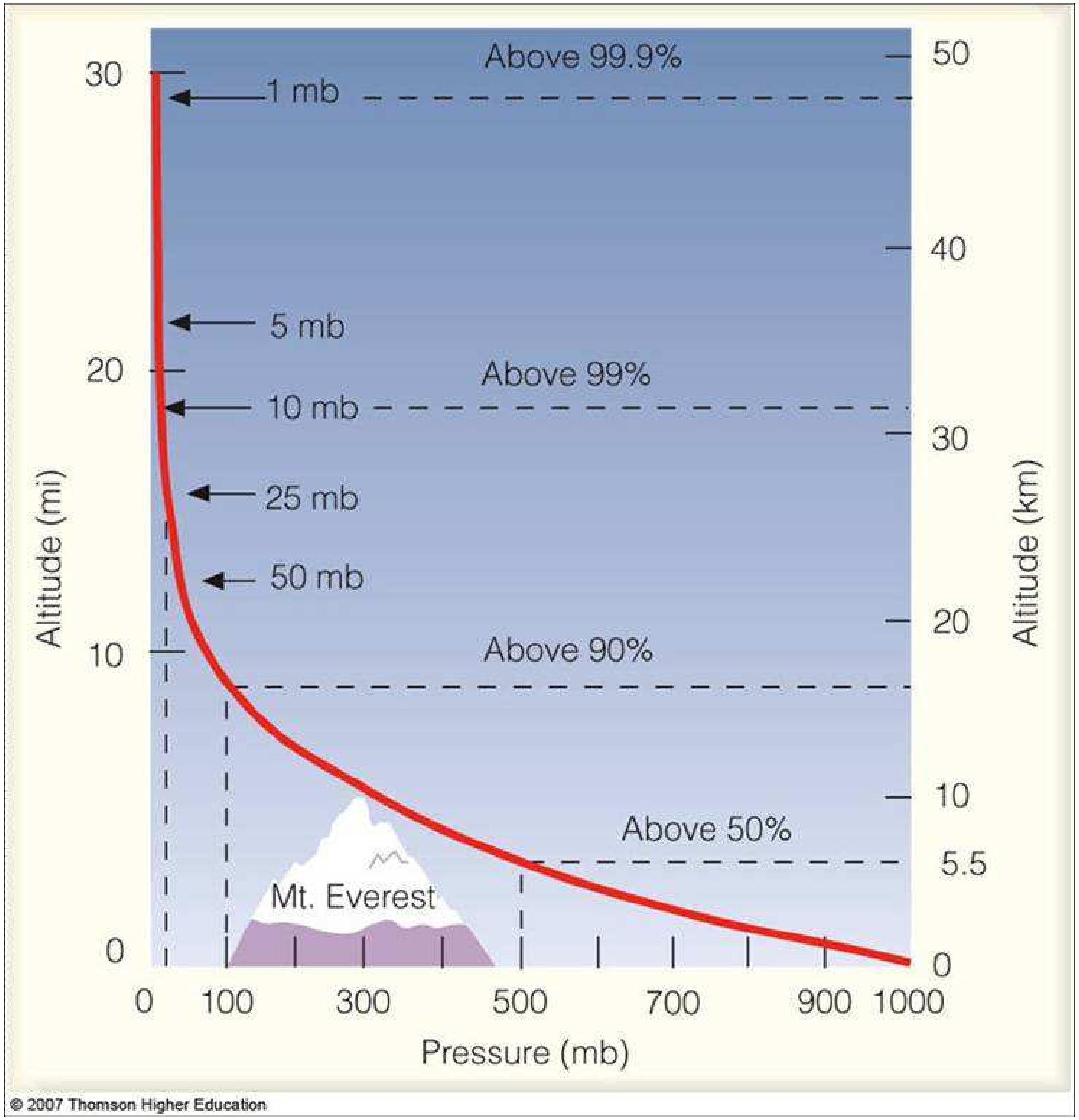


Vertical profile of atmospheric pressure

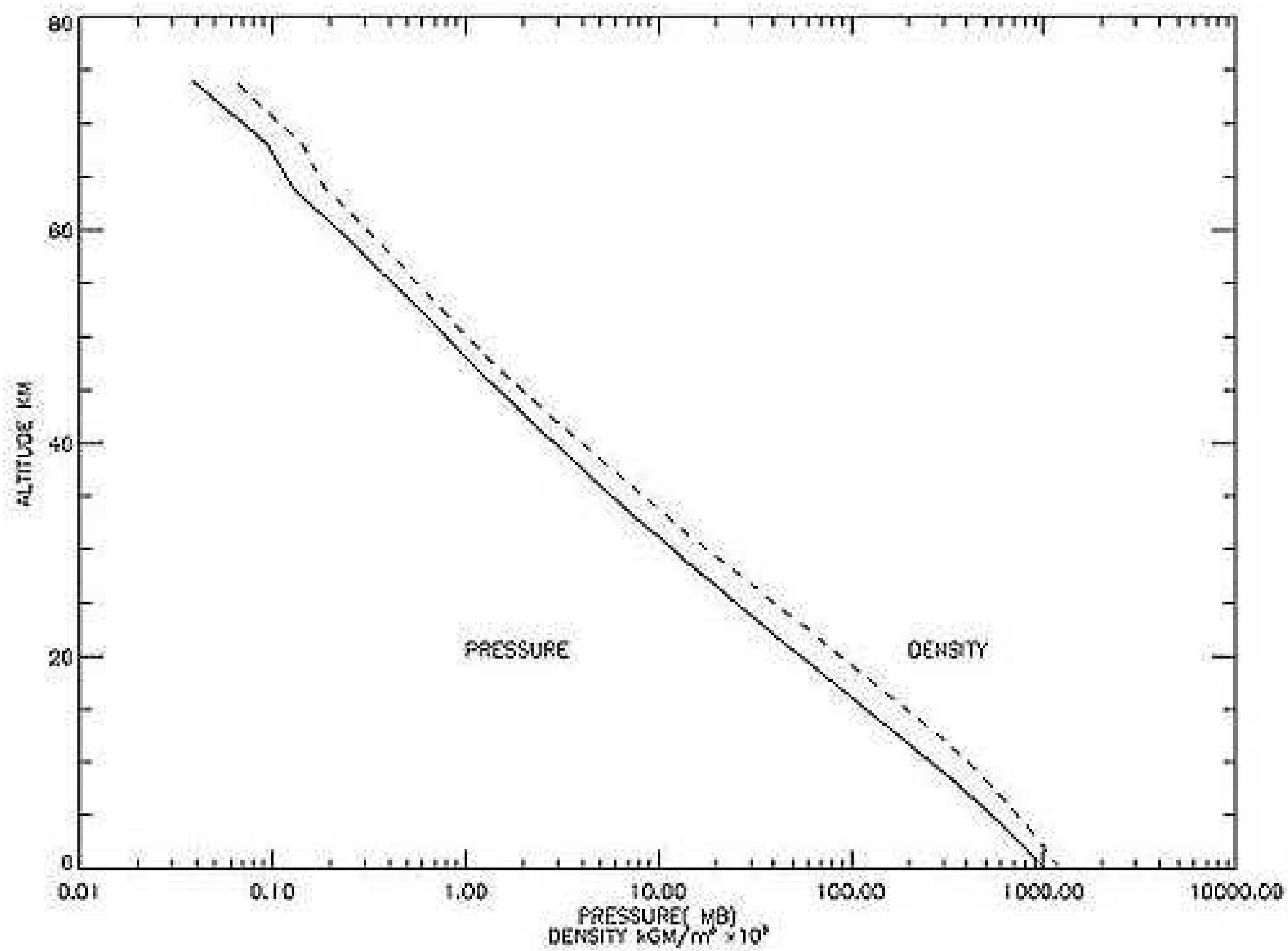
$$p(z) \approx p_0\, e^{-z/H}$$

$$H = \text{scale height}$$

$$p_0 = \text{reference pressure}$$



Vertical profile of atmospheric density



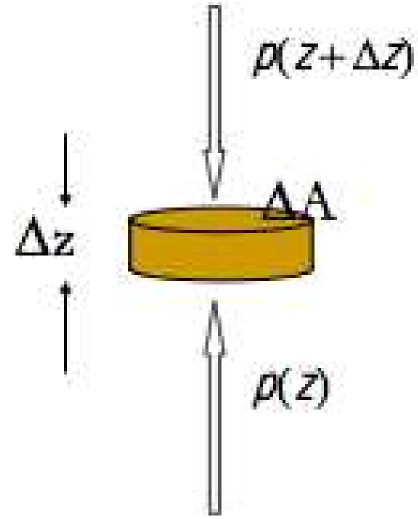
$$\rho(z) \approx \rho_0 \, e^{-z/H}$$

A simple hydrostatic model

(1) Assume the atmosphere is at rest and in static equilibrium, the net force on a small cylinder of air is zero:

$$p(z)\,\Delta A = p(z+\Delta z)\,\Delta A + g\,\rho(z)\,\Delta z\,\Delta A\,,$$

$$p(z+\Delta z) \approx p(z) + \Delta z\,\frac{dp}{dz}\,.$$



We get the hydrostatic balance equation,

$$\frac{dp(z)}{dz} = -\rho(z)\,g\,.$$

A simple hydrostatic model

(2) Assume the atmosphere behaves as an ideal gas:

$$pV = nR^*T\,,$$

n = number of modes, R^* = universal gas constant.

In terms of ρ instead of V,

$$p = \rho RT\,,$$

$R \equiv R^*/M$ where M is the molar mass.

For dry air, M = 0.028964 kg.

A simple hydrostatic model

Combining (1) and (2),

$$\frac{dp}{dz} = -\frac{g}{RT} p ,$$

$$p(z) = p_0 \exp\left[-\frac{g}{R}\int_0^z \frac{1}{T(z')}\,dz'\right] .$$

(3) Assume the atmosphere is isothermal: $T = T_0$,

$$p(z) = p_0\, e^{-\frac{g}{RT_0} z} ,$$

$$\rho(z) = \rho_0\, e^{-\frac{g}{RT_0} z} .$$

Hence, the scale height $H = g/RT_0$.

Take $T_0 = 290$ K $\Rightarrow$ $H \approx 7.1$ km.