Evolution of Earth’s Atmosphere

SEA2004F

Week 4 Lecture 1

Katye Altieri

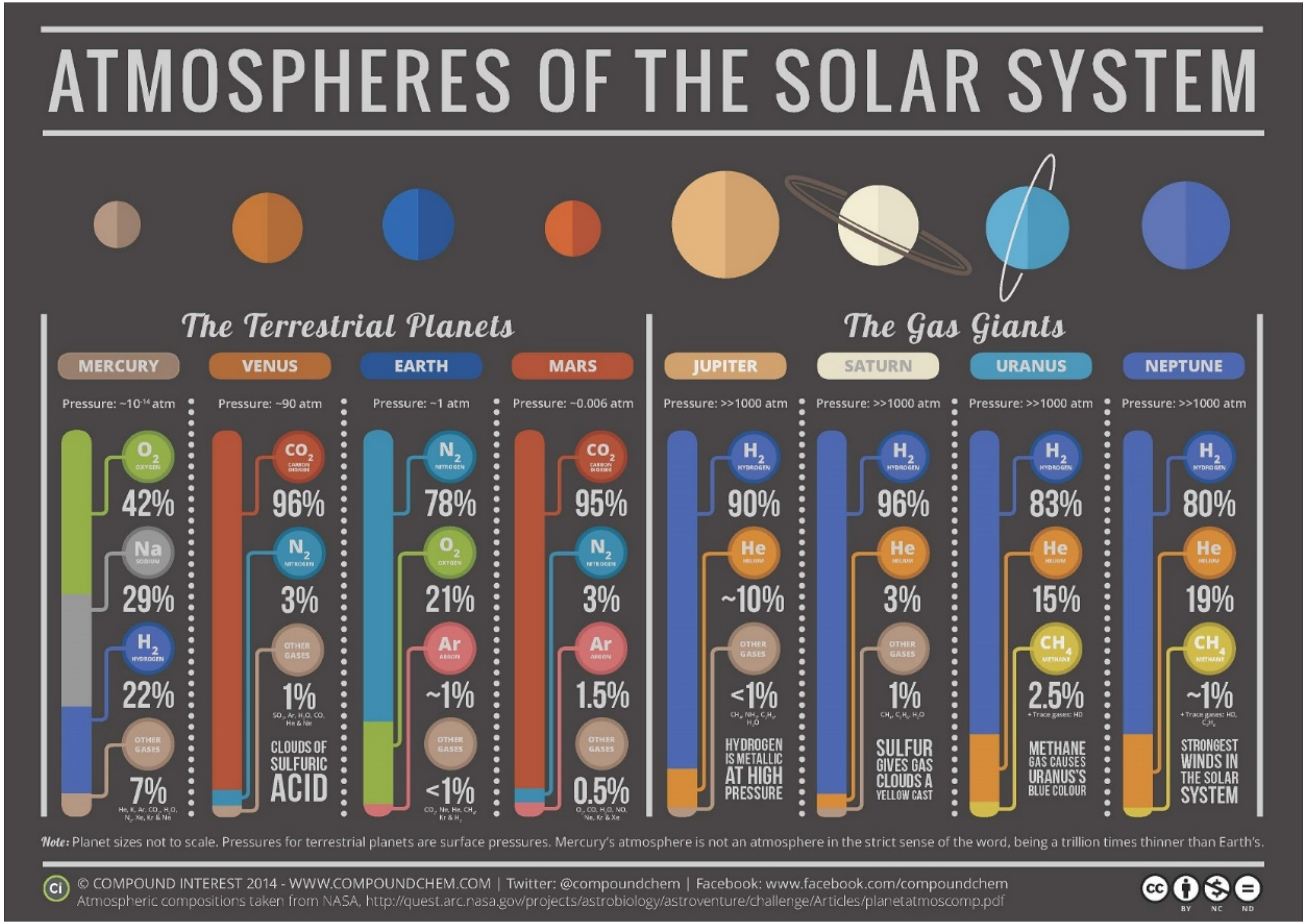
katye.altieri@uct.ac.za, R.W. James, Level 1 Room 113

What will you learn today?

- Understand the history and evolution of the Earth’s atmosphere
  - How did the atmosphere evolve into what it is today?
  - What are the main constituents of the modern atmosphere?
- Identify the layers of the atmosphere
  - What characteristics define the atmospheric layers?

Part I. Evolution of Earth's Atmosphere

Earth vs. other planets



- Mercury's atmosphere is a trillion times thinner than Earth's
- Venus has a runaway GHG effect
- Mars has lost most of its atmosphere

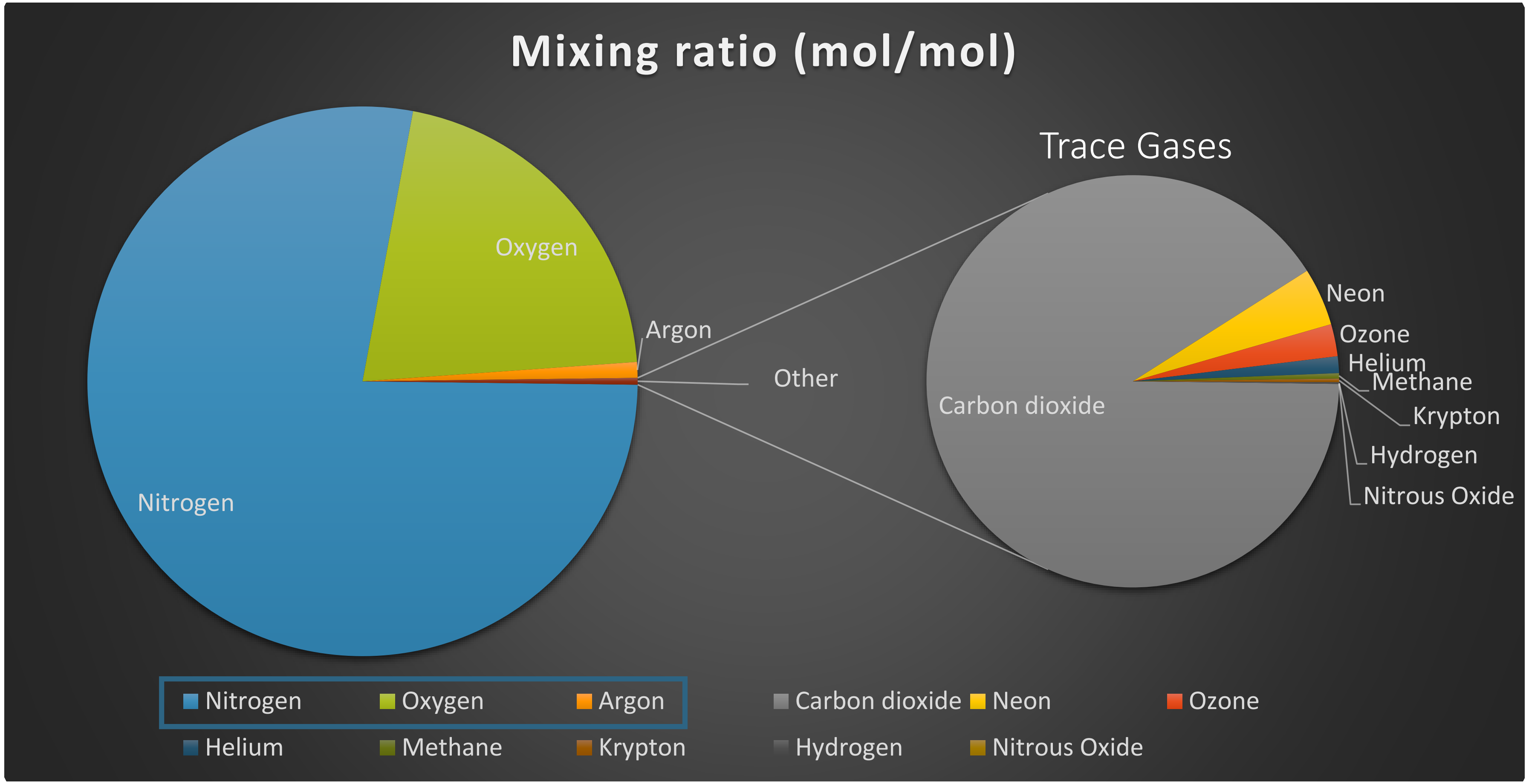
Atmos ~ Greek 'vapour'
Sphaira ~ Greek 'ball'

Hot, Barren, Waterless Early Earth

- Shortly after accretion, Earth was
  - a rapidly rotating, hot, barren, waterless planet
  - bombarded by meteorites and comets
  - with no continents, intense cosmic radiation
  - and widespread volcanism
- Earth's early atmosphere and hydrosphere were quite different than they are now

Present-day Atmosphere

Gas	Mixing ratio (mol/mol)
Nitrogen (N_2)	0.78
Oxygen (O_2)	0.21
Argon (Ar)	0.0093
Carbon dioxide (CO_2)	402×10^{-6}
Neon (Ne)	18×10^{-6}
Ozone (O_3)	$(0.1\text{-}10) \times 10^{-6}$
Helium (He)	5.2×10^{-6}
Methane (CH_4)	1.7×10^{-6}
Krypton (Kr)	1.1×10^{-6}
Hydrogen (H_2)	500×10^{-9}
Nitrous oxide (N_2O)	328×10^{-9}



Units and Conversions

Mixing ratios are given in units of *parts per million volume* (ppmv or ppm), *parts per billion volume* (ppbv or ppb), or *parts per trillion volume* (pptv or ppt)

1 ppmv = 1×10^{-6} mol/mol

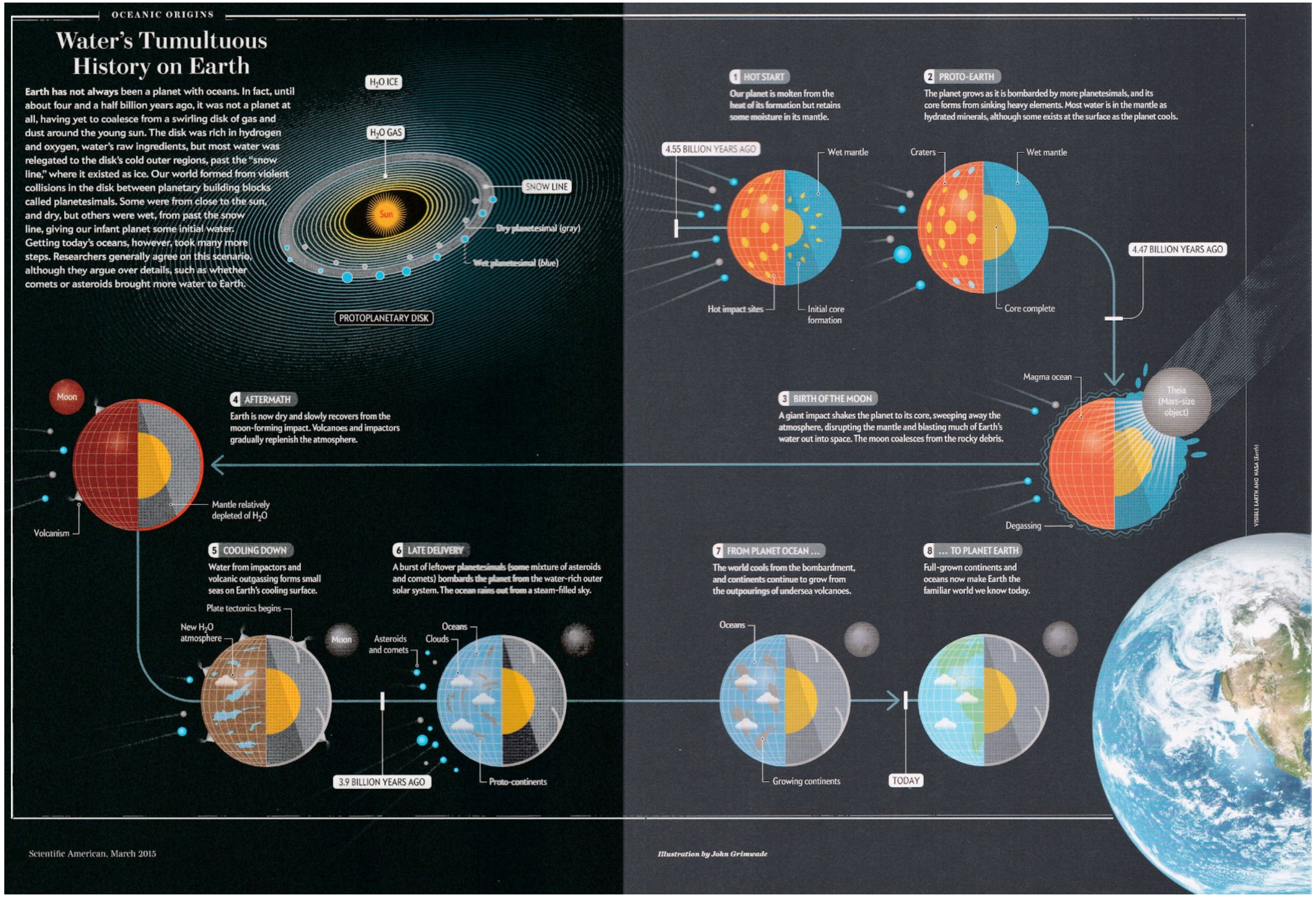
1ppbv = 1×10^{-9} mol/mol

1 pptv = 1×10^{-12} mol/mol

Normal interglacial CO_2 concentration is 280 ppm = 280×10^{-6} mol/mol

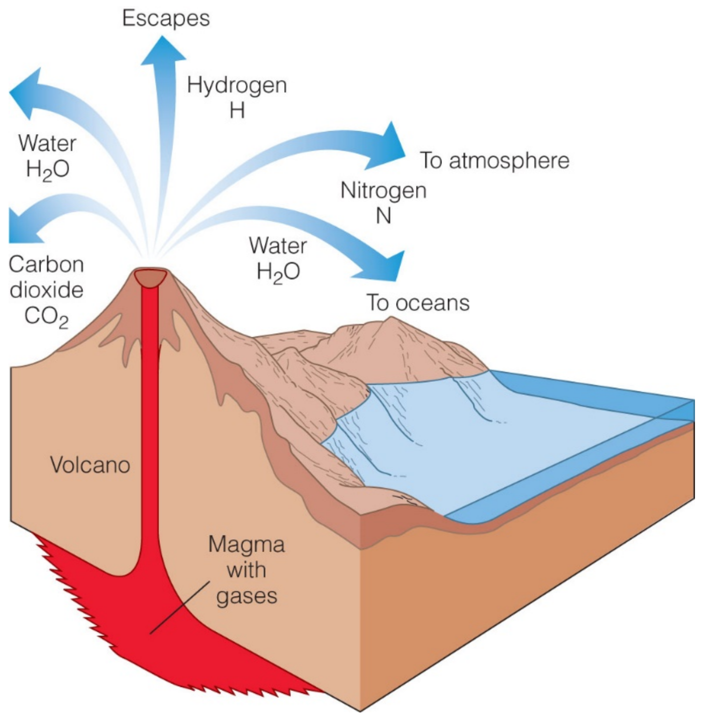
Earth's **Very** Early Atmosphere

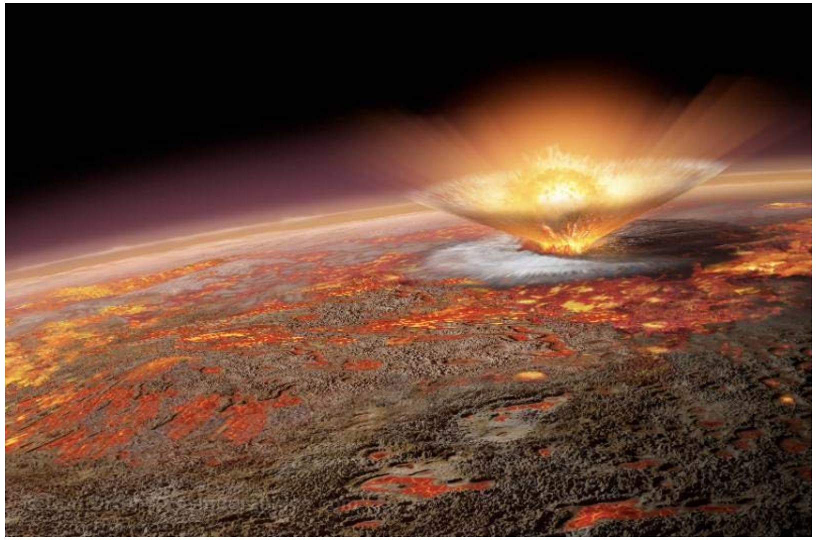
- Earth formed by accretion of solid materials that condensed from the solar nebula
- Earth formed over 10 to 100 million years, moon formed, volatile compounds were released forming a transient steam atmosphere
- Surface heat flux dwindles as accretion ends, steam atmosphere rains out to form ocean



Earth’s Early Atmosphere

- Archaean volcanic gases include CO_2, N_2, H_2O, trace amounts of H_2
- Early atmosphere composition was driven by volcanic outgassing





- Frequent bombardment by planetesimals until 3.8 billion years ago – removes atmosphere by shock waves and heating upper atmosphere

Earth's Early Atmosphere

- Almost all the H_2O condensed out to form the oceans, bulk of the CO_2 formed carbonates in sedimentary rocks, leaving N_2 to accumulate
- Bombardment ended ~ 3.8 Ga – evidence of life as of 3.5 Ga
  - Narrow time frame for life to develop
- Atmosphere plays a major role in many theories on the origin of life on Earth – motivation to understand its composition – relationships to other planets atmospheres and potential for extra-terrestrial life
- Still no mention of oxygen…why?

Photosynthesis

- Photosynthesis is a metabolic process in which carbon dioxide and water make organic molecules and oxygen is released as a waste product

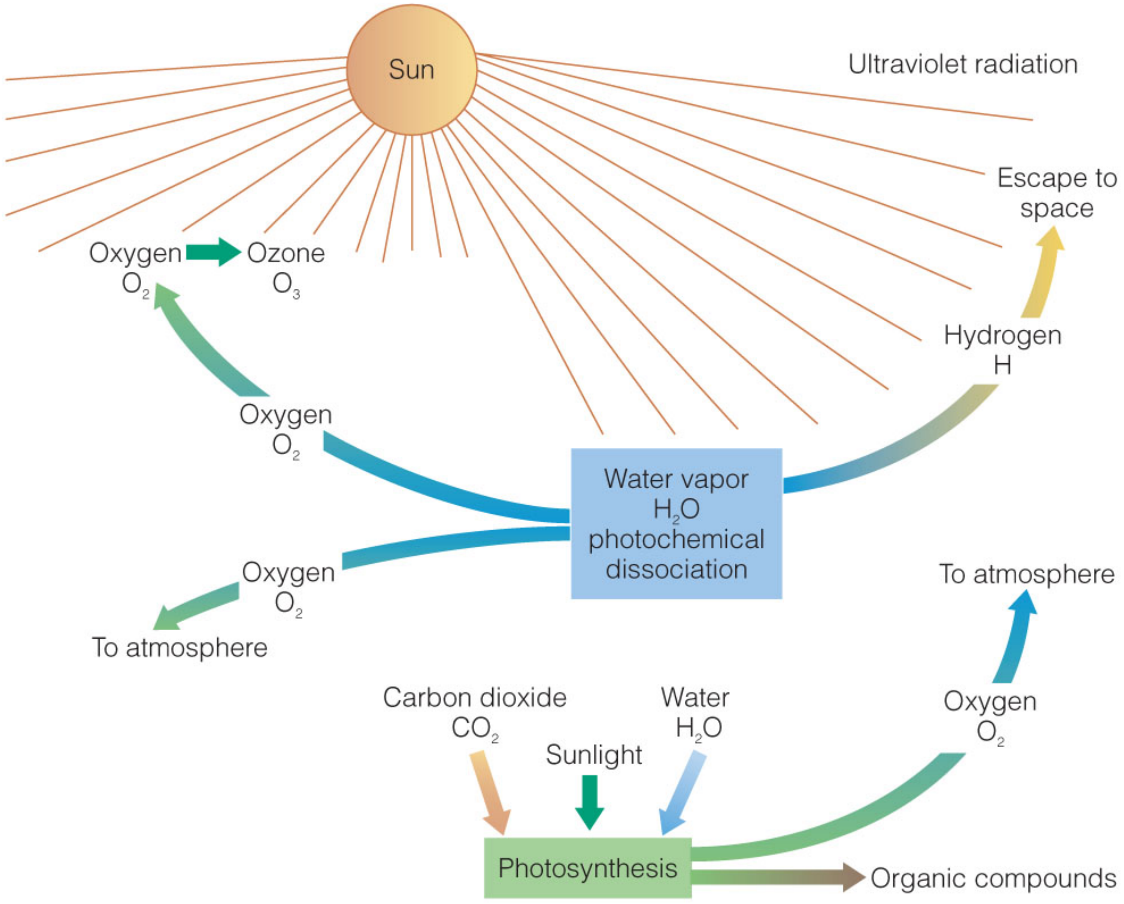
  CO_2 + H_2O ==> organic compounds + O_2

- Burial of organic carbon prevents it from being reoxidized

Oxygen Forming Processes

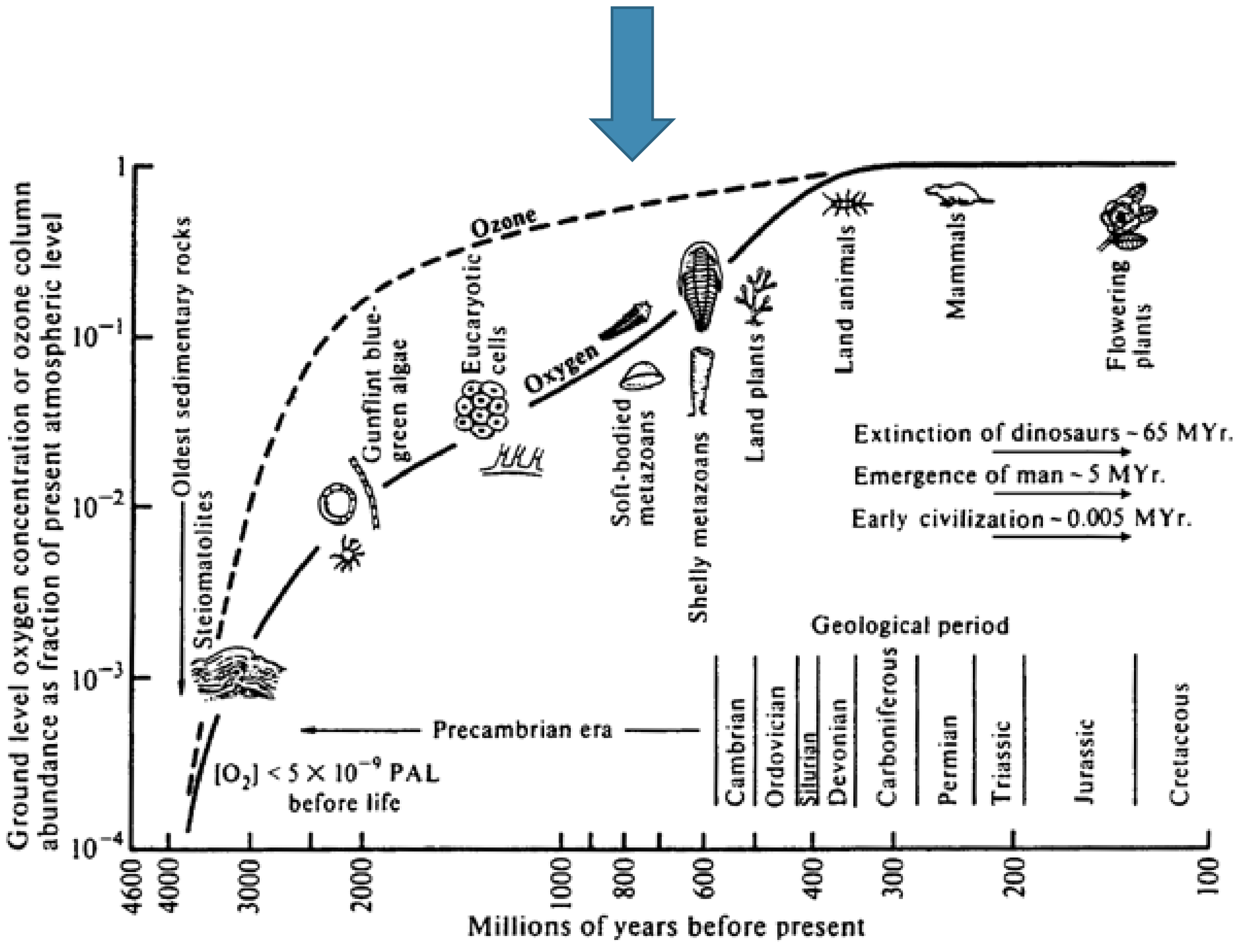
- Photochemical dissociation and photosynthesis added free oxygen to the atmosphere

Once free oxygen was present an ozone layer formed and blocked incoming ultraviolet radiation



Evolution of oxygen, ozone, and life on Earth

- Long term evolution of the atmosphere – and the ozone layer
- Higher life forms do not appear until the ozone layer is almost fully developed



Wayne, Chemistry of Atmospheres, 2000

Biology's influence on the atmosphere

- Photosynthetic production overwhelmed oxygen sinks such that the rise of O_2 in the atmosphere could occur
- Marine organisms repartition CO_2 between the atmosphere, oceans, and limestone rocks by precipitating carbonate – such that CO_2 in the atmosphere would be much higher without biology
- Denitrification recycles oxides of nitrogen back to the atmosphere – without denitrification the N_2 in the atmosphere would have been removed in about a billion years

Faint Young Sun Paradox

FYS Video

- Solar luminosity has steadily increased by about 40% since the Sun formed
- Earth's mean surface temperature should have been below freezing point of water before about 2 Ga
- But…sedimentary record shows that liquid water has been present on Earth since at least 3.8 Ga
- Would need 600 X present atmospheric level (PAL) of CO_2

Take Home Messages from Part I

- The formation of an atmosphere containing N_2 and CO_2 and an ocean containing H_2O was a natural consequence of planetary accretion
- The weakly reducing (i.e., not oxygen containing) primitive atmosphere provided an environment conducive to the origin of life
- Atmospheric O_2 levels rose slowly as a consequence of photosynthesis and organic carbon burial
- At the same time as O_2 was rising, CO_2 and other GHGs were declining to compensate for the brightening sun

Part II. Layers of the Modern Atmosphere

From this point forward – focus will be on current atmosphere

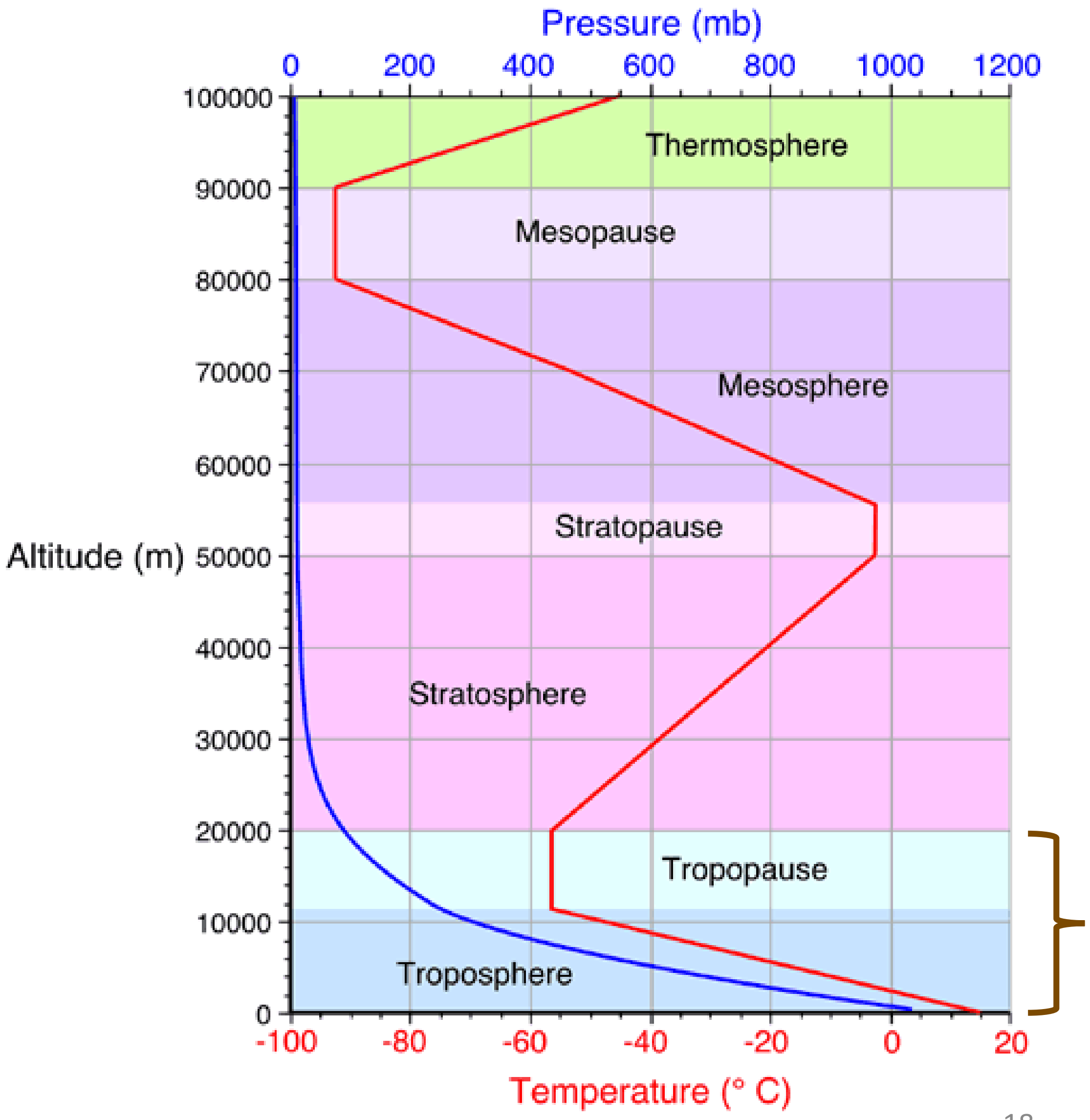
Layers of the atmosphere

Troposphere

- Lowest layer of the atmosphere
- Height of tropopause typically 10 – 15 km depending on latitude and time of year
- Characterized by decreasing temperature with height
- Rapid vertical mixing

Planetary boundary layer → surface to 1km

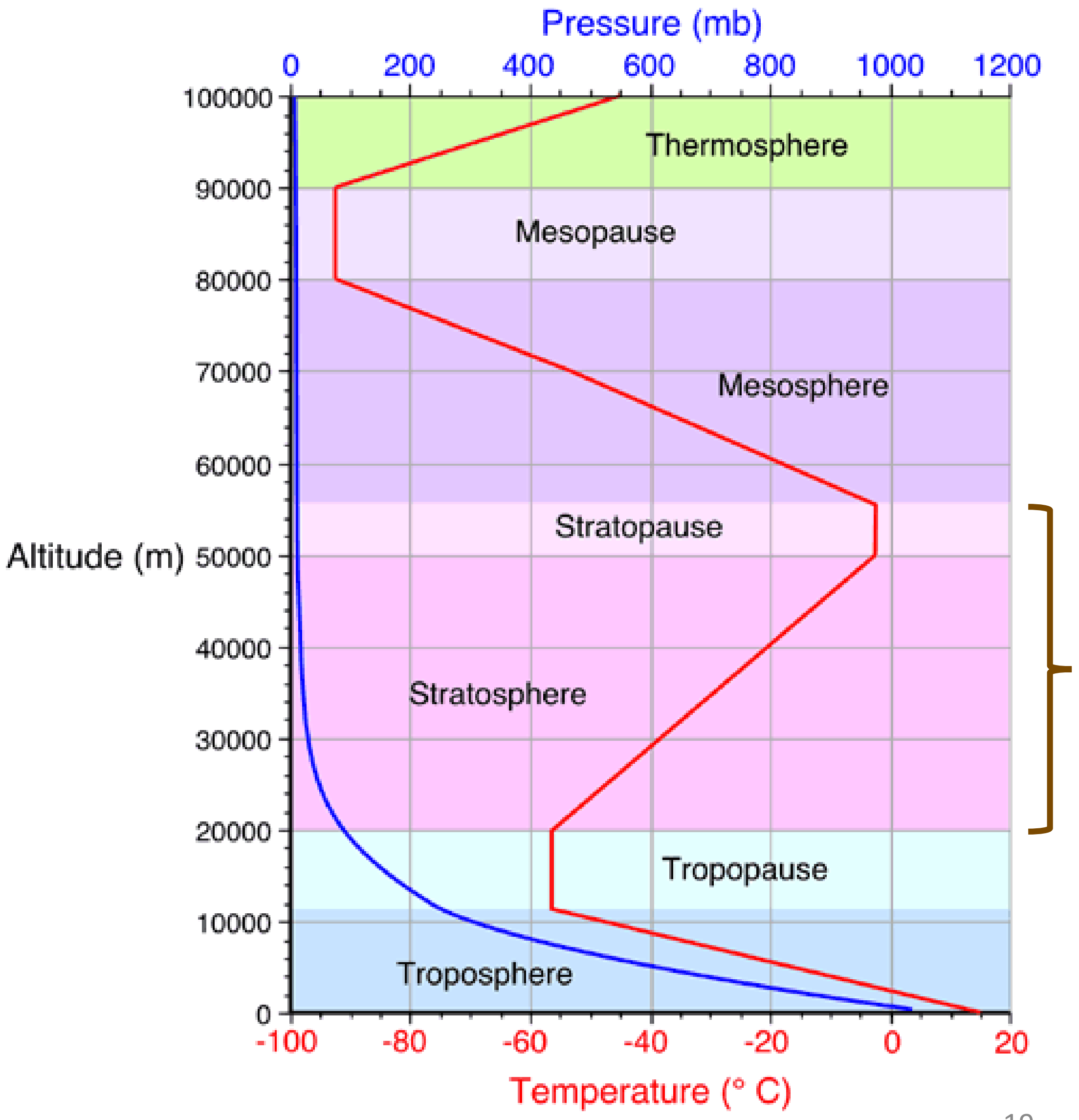
Free troposphere → 1 km to tropopause



Layers of the atmosphere

<u>Stratosphere</u>

- From tropopause to stratopause (45 to 55 km)
- Temperature increases with altitude
- Slow vertical mixing
- 90% of atmospheric ozone is in the stratosphere



Stratospheric ozone = Good
Tropospheric ozone = Bad

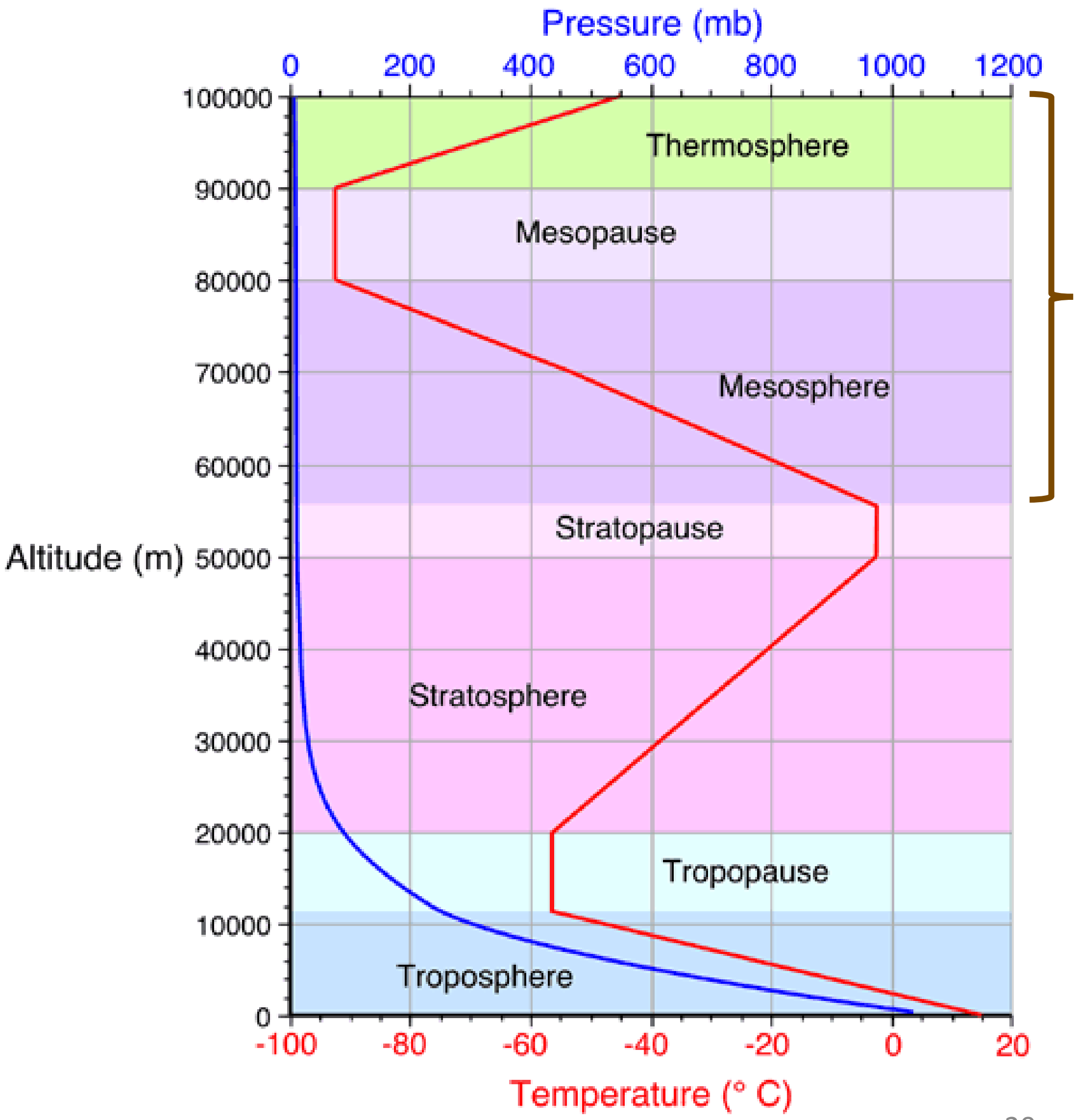
Layers of the atmosphere

Mesophere

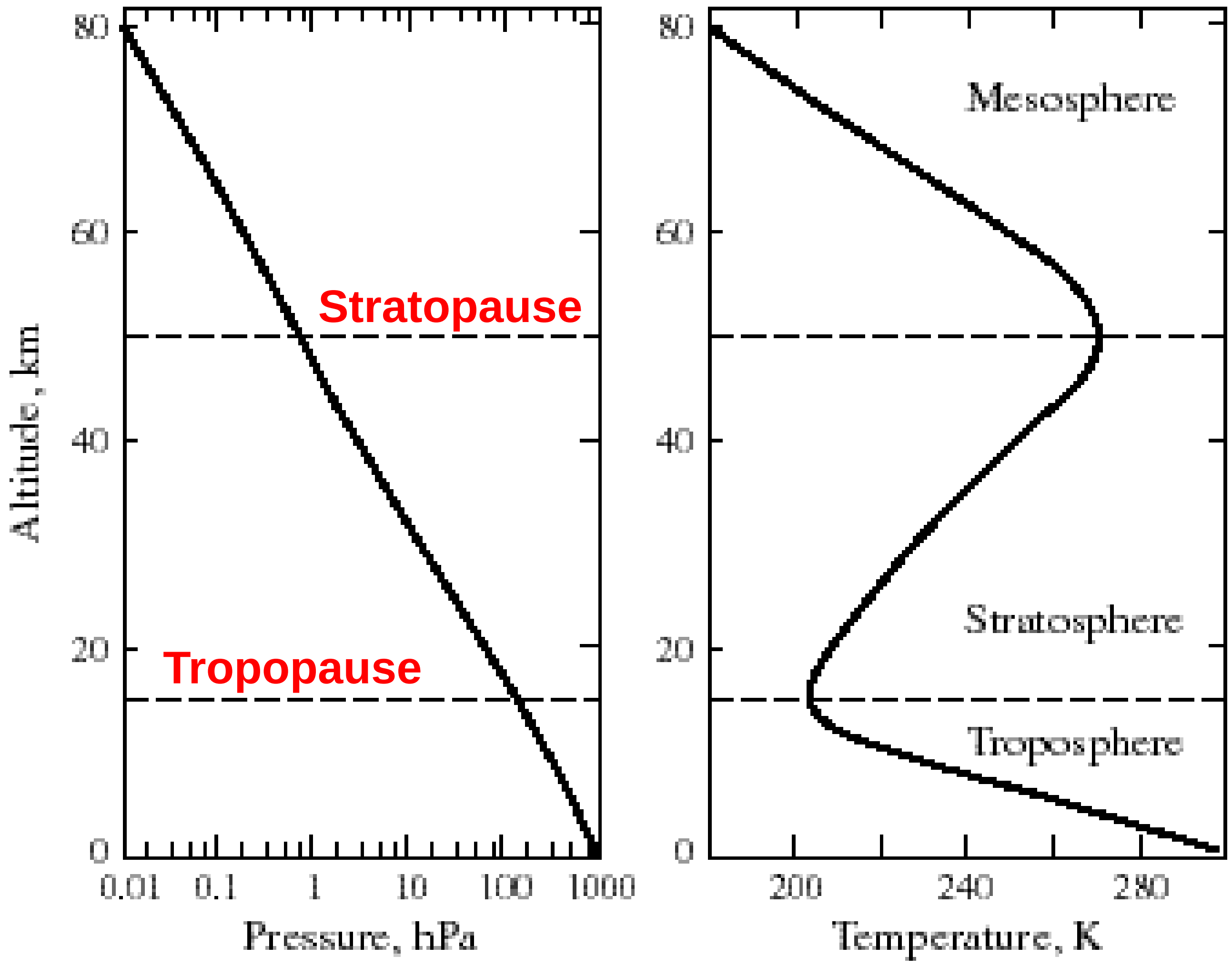
- From stratopause to mesopause (80 to 90 km)
- Temperature decreases with altitude
- Mesopause is coldest point in the atmosphere
- Rapid vertical mixing

Thermosphere

- Region above mesosphere
- High temperatures due to absorption of short-wavelength radiation
- Rapid vertical mixing
- Contains ionosphere (where ions are produced



VERTICAL PROFILES OF PRESSURE AND TEMPERATURE
Mean values for 30^{o}N, March



Note: Different Units for P and T

Atmospheric Pressure

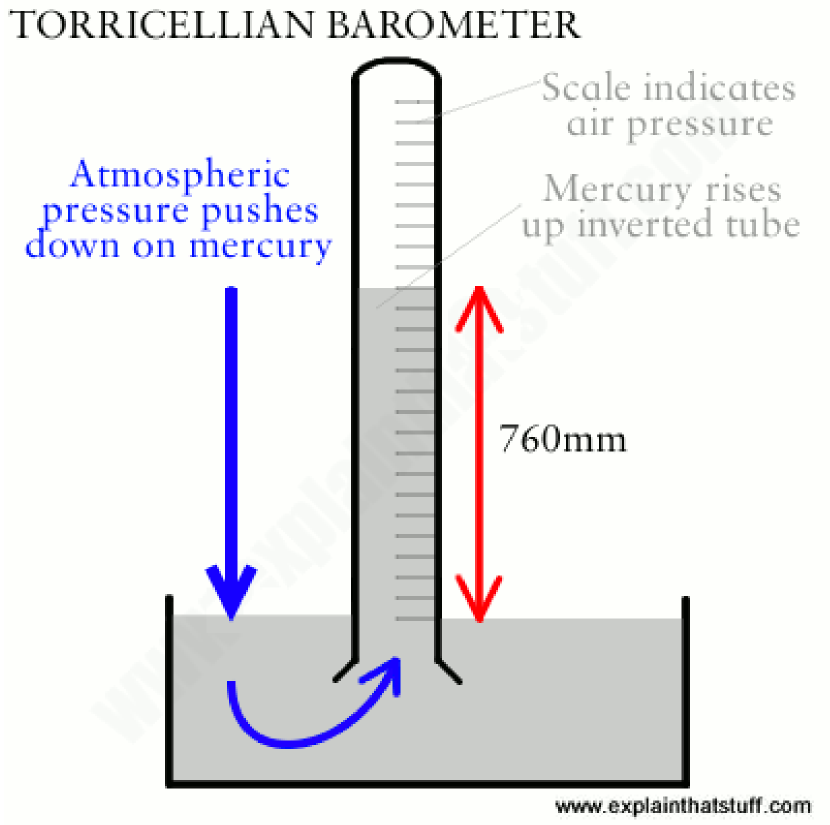
- Weight exerted by the overhead atmosphere on a unit area of surface
- Measured using mercury barometer

$$P_a = \rho_{Hg} g h$$

Where ρ_{Hg} is the density of mercury = 13.595 g cm^{-3}

Where g is the acceleration of gravity = 9.807 m s^{-2}

where h is height measured by barometer in cm



Units and Conversions

SI unit of pressure → *pascal* (Pa)

Other units = *atmosphere* (atm), *bar* (b), *millibar* (mb), *hectopascals* (hPa)

1 Pa = 1 N m^{-2} = 1 kg m^{-1} s^{-2}

1 atm = 1.01325 x 10^5 Pa

1 b = 10^5 Pa

1 mb = 100 Pa = 1 hPa

1 torr = 1 mm Hg = 134 Pa

Mean atmospheric pressure at *sea level* is
1.01325 x 10^5 Pa = 1013.25 hPa = 1013.25 mb = 1 atm = 760 torr

Atmospheric mass

Global mean pressure at the surface of the Earth is P_s = 984 hPa

- Why is it slightly less than the mean sea-level pressure?

Once you know the global mean pressure at the surface of the Earth, the total mass of the atmosphere (m_a) can be calculated:

$$m_a = \frac{4\pi R^2 P_s}{g}$$

Take home messages from Part II

- The atmosphere is divided into lower and upper regions
- The variation of the average temperature profile with altitude is the basis for defining the layers of the atmosphere
- Meteorology is the study of the lower atmosphere, the troposphere and stratosphere
- Temperature and pressure vary with height in the atmosphere