*School of Physics, Trinity College Dublin*

# Atmospheric Physics for Earth Science

Part of SF Module PY2P30

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# Atmospheric Physics for Earth Science


## Acknowledgement

These lecture notes contain many figures, tables and explanations taken from books and web pages without proper referencing.

In particular the online lecture notes on Atmospheric Physics by Andreas Richter are used extensively
http://www.iup.uni-bremen.de/materials/richter/AtmosphericPhysics_03_web.pdf

As is Roland Stull's book:
https://www.eoas.ubc.ca/books/Practical_Meteorology/

…and probably lots from NASA!

# Atmospheric Physics for Earth Science

## Course format

- 10 one-hour lectures
- Problem sheets x2 (solutions in tutorials)
- Read sections of physics textbook and useful material on the web

## Books

- Physics: Principles with Applications
  *Giancoli*
- Atmospheric Science: an Introductory survey
  *J M Wallace and P V Hobbs*
- The Atmosphere: an Introduction to Meteorology
  *F K Lutgens, E J Tarbuck, and D. Tasa*
- Atmosphere, Clouds, and Climate
  *D Randall*

# Why?

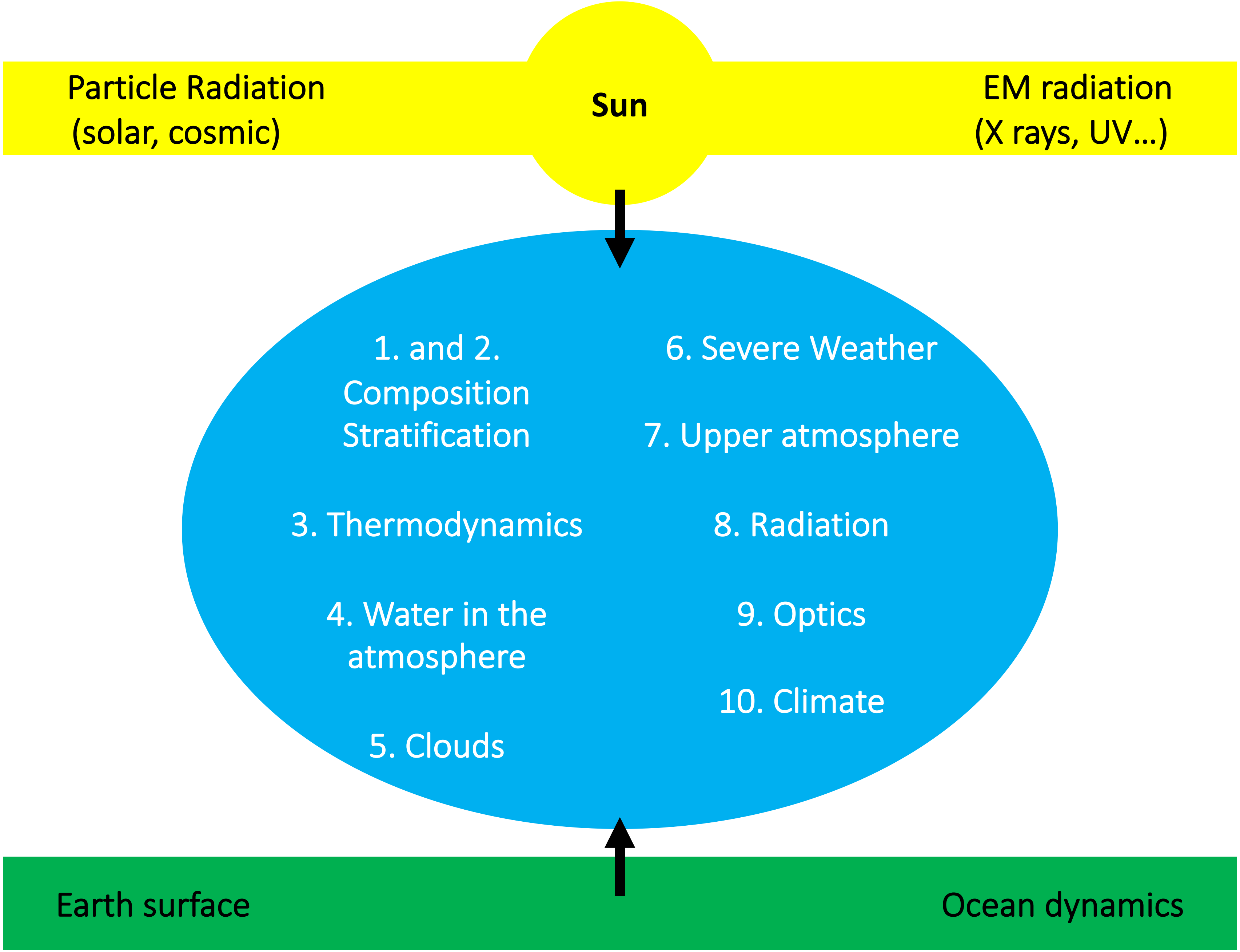
The physics of the Earth, its systems and processes.

- The surface provides resources (minerals, water, heat) but is also a source of hazards (landslips, volcanoes, earthquakes, tsunamis).
- Similarly, the atmosphere provides resources (air, water, heat) but is also a source of hazards (hurricanes, tornados, snowstorms, space weather).

Physics is the one tool we have for probing the Earths interior and atmopshere.
We use physics to

- locate resources that we can extract for economic value,
- monitor for hazards and understand how our climate is changing,
- model these hazards, learn about them, and try to mitigate their impact.
- understand the impact to human infrastructure, from bridges and houses to pipelines and pylons.

# Earth system schematic overview



# What is an atmosphere?

*"…a gaseous or volatile material gravitationally bound to a solid body"*

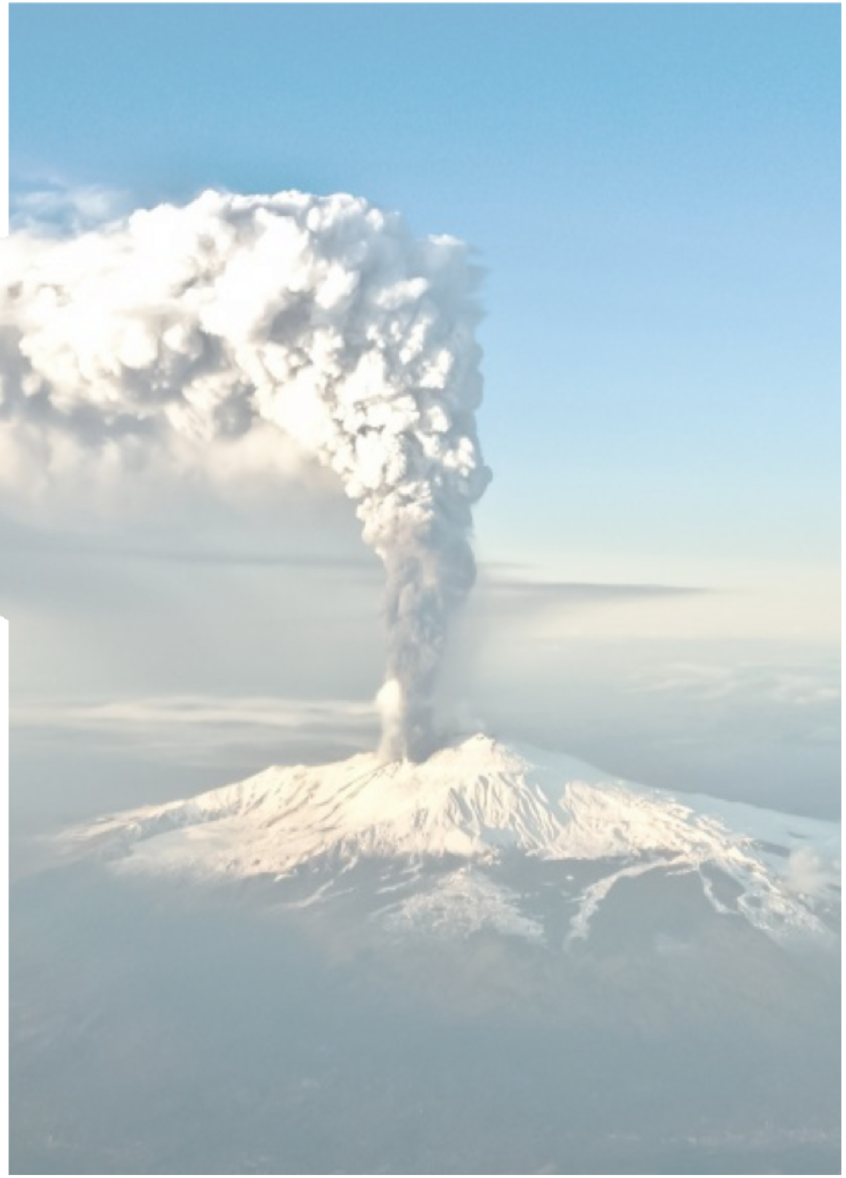
# Early atmosphere of Earth

4.6 billion years ago:

- Earth's gravity too weak to hold hydrogen and helium (unlike Sun, Jupiter, Saturn, Uranus)

- Intense volcanic activity in first billion years (out-gassing)
  - Lots of carbon dioxide ($CO_2$)

- Hydrogen (H), Helium (He), Methane ($CH_4$) and Ammonia ($NH_3$)
  - Little or no oxygen!



# Evolution of Earth's atmosphere

- As the earth cooled volcanic eruptions emitted water vapour ($H_2O$), carbon dioxide ($CO_2$) and nitrogen ($N_2$).
  - Water vapour condensed to form oceans.

- Oxygen formed by break-up of water by sunlight.
  - Ozone ($O_3$) formed in the upper atmosphere, filtering out harmful ultraviolet radiation from the sun. This allowed plants and animals to develop on land.

- The molecular oxygen ($O_2$) in the current atmosphere came about as single celled algae developed in the oceans about 3 billion years ago.
  - Photosynthesis used the $CO_2$ to produce $O_2$.

# COMPOSITION

# Chemistry revision

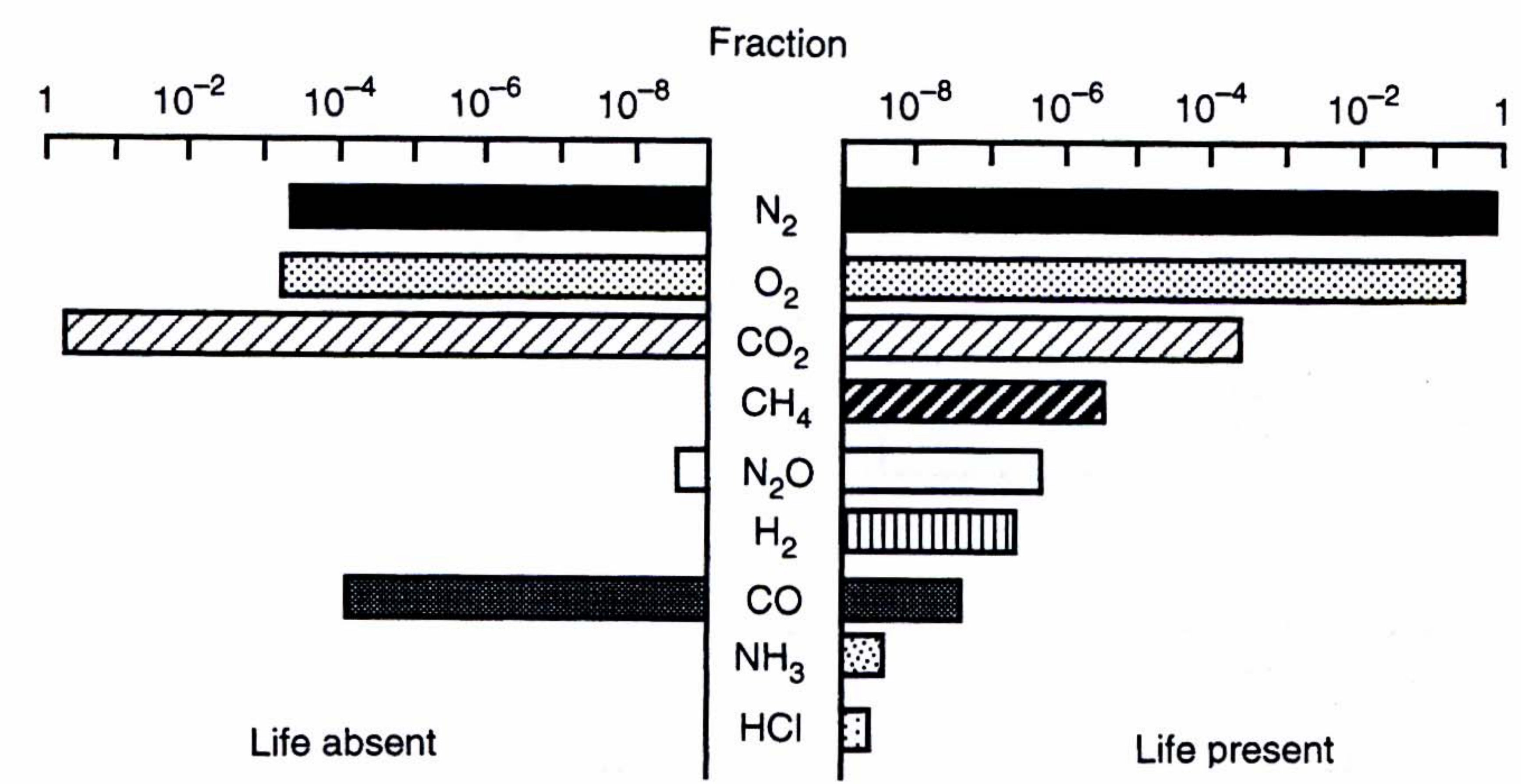
- Relative molecular mass is the mass of a molecule
  - (sum of atomic weights) x (number of atoms)
- Mole is the SI unit of measurement for the amount of a substance
  - amount of something that contains as many constitutive particles as there are atoms in 12 grams of carbon-12 ($^{12}C$)
  - Avogadro's constant $6.0221 \times 10^{23}$ $mol^{-1}$, is number of particles that are contained in the amount of substance given by one mole
- Molar mass (molecular weight) is mass of a substance divided by amount of a substance (SI unit kg/mol), i.e., mass per unit mole.
- Parts-per notation is a set of pseudo-units to describe small values of miscellaneous dimensionless quantities
  - Parts-per-million, ppm $10^{-6}$. NOT part of SI system!
  - Used in chemistry to describe dilute solutions
  - "1 ppm" can be used for a mass fraction if a water-borne pollutant is present at one-millionth of a gram per gram of sample solution.

# Current composition of Earth's atmosphere

| Constituent | Molecular Weight [g / mol] | Content [%] | Content (ppm) |
|---|---|---|---|
| Nitrogen ($N_2$) | 28.016 | 78 | 780840 |
| Oxygen ($O_2$) | 32.00 | 21 | 209460 |
| Argon (Ar) | 39.94 | 0.9 | 9340 |
| Water vapour ($H_2O$) | 18.02 | 2.5 | 25000 |
| Carbon Dioxide ($CO_2$) | 44.01 | 0.04 | 370 |
| Neon (Ne) | 20.18 | 0.002 | 18 |
| Helium (He) | 4.00 | 0.0005 | 5 |
| Methane ($CH_4$) | | 0.0002 | 1.7 |
| Krypton (Kr) | 83.7 | 0.0001 | 1.14 |
| Hydrogen ($H_2$) | 2.02 | 0.00005 | 0.55 |
| Ozone ($O_3$) | 48.00 | 0.0000004 | 0.04 |

- Mean molecular weight of air is 28.97 g/mol
- For most constituents the concentrations are very stable, has remained much the same for past 200 million years!
- Except $H_2O$ and $O_3$ (vary in space and time), and $CO_2$ is slowly increasing.

# Impact of biosphere




- Earth atmosphere is far from the equilibrium expected for a planet without life.
- The situation is sustained by exchange with biosphere.

# Some planetary atmospheres

| Planet | Surface gravity (relative to Earth) | Surface Temperature [K] | Surface pressure [1 atm = 101,325 Pa] | Chemical composition |
|---|---|---|---|---|
| Venus | 0.91 | 700 | 90 | $CO_2$ (97 %)<br>$N_2$ (3.5 %) |
| Earth | 1 | 290 | 1 | $N_2$ (78 %)<br>$O_2$ (21 %)<br>$H_20$ |
| Mars | 0.38 | 210 | 0.01 | $CO_2$ (96 %)<br>Ar (2 %)<br>$N_2$ (2 %)<br>$O_2$ (0.2 %) |
| Titan | 0.14 | 94 | 1.5 | $N_2$ (98 %)<br>$CH_4$ (1.4 %)<br>$H_2$ (0.2 %) |

The existence of an atmosphere depends on the body's surface temperature, and the size and mass of the body.

# Permanent gases

Fairly constant up to ~ 100km
Balance between destruction and production (within a cycle)

**Nitrogen**
- Removed by soil bacteria
- Returned by decay of organisms

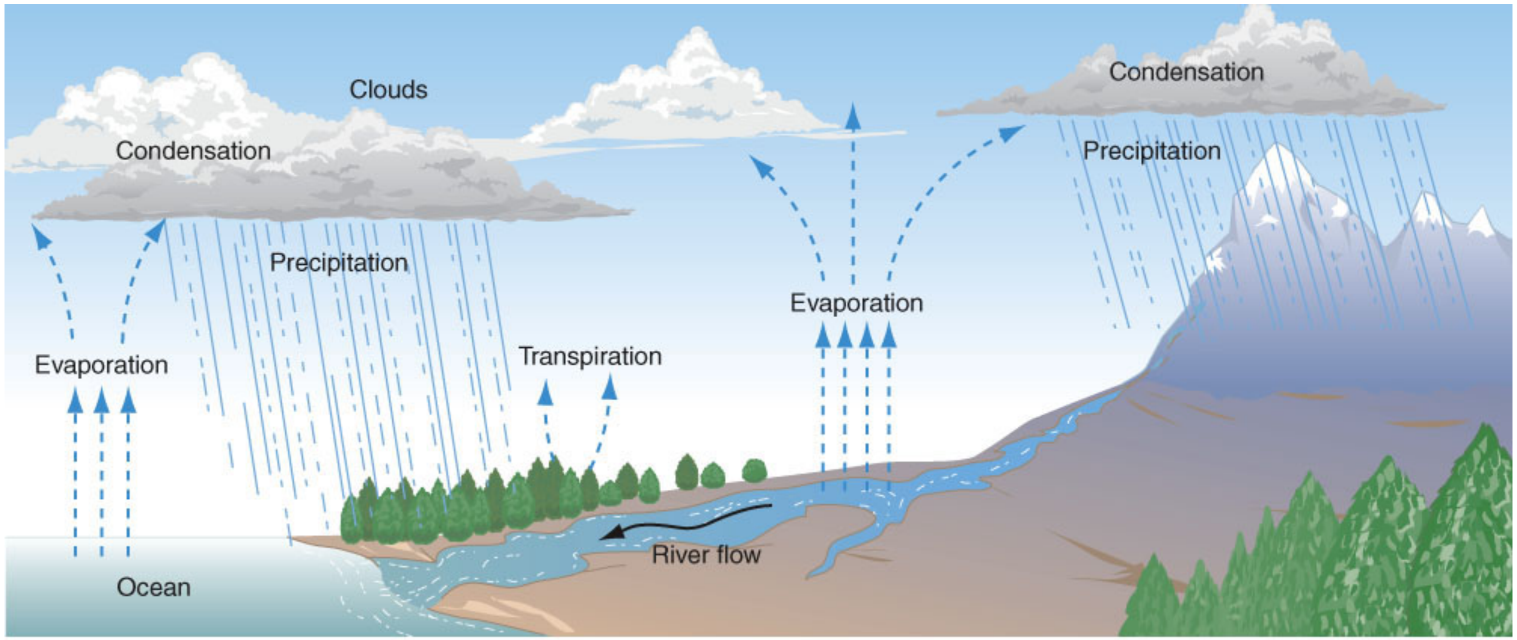
**Oxygen**
- Removed by organism decay, oxidation, animals breathing
- Returned by plant photosynthesis

**Argon and other trace gases**

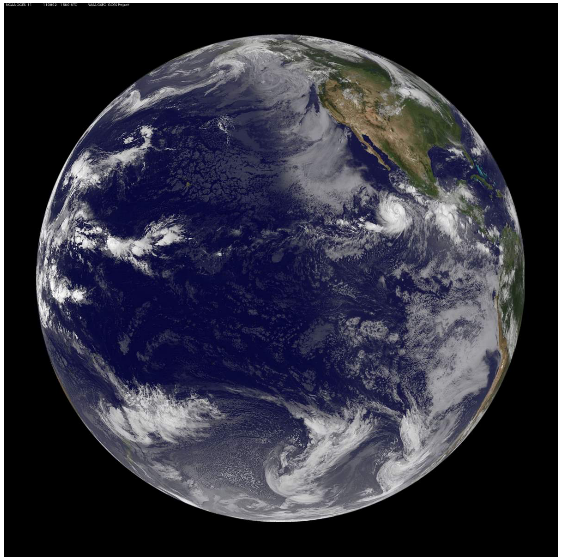
# Variable (greenhouse) gases

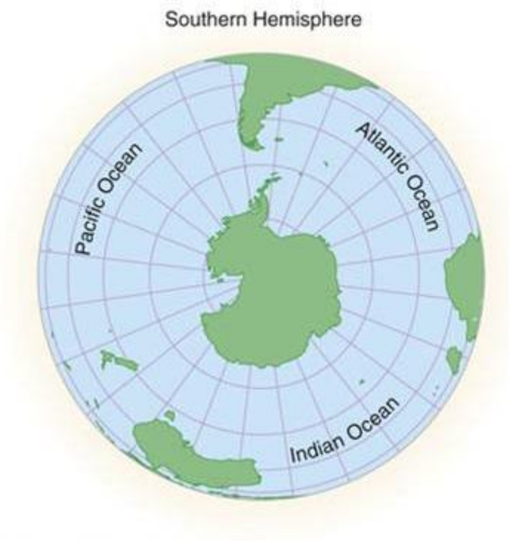
## Water vapour

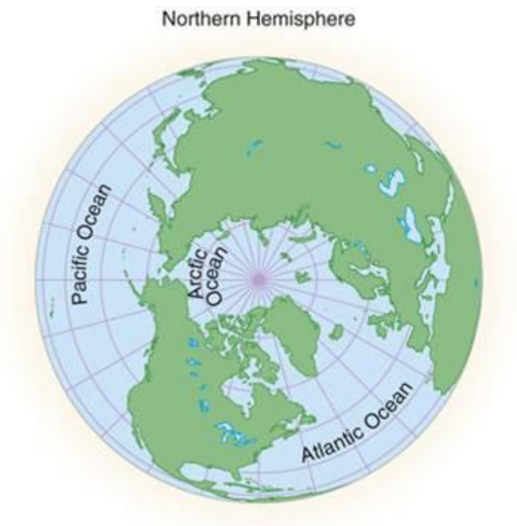
- Earth is only planet in the solar system where water can exist in all three phases (solid, liquid, gas).
- Water concentration in the atmosphere varies strongly with height, location, temperature.
- Evaporation and condensation of water involves large changes in latent heat that are crucial for energy transport in the atmosphere, and drive atmospheric dynamics.



# The importance of water





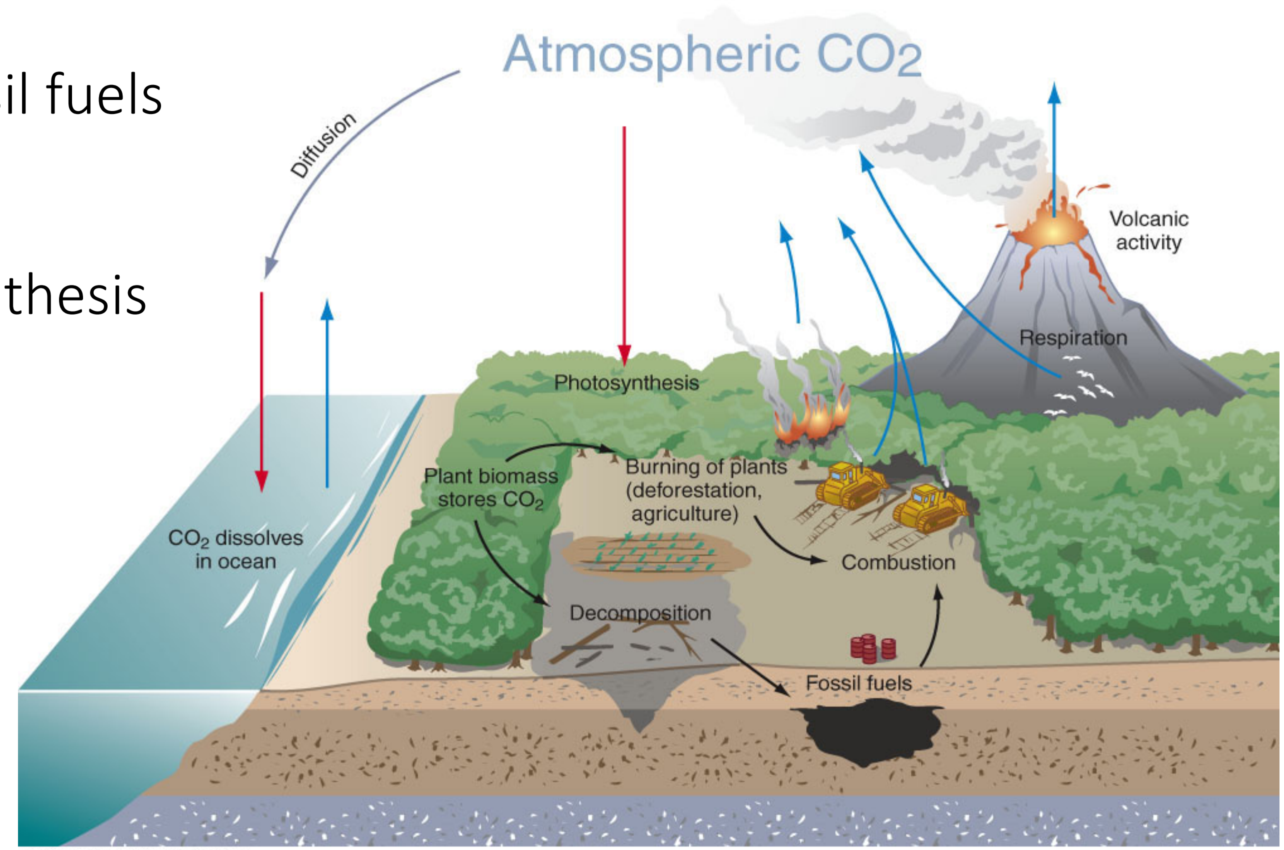

Only a very small fraction of the water is in the atmosphere

- 97% in oceans (71 % of globe covered by water)
- 2.4% in ice
- 0.6% in underground fresh water
- 0.02% in lakes and rivers
- 0.001% the atmosphere

# Variable (greenhouse) gases

**Carbon dioxide**

- Sources
  - Plant/animal respiration
  - Plant decay
  - Volcanoes
  - Burning of fossil fuels
  - Deforestation
- Sinks
  - Plant photosynthesis
  - Oceans
  - Carbonates

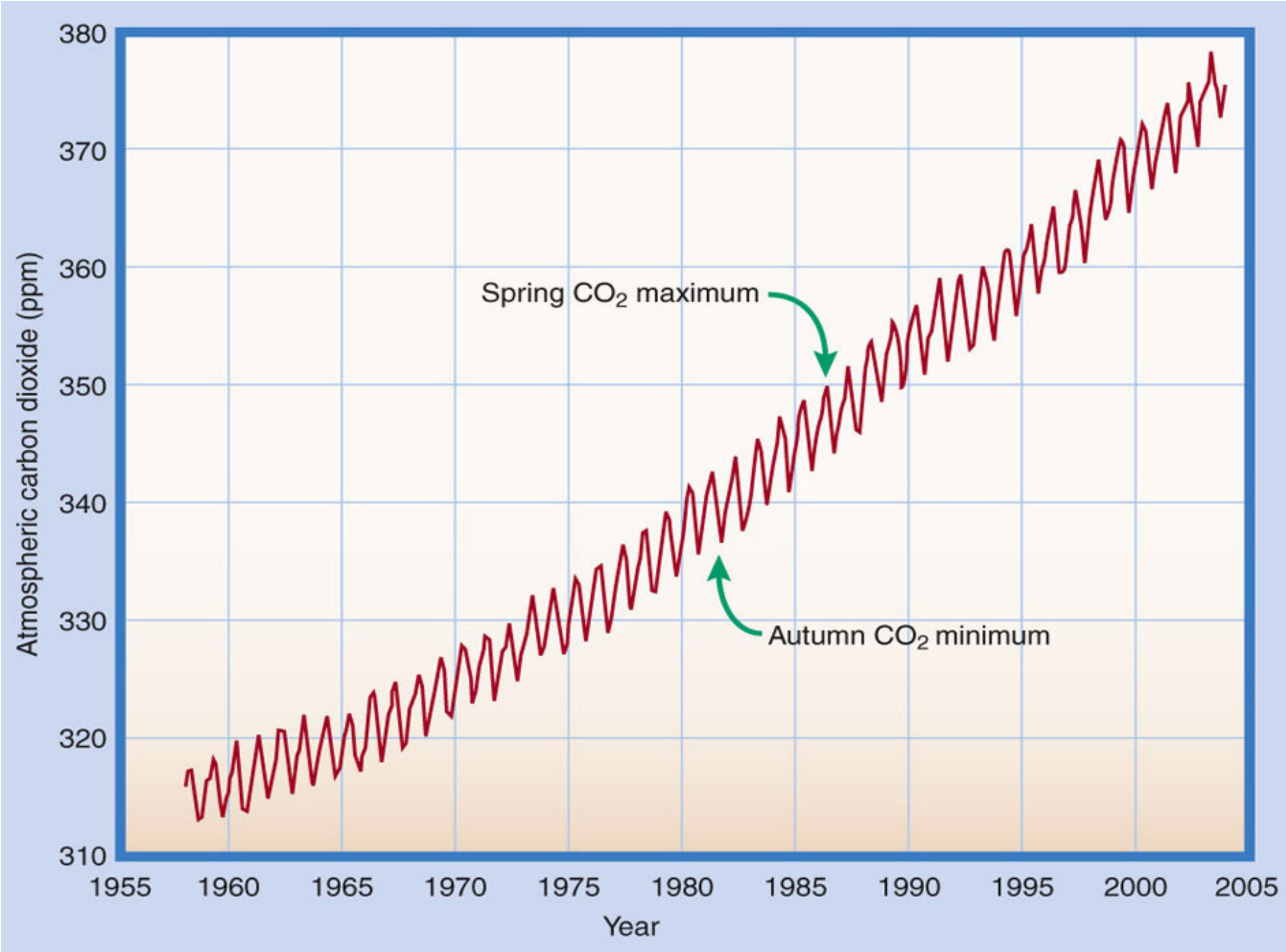




**Methane**

**Ozone… et al**

# Carbon dioxide increase



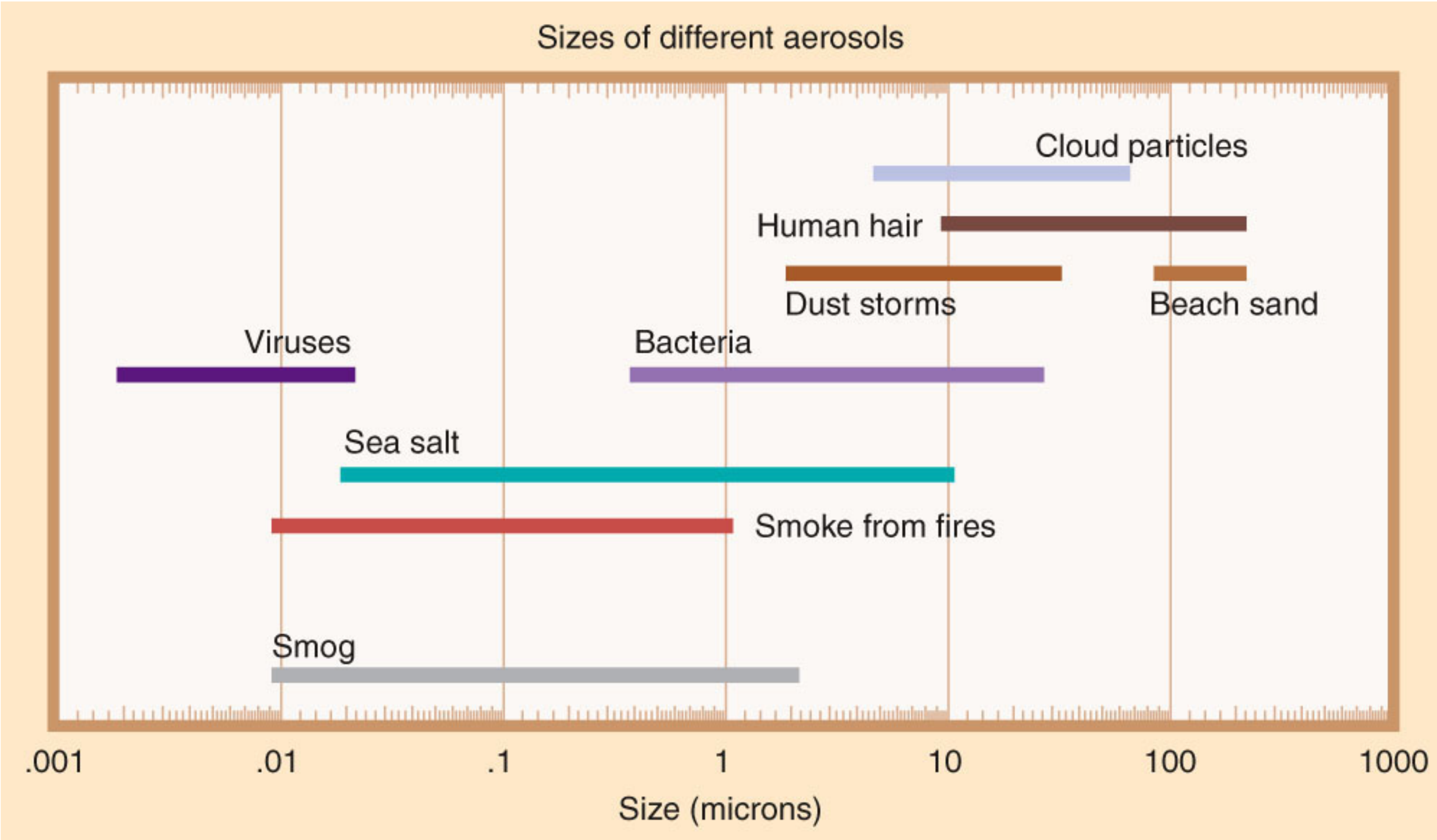


Anthropogenic increase of 25% since 1800

# Aerosols

- Particles suspended in the atmosphere
- Micron diameter
  (1 micron = 1 millionth of a meter)
- Modify the amount of solar energy reaching the surface of Earth
- Act as condensation nuclei for cloud droplets.
- Primary sources
  - Sea salt spray
  - Wind erosion
  - Volcanoes
  - Fires
  - Human activity
- Rain is essential for the removal of particles and many gases from the atmosphere

# Aerosols



Sizes of different aerosols
Cloud particles
Human hair
Dust storms
Beach sand
Viruses
Bacteria
Sea salt
Smoke from fires
Smog
.001
.01
.1
1
10
100
1000
Size (microns)

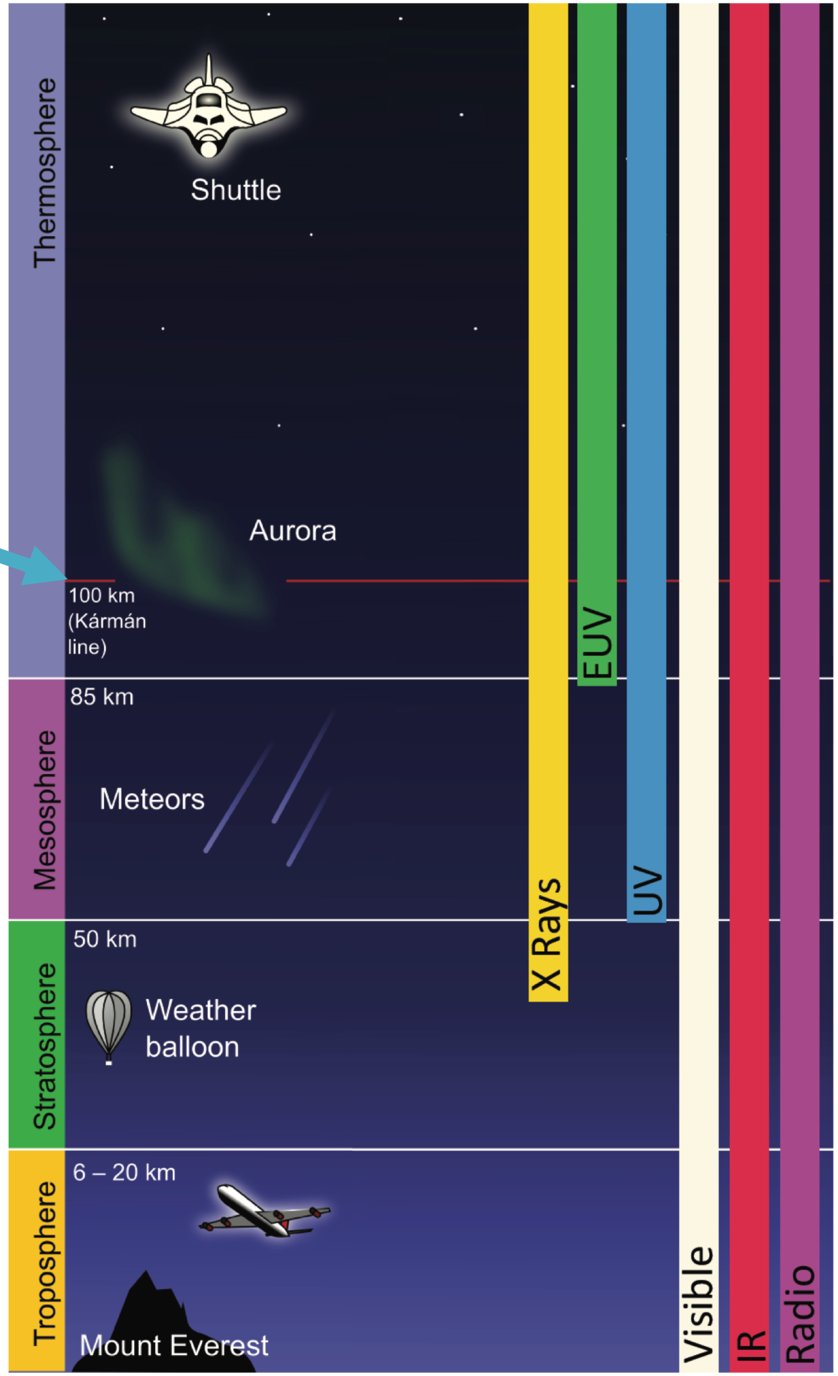
# STRATIFICATION

# How does the air change with altitude?

90% of the atmosphere is within ~30km of the Earth's surface.

# Edge of space

- International Aeronautics Federation defines Kármán line as the boundary between Earths atmosphere and outer space at 100km.
- Space below the line is regulated by the country and above it is not subject to any sovereignty claim.
- Why 100km? Physics!




NOAA

# Physics revision

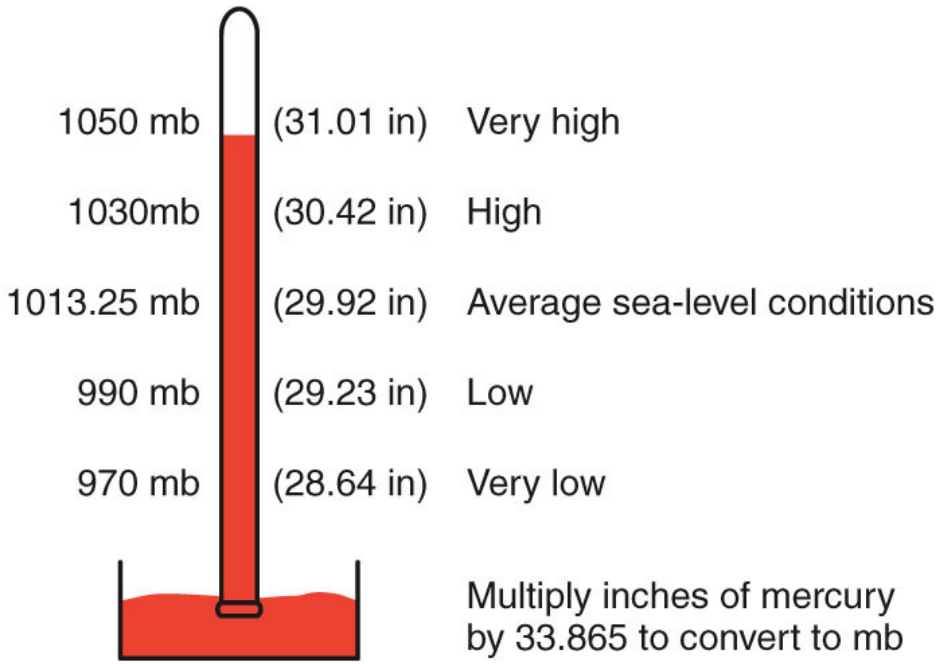
- The density, temperature [K] and pressure of a gas are related to each other.

- Density of a gas:
  - Number of molecules per unit volume (concentration).
  - Mass per unit volume, $\rho = \frac{\mathbf{m}}{\mathbf{V}}$ [$kgm^{-3}$]

- Gas pressure results when gas molecules move and collide with a surface.
  - Gas pressure is exerted in all directions.
  - Pressure is the force exerted on unit area,

    $\mathbf{P} = \frac{\mathbf{F}}{\mathbf{A}}$ (where F =ma) [1 Pa = 1 $Nm^{-2}$]
- Pressure at a point in atmosphere is the weight of air above that point.

# Pressure and altitude




STP (standard temperature and pressure)

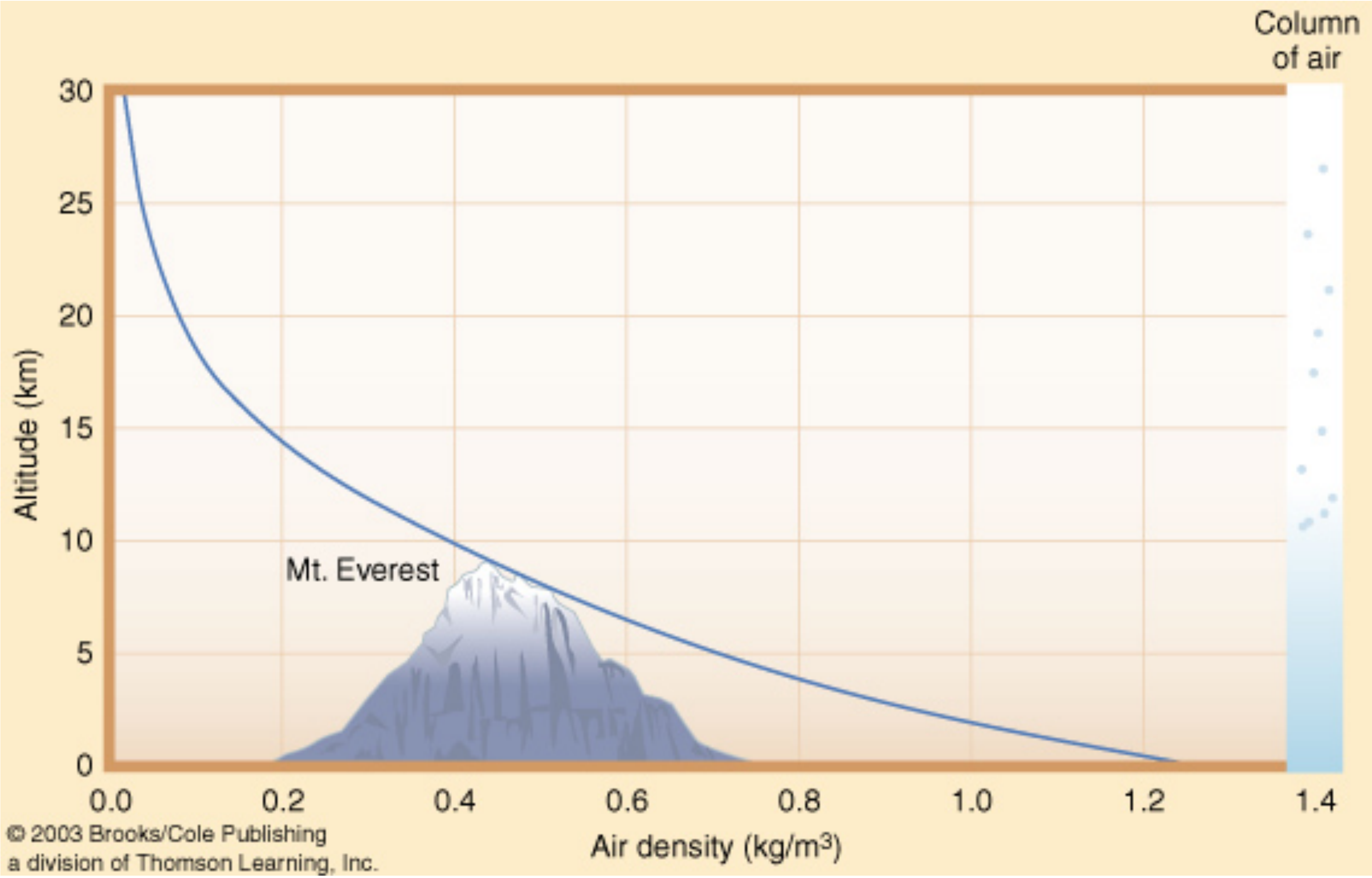
- 273.15 K ( 0°C)
- 1 bar = $10^5$ Pa

*(previously 1 atm = 1.103 x $10^5$ Pa)*

In weather forecasting measurements air pressure is corrected to report what it would be at sea level (sea level pressure) in order to subtract the effect of station elevation.

- Density of atmosphere at sea level and 15 °C = 1.2 kg $m^{-3}$
- Average sea-level pressure is 760 mm (29.92 inches) of mercury or 1013.25 hPa (millibars).

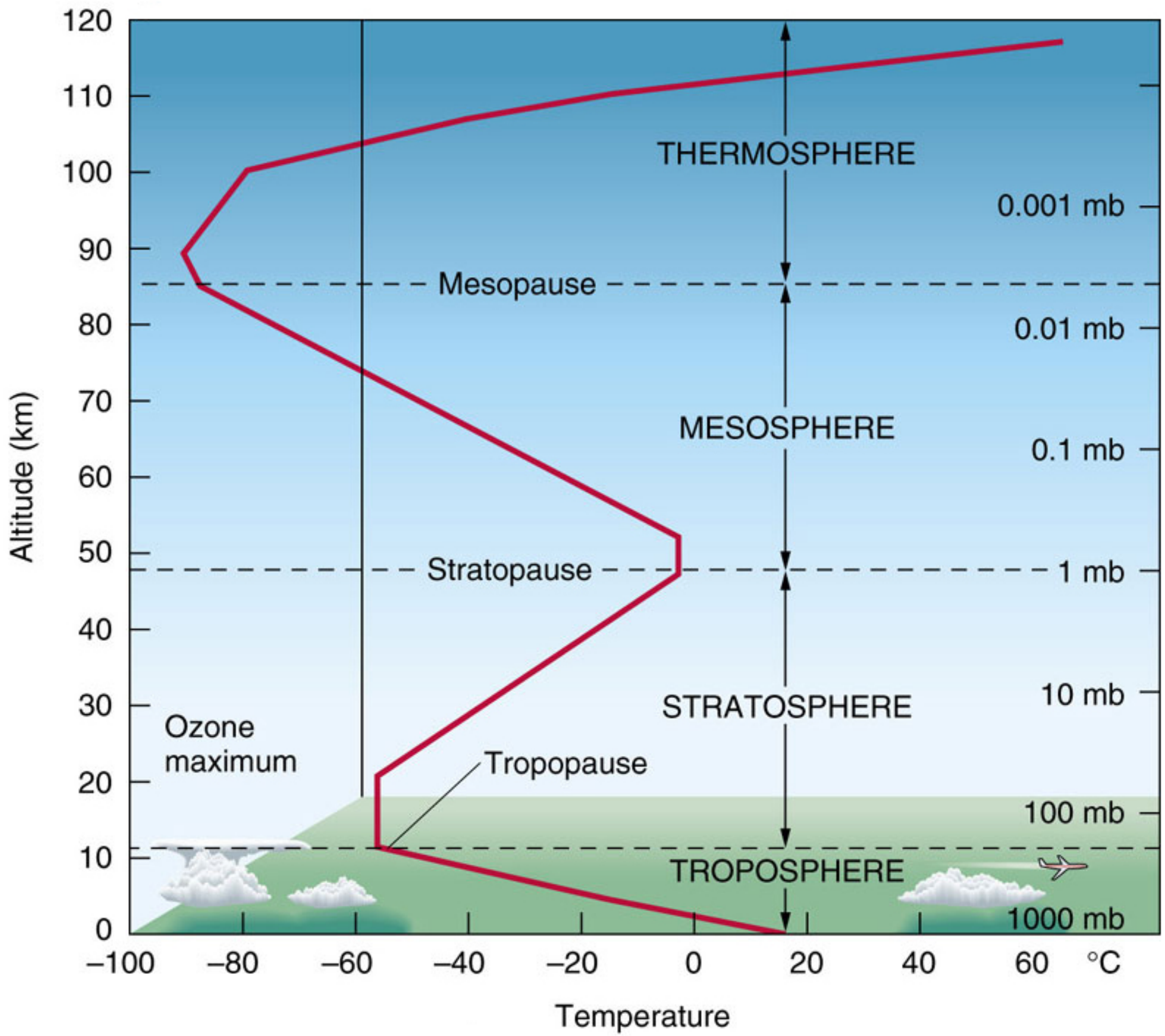
# Pressure and altitude




Density and pressure decrease with altitude.

# Stratification of the atmosphere

Defined by temperature variation with altitude



# Stratification of the atmosphere

Classify by temperature change with altitude:

**Troposphere (<12 km)**

- Temperature decreases with height because the troposphere is heated by the Earth's surface and not directly by sunlight.
- Literally means region where air "turns over"
- Almost all of what we call "weather" occurs in the troposphere (nearly all clouds)
- Contains 80% of the atmosphere's mass
- Top of troposphere is call **tropopause**

**Stratosphere (~12 – 50 km)**

- Temperature increases with height
- Very stable, little mixing occurs
- Solar UV radiation interacts with $O_2$ producing $O_3$
- Top of stratosphere is called **stratopause**

# Stratification of the atmosphere

Mesosphere (~ 50 – 90 km)

- Temperature again decreases with height (but more slowly)
- Optically thin atmosphere in IR - gases radiate directly to space
- Top of mesosphere called **mesopause**

Thermosphere (~ 90 – 700 km)

- Temperature increases with height
- Region of highest temperature in atmosphere due to absorption of high photon energy radiation
- Very low density: contains very little of atmosphere's mass
- Location of **ionosphere** (mixture of positively charged ions and electrons) that reflects radio waves
- Location of aurora (produced in the **magnetosphere**)
- No clear separation with interplanetary space (**exosphere** extends out to ~10,000km and merges with solar wind)

# Stratification of the atmosphere

Reasons for the temperature profile:

- adiabatic vertical transport
- radiative cooling by water vapour
- absorption in the ozone layer
- oxygen absorption in the thermosphere

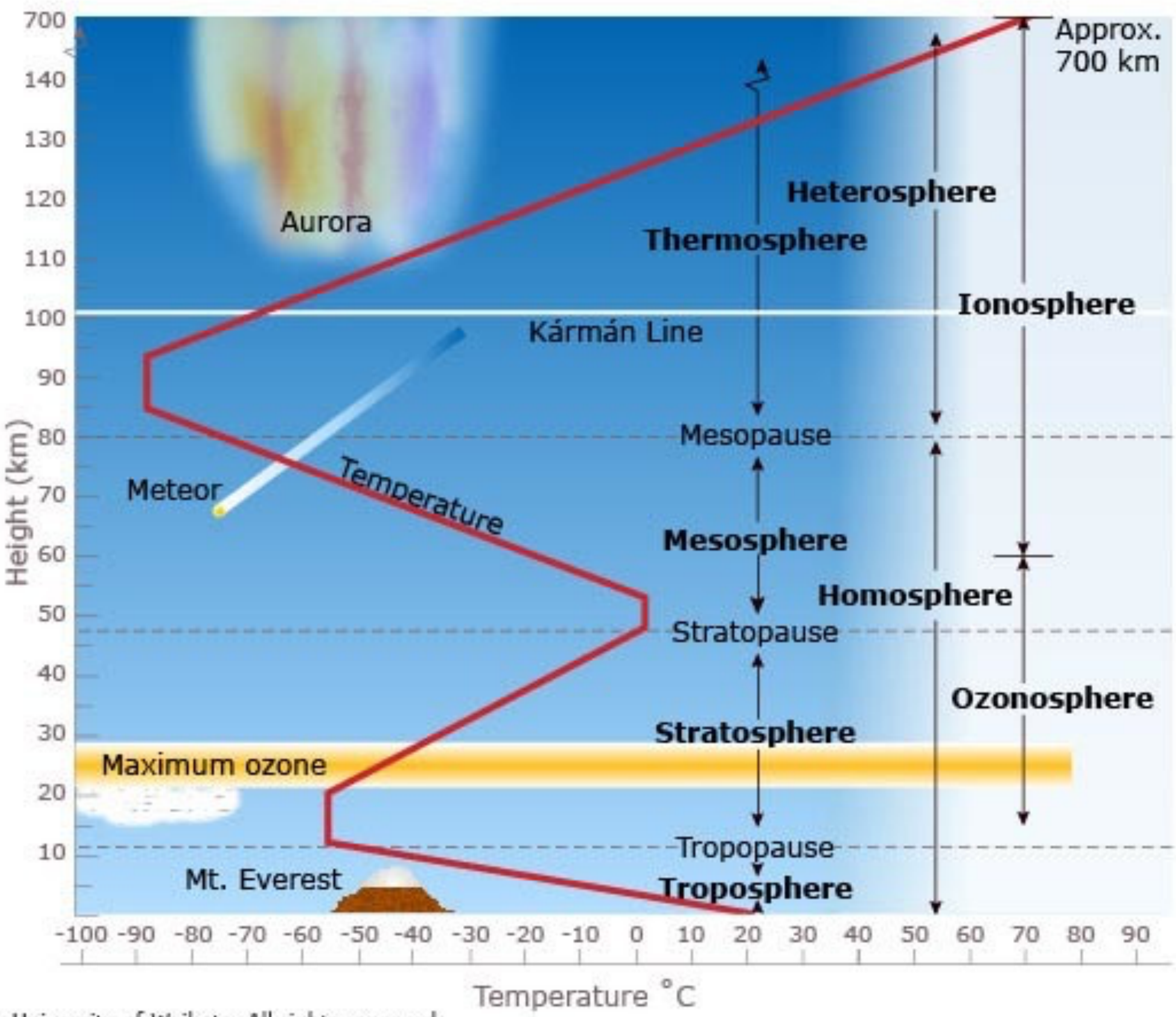
Can also make classification of layers according to degree of mixing:

**Homosphere**
Below mesopause (100 km) the different gases are well mixed by collisions

**Heterosphere**

- Above 100 km the mean free path (mfp) between molecular collision is greater than 1m.
- Then each gas behaves as if it were alone and concentrations of heavier gases decrease more rapidly than lighter gases.
- Composition of outer regions of atmosphere dominated by H, $H_2$, He….
- When Sun is active H above 500 km acquires sufficiently high velocities to escape Earth's gravitational field.

# Atmosphere in perspective





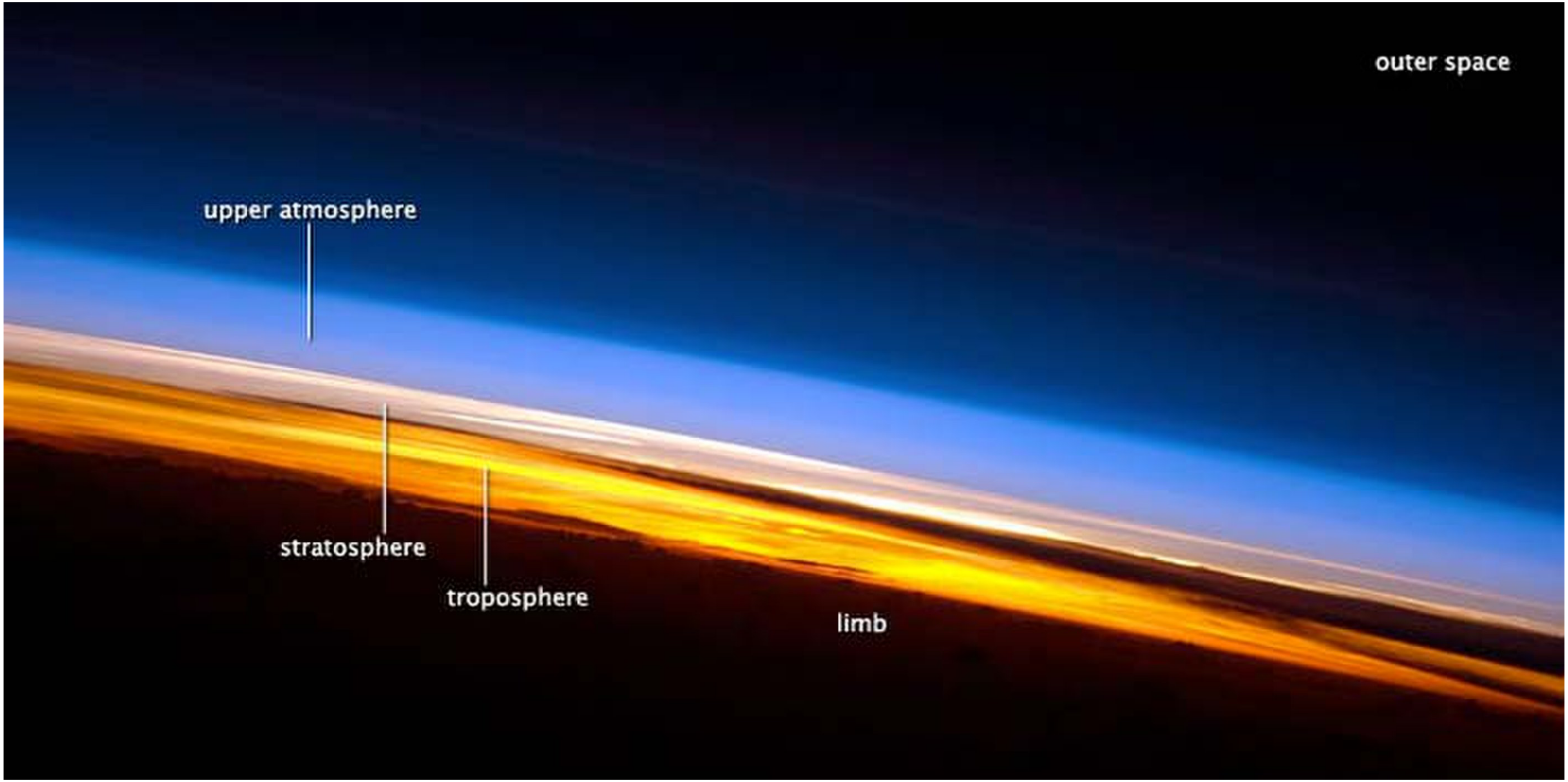

**1 AU**
**$1.5 \times 10^8$ km**

**Heterosphere**
**1000 km**

**Homosphere**
**100 km**

**Troposphere**
**10km**

**$R_E$ = 6,371 km**


outer space
upper atmosphere
stratosphere
troposphere
limb

# Summary

Physics is key to understanding the interconnectivities of the Earth system

- How the lithosphere, hydrosphere, atmosphere, etc interacts.

Composition of the atmosphere

- Chemistry revision – relative molecular mass, moles
- Content in terms of elements

Stratification of the atmosphere

- Physics revision – temperature, pressure, density
- Layers

Next week

- Composition: Ideal gas equation
- Stratification: Hydrostatic equation