ATM 241, Spring 2020
Lecture 3
Atmospheric Structure

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Marshall & Plumb
Ch. 1, 3.1

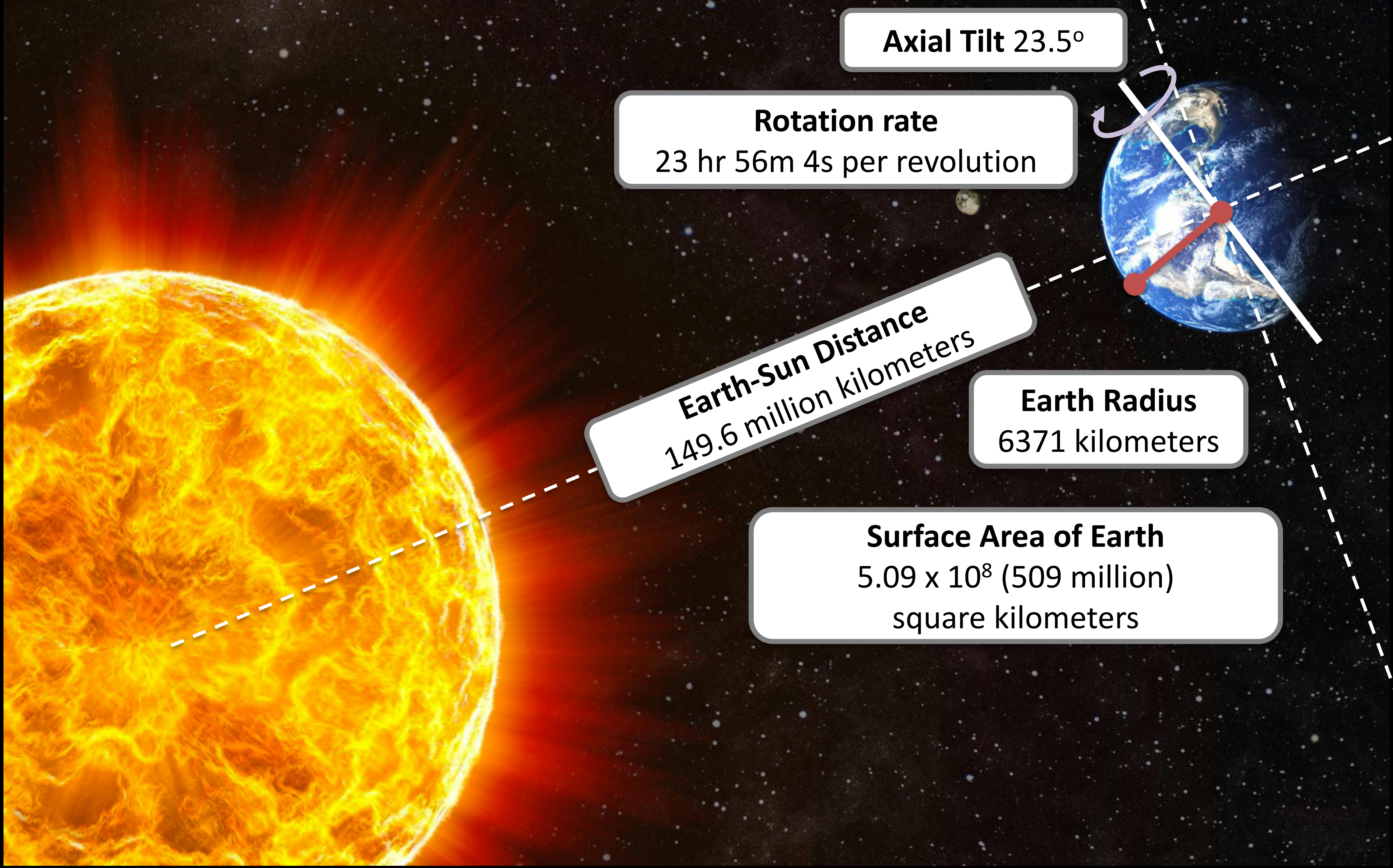
In this section…

Definitions

- Keeling curve
- Troposphere
- Stratosphere
- Mesosphere
- Thermosphere
- Tropopause
- Stratopause
- Mesopause
- Clausius-Clapeyron
- Dew point temperature

Questions

- What are the chemical constituents of the Earth’s atmosphere?
- How do these constituents influence climate?
- What are the layers of the Earth’s atmosphere and how are they distinguished?
- What are the characteristics of each layer of the Earth’s atmosphere?
- Why does water vapor in the atmosphere decay rapidly with height?
- Why is tropical air moister than air at the poles?



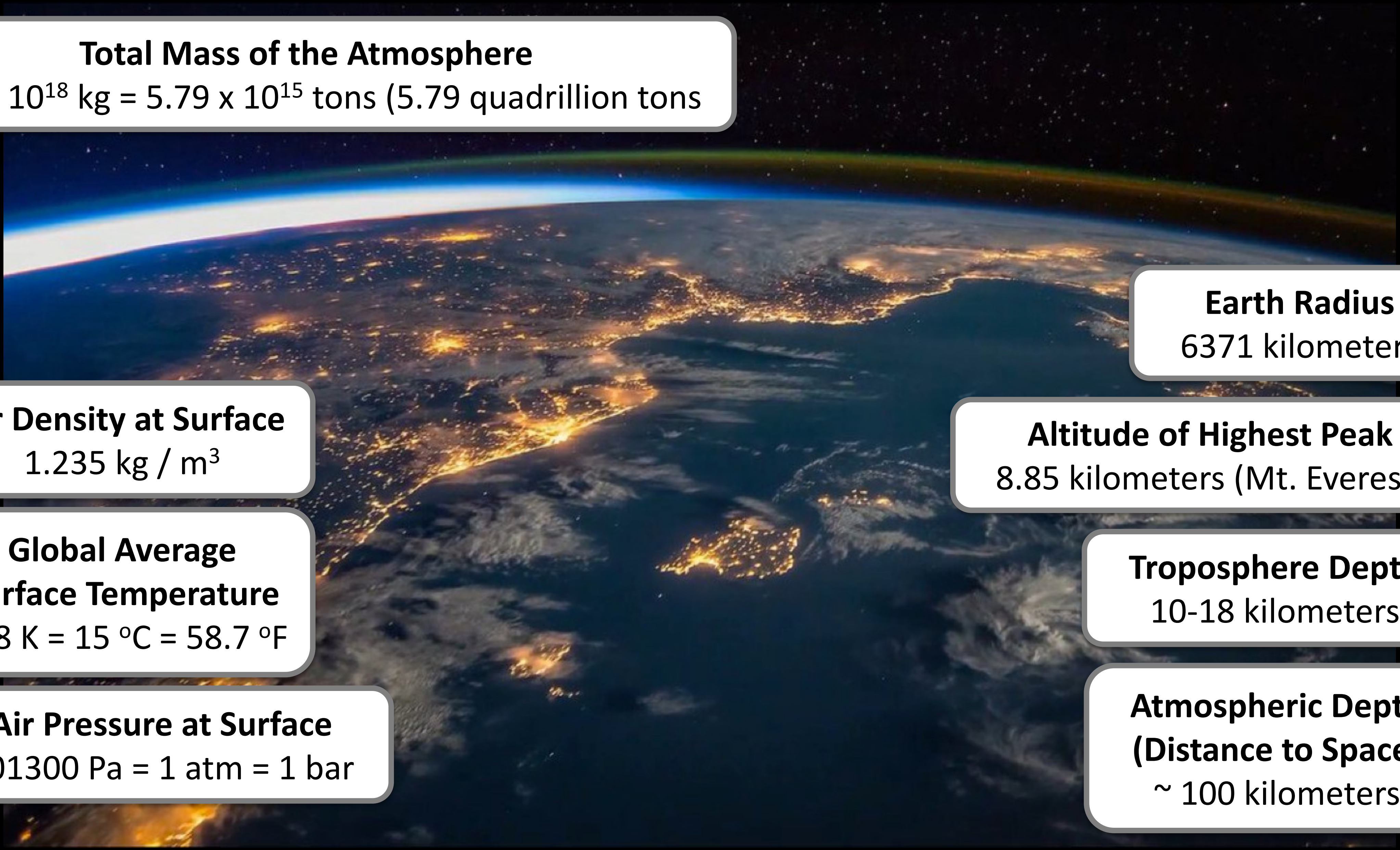
Axial Tilt 23.5^{o}

Rotation rate
23 hr 56m 4s per revolution

Earth-Sun Distance
149.6 million kilometers

Earth Radius
6371 kilometers

Surface Area of Earth
5.09×10^{8} (509 million)
square kilometers



Total Mass of the Atmosphere
5.26×10^{18} kg = 5.79×10^{15} tons (5.79 quadrillion tons

Air Density at Surface
1.235 kg / m^3

Global Average Surface Temperature
288 K = 15 °C = 58.7 °F

Air Pressure at Surface
101300 Pa = 1 atm = 1 bar

Earth Radius
6371 kilometers

Altitude of Highest Peak
8.85 kilometers (Mt. Everest)

Troposphere Depth
10-18 kilometers

Atmospheric Depth (Distance to Space)
~ 100 kilometers

Atmospheric Chemistry

The chemistry of the Earth's atmosphere plays a major role in determining the balance of energy in the Earth system.

Knowledge of its constituents is thus important for understanding energy in the climate system.

Species	Molecular Mass (g/mol)	Proportion by volume

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Atmospheric Chemistry

Together, nitrogen gas (N_2) and oxygen gas (O_2) represent approximately 99% of the total gaseous composition of the atmosphere.

Species	Molecular Mass (g/mol)	Proportion by volume
N_2	28.01	78%
O_2	32.00	21%

Species	Molecular Mass (g/mol)	Proportion by volume

Atmospheric Chemistry

Argon (Ar) is the oft-forgotten third most abundant component of the Earth's atmosphere. It is generally forgotten since it is largely unreactive and unimportant to climate.

Species	Molecular Mass (g/mol)	Proportion by volume
N_2	28.01	78%
O_2	32.00	21%
Ar	39.95	0.93%

Species	Molecular Mass (g/mol)	Proportion by volume

Atmospheric Chemistry

Water vapor (H_2O) concentration varies significantly throughout the atmosphere.

Practically all water vapor is confined to the lower 10km of the atmosphere.

Whereas the warmest tropical air is almost 4% water vapor by volume, in polar regions water vapor may be as low as 0.2%.

Species	Molecular Mass (g/mol)	Proportion by volume
N_2	28.01	78%
O_2	32.00	21%
Ar	39.95	0.93%
H_2O	18.02	~ 0.5%

Species	Molecular Mass (g/mol)	Proportion by volume

Atmospheric Chemistry

Carbon dioxide (CO_2) is the next most abundant gas, presently making up 410 parts per million (ppm) of the atmosphere (1 ppm = 0.0001%). This means for every one million air molecules, approximately 410 are carbon dioxide.

CO_2 levels continue to rise from preindustrial levels of 280ppm as a result of human activity.

Species	Molecular Mass (g/mol)	Proportion by volume
N_2	28.01	78%
O_2	32.00	21%
Ar	39.95	0.93%
H_2O	18.02	~ 0.5%
CO_2	44.01	~ 410 ppm

Species	Molecular Mass (g/mol)	Proportion by volume

Atmospheric Chemistry (Carbon Dioxide)

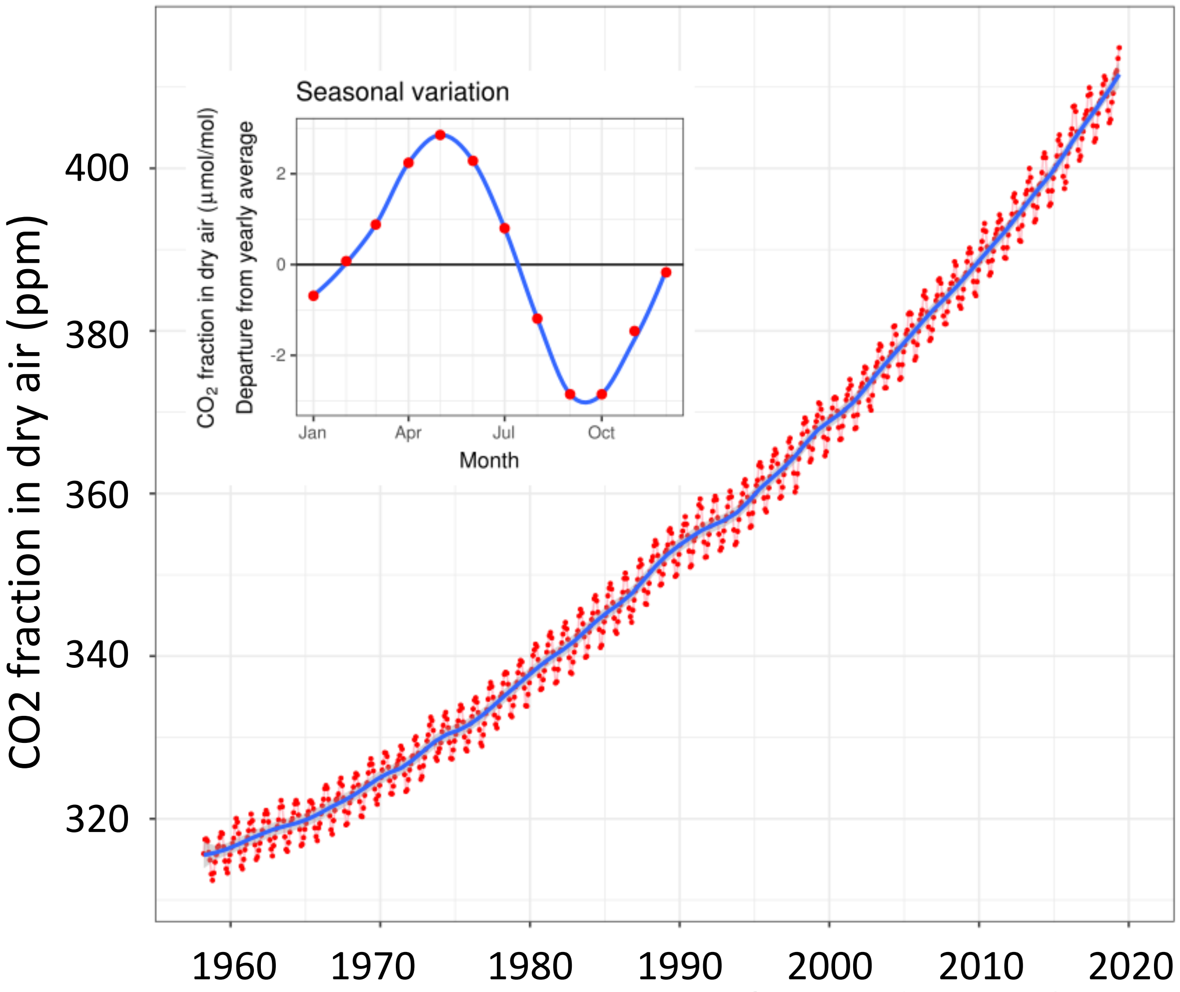
The **Keeling Curve** is named after Charles David Keeling, who started the CO_2 monitoring program at Mauna Loa Observatory in 1958 and supervised it until his death in 2005.

Carbon dioxide levels typically reach a maximum in the Northern Hemisphere Spring and minimum in the Northern Hemisphere Fall.

As of 2020, CO_2 has reached approximately 410ppm concentration. This is above pre-industrial levels of 280ppm and glacial periods when CO_2 concentration was closer to 180ppm.

https://en.wikipedia.org/wiki/Keeling_Curve

Monthly mean CO2 concentration, Mauna Loa 1958-2019



[illegible]
Scripps CO2 Program (http://scrippsco2.ucsd.edu). Accessed 2019-07-20

Atmospheric Chemistry

Of the next five most abundant gases, neon (Ne), Helium (He), and Krypton (Kr) are unreactive.

Only methane (CH_4) is relevant to energy balance. Its concentration in the Earth’s atmosphere has also been increasing because of human activity (approximately 1800ppb in 2020, compared with 720ppb in preindustrial).

Species	Molecular Mass (g/mol)	Proportion by volume
N_2	28.01	78%
O_2	32.00	21%
Ar	39.95	0.93%
H_2O	18.02	~ 0.5%
CO_2	44.01	~ 410 ppm
Ne	20.18	19 ppm
He	4.00	5.2 ppm
CH_4	16.04	1.8 ppm
Kr	83.8	1.1 ppm
H_2	2.02	~ 500 ppb

Species	Molecular Mass (g/mol)	Proportion by volume

Atmospheric Chemistry

Excluding trace species, the remaining gases include:

ozone (O_3)
nitrous oxide (N_2O)
carbon monoxide (CO)
ammonia (NH3)
nitrogen dioxide (NO_2)
chlorofluorocarbons*
sulphur dioxide (SO_2)
hydrogen sulfide (H_2S)

* no natural sources

Species	Molecular Mass (g/mol)	Proportion by volume
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H_2	2.02	~ 500 ppb

Species	Molecular Mass (g/mol)	Proportion by volume
O_3	48.00	~ 500 ppb
N_2O	44.01	310 ppb
CO	28.01	120 ppb
NH_3	17.03	~ 100 ppb
NO_2	46.00	~ 1 ppb
CCl_2F_2	120.91	480 ppt
CCl_3F	137.37	280 ppt
SO_2	64.06	~ 200 ppt
H_2S	34.08	~ 200 ppt
AIR	28.97	

Atmospheric Chemistry

The gases highlighted in **red** are the infamous **greenhouse gases**, which are particularly important for understanding the energetics of the Earth’s atmosphere.

They include **water vapor**, **carbon dioxide**, **methane**, **ozone**, **nitrous oxide**, and the **chlorofluorocarbons**.

Species	Molecular Mass (g/mol)	Proportion by volume
N_2	28.01	78%
O_2	32.00	21%
Ar	39.95	0.93%
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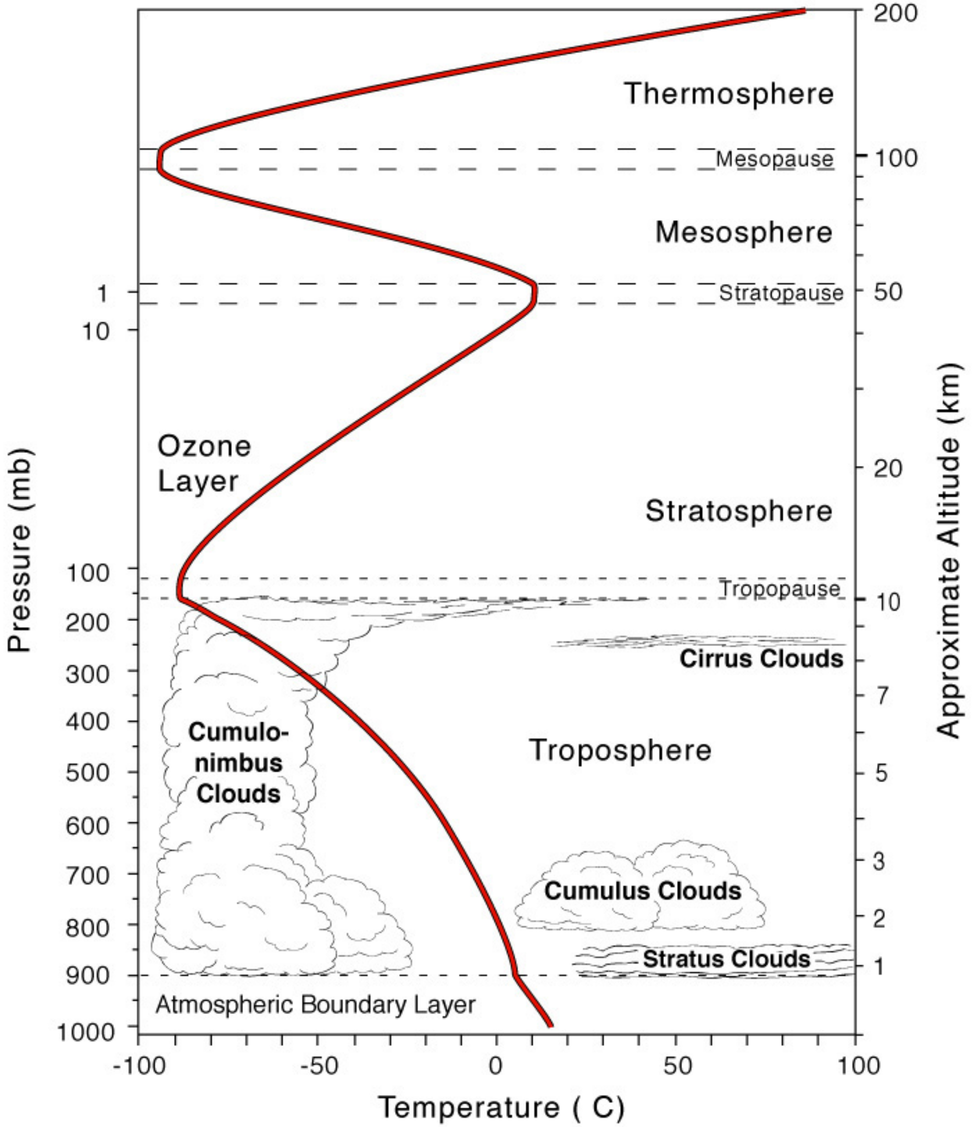
AIR	28.97	

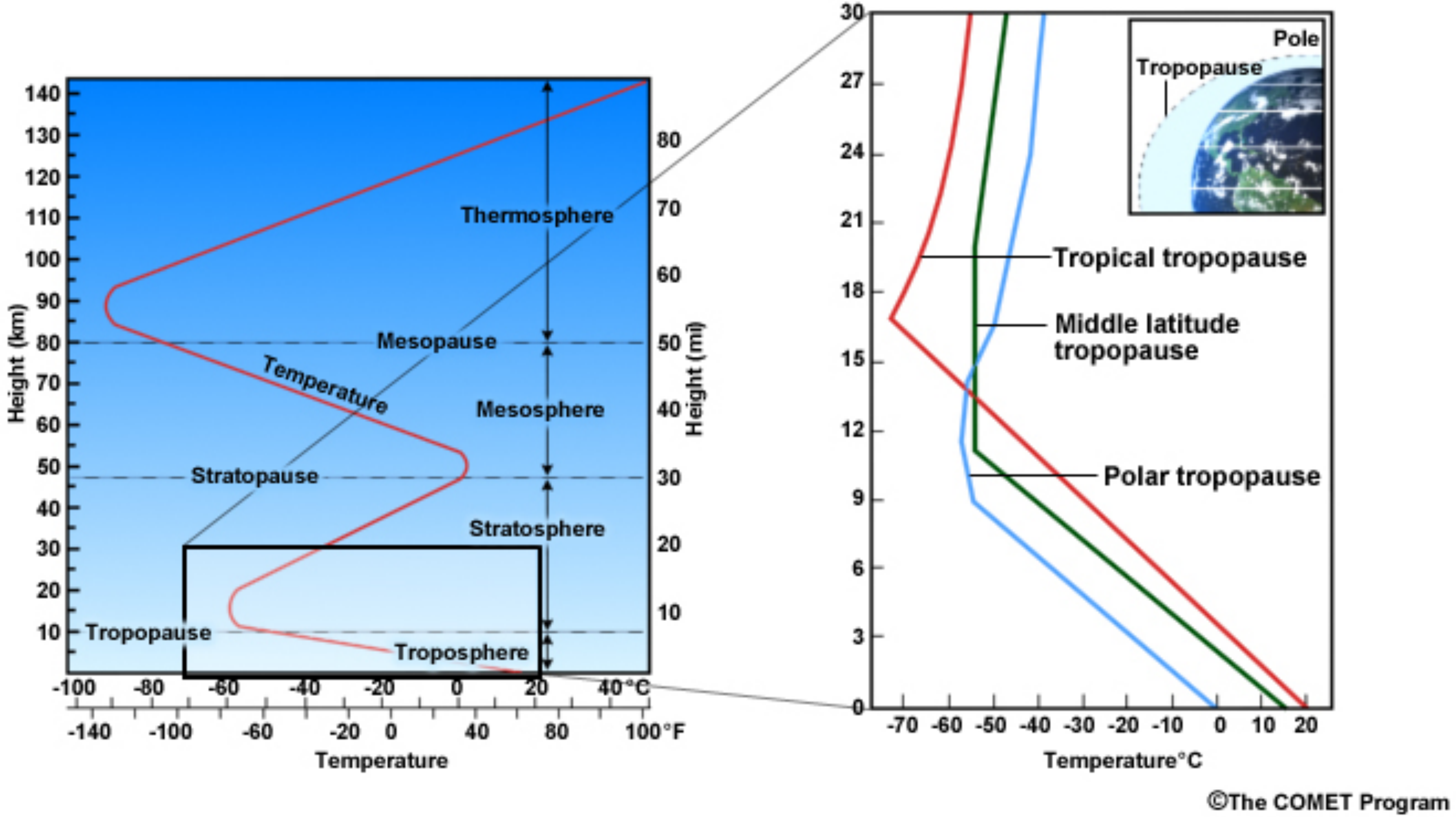
Vertical Structure of the Earth's Atmosphere

The Earth's atmosphere roughly consists of four distinct layers: from bottom to top they are the **troposphere**, the **stratosphere**, the **mesosphere**, and the **thermosphere**.

These layers are distinguished by how temperature changes with altitude, and separated by regions of relatively constant temperatures: the **tropopause** (above the troposphere), the **stratopause** (above the stratosphere), and the **mesopause** (above the mesosphere).



Temperature Profile of the Earth's Atmosphere



©The COMET Program

Temperature Profile of the Earth's Atmosphere

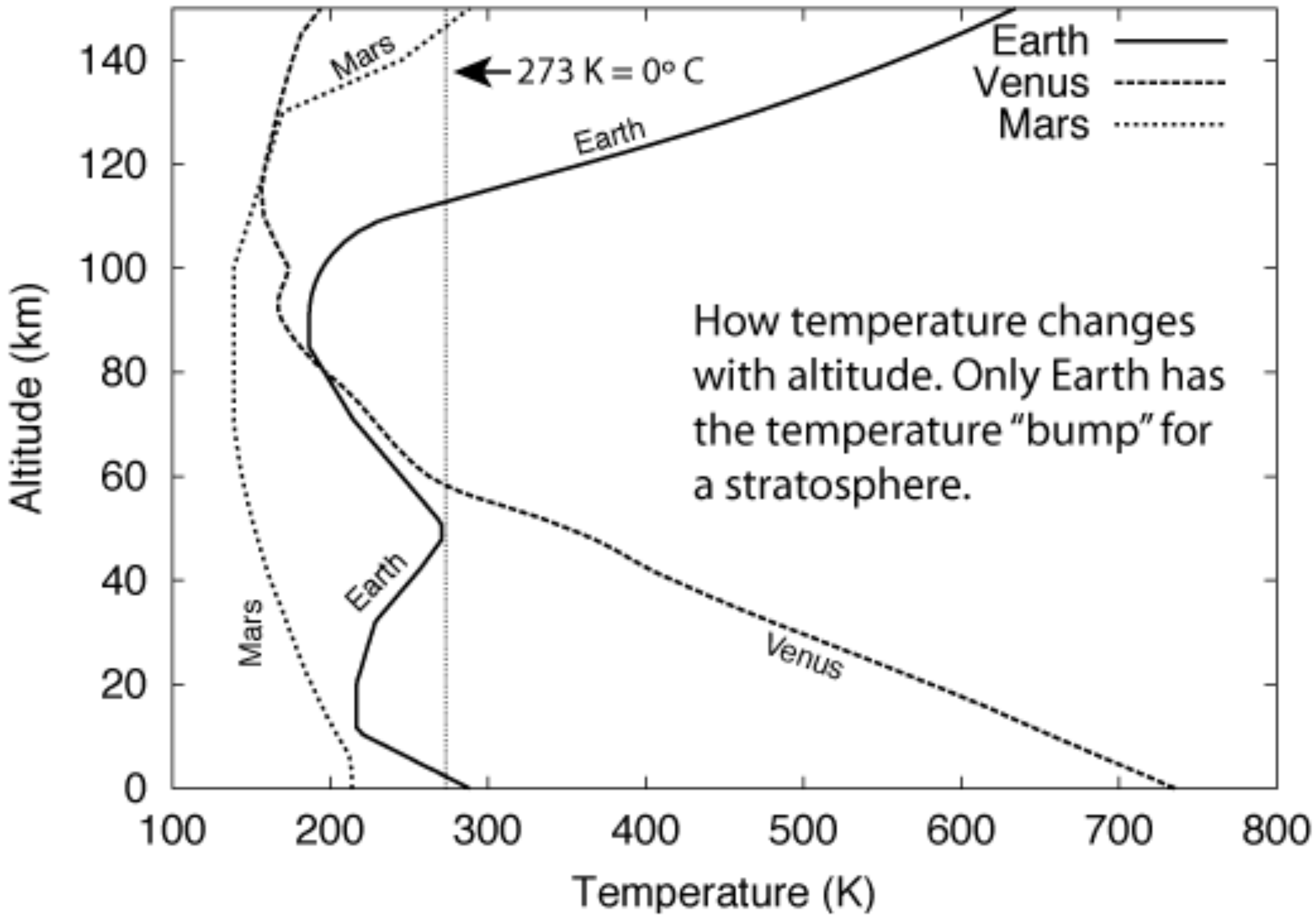
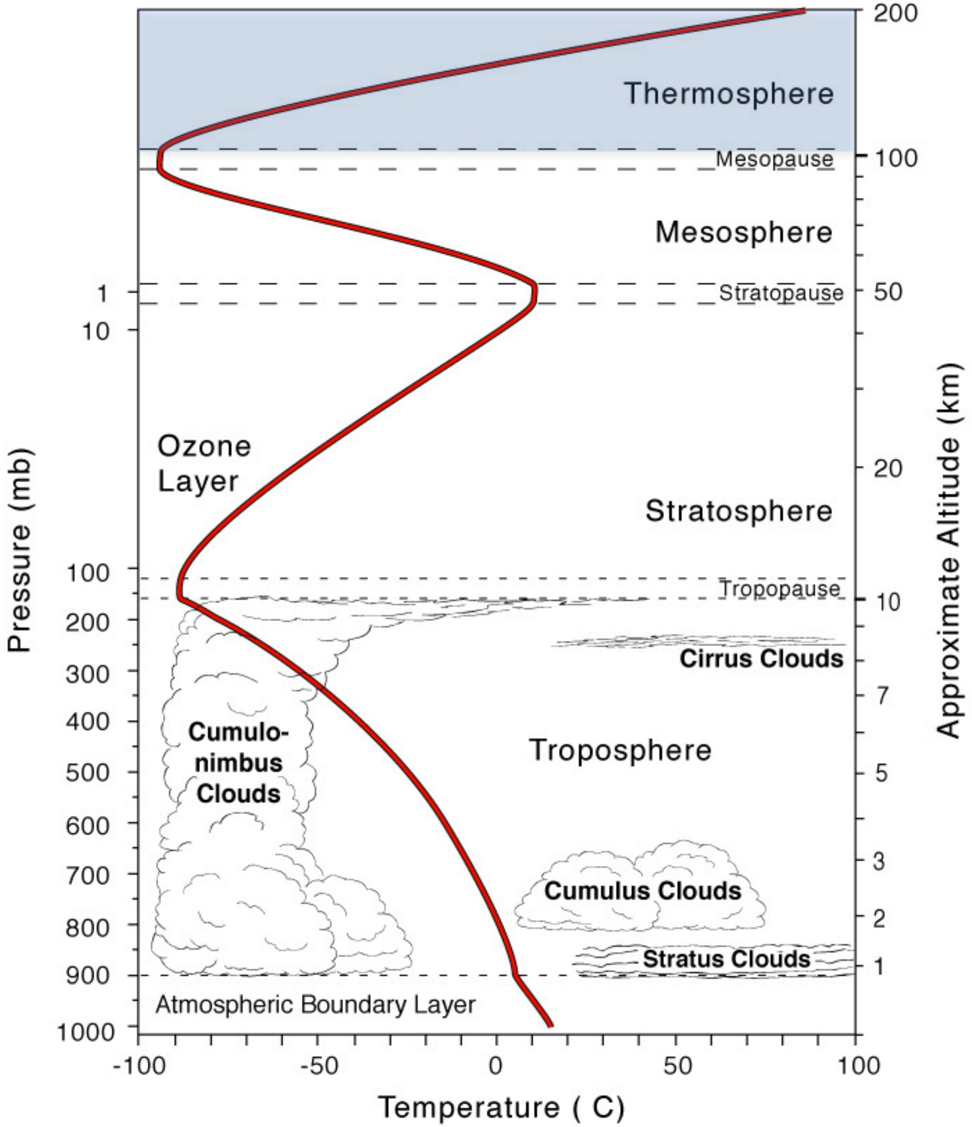


Figure: Vertical temperature profiles from Mars, Earth and Venus. Copyright Nick Strobel [http://www.astronomynotes.com/solarsys/s3c.htm]

Vertical Structure (Thermosphere)

Thermosphere: (Edge of Space) Temperature is very high and variable. Short wavelength ultraviolet radiation is absorbed here by oxygen. Molecules are dissociated with high-energy ultraviolet radiation from the sun (λ < 0.1 μm). Temperatures can get very high (up to 1000K), even though air density is very low.



Vertical Structure (Thermosphere)

Auroras are produced when the solar wind disturbs the magnetosphere and causes charged particles to be deflected into the thermosphere / exosphere.

https://commons.wikimedia.org/wiki/File:Northern_Lights_02.jpg

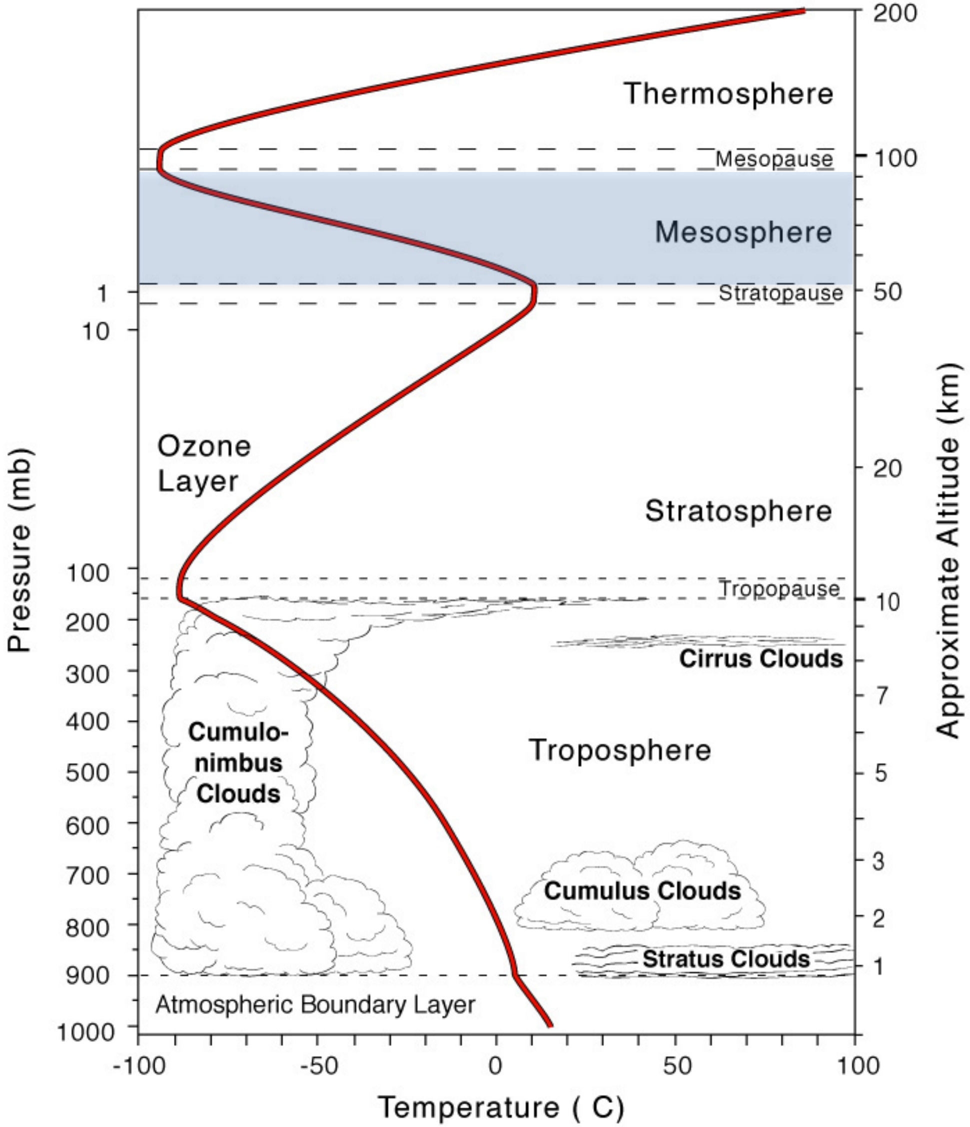
Vertical Structure (Mesosphere)

Mesosphere: Temperature increases towards the surface in this layer, driven by increased ozone concentration.

Ozone: Presence of ozone is driven by *photodissociation* of oxygen:

$$O_2 + h\nu \rightarrow O + O$$
$$O + O_2 + M \rightarrow O_3 + M$$

Maximum concentration of **ozone is closer to 20km-30km**, but its strong opacity to solar radiation leads to **higher temperatures near 50km**.



Vertical Structure (Stratosphere)

Ozone: Presence of ozone is driven by *photodissociation* of oxygen through the Chapman process:

$$O_2 + h\nu \rightarrow O + O$$

$$O + O_2 + M \rightarrow O_3 + M$$

Maximum concentration of ozone is **closer to 20km-30km**, but its strong opacity to solar radiation leads to **higher temperatures near 50km**.

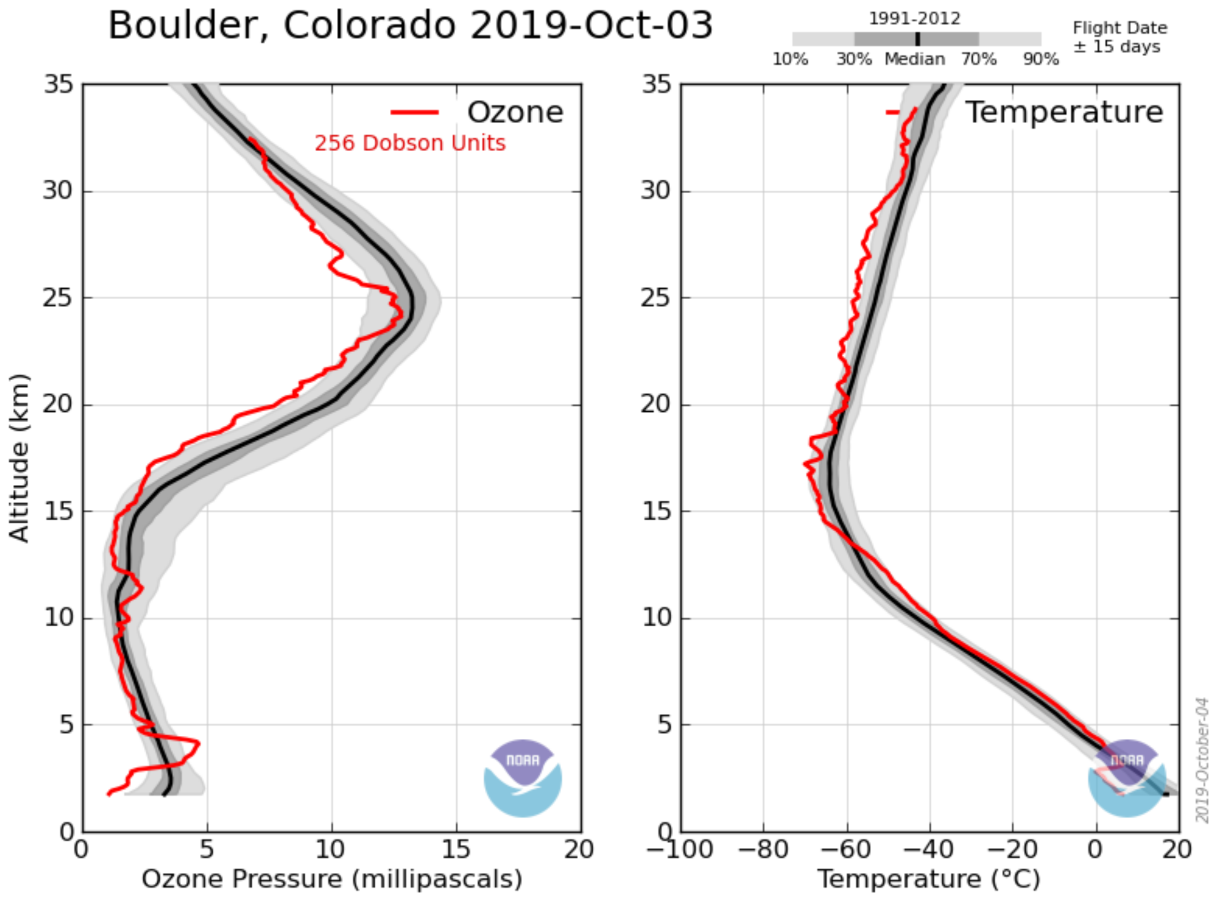
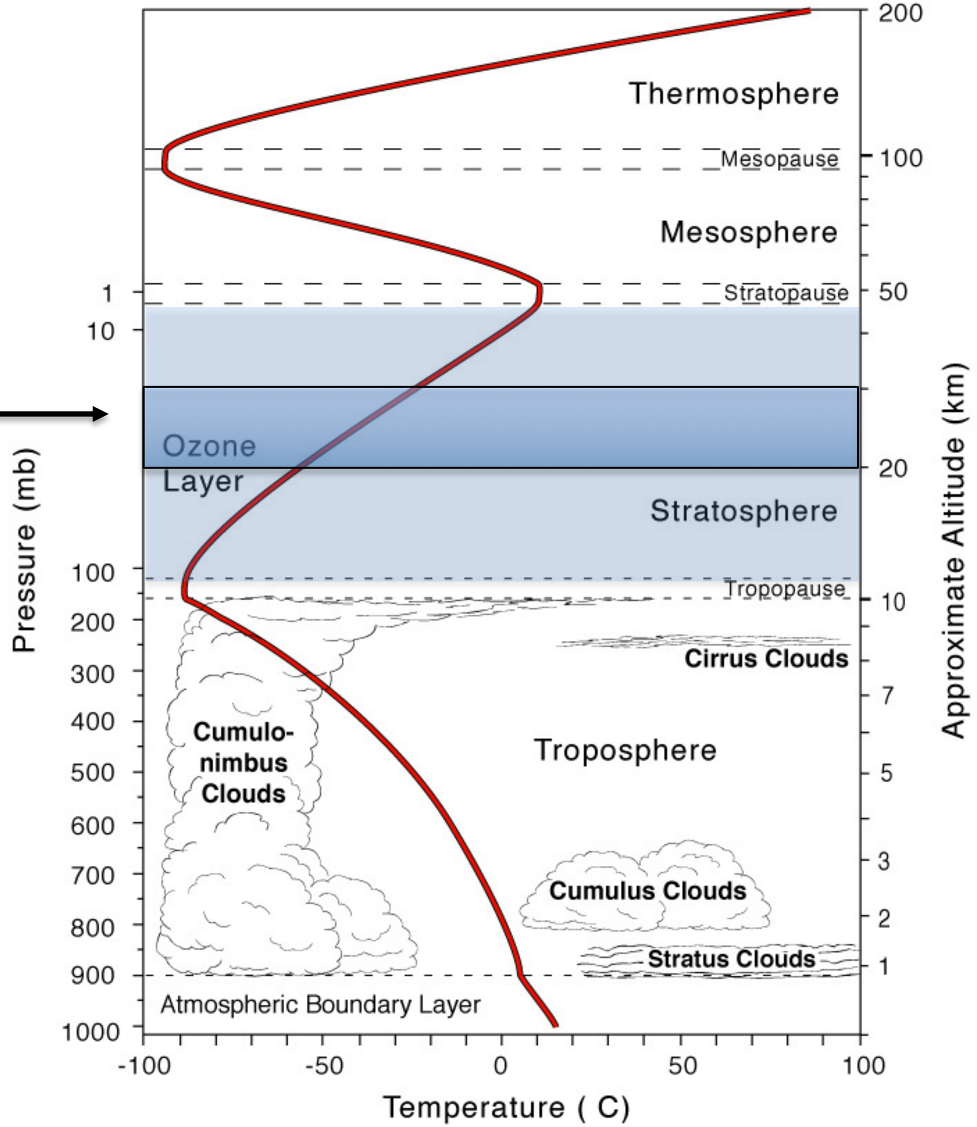


Figure: A NOAA ozonesonde vertical profile from Boulder Colorado on October 3^{rd}, 2019.

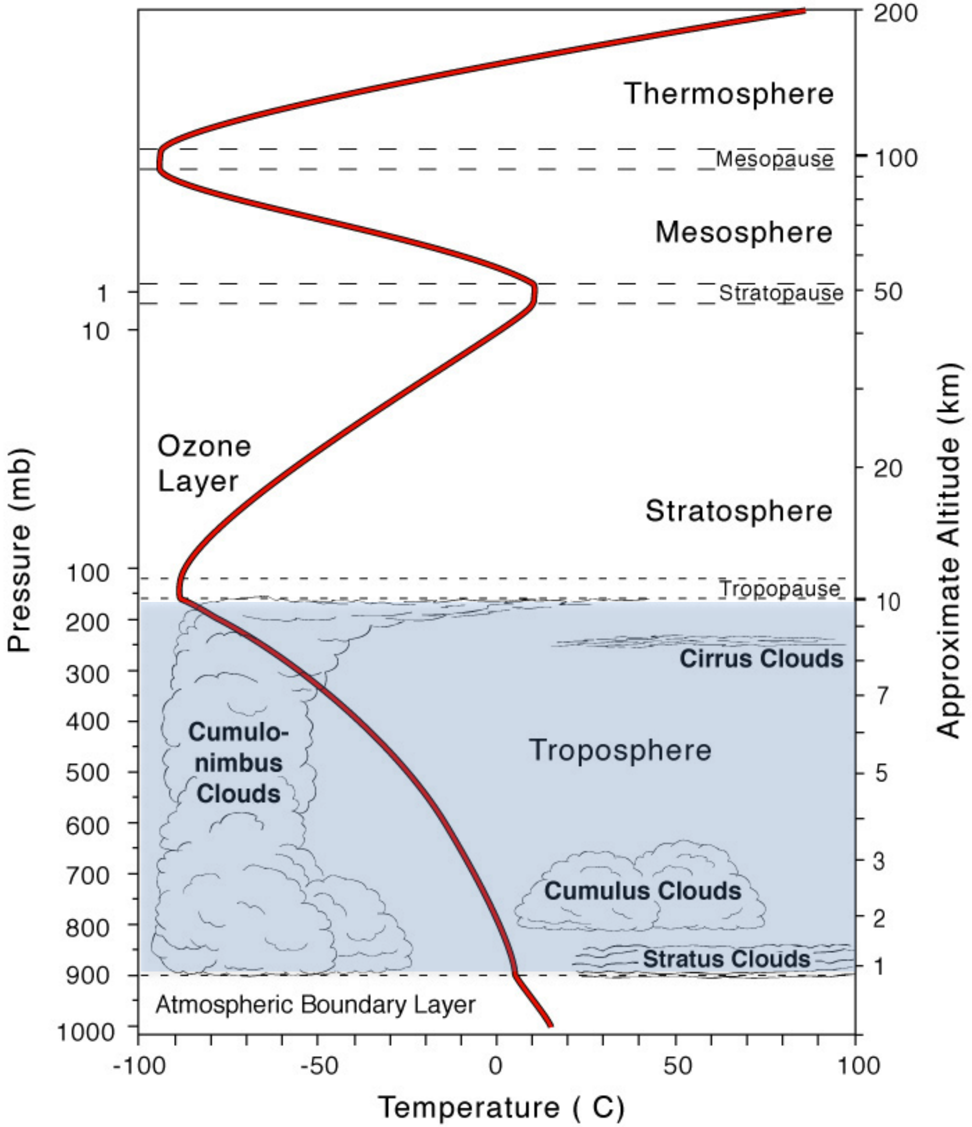
Vertical Structure (Stratosphere)

Stratosphere: Exhibits a temperature increase with altitude due to the presence of the **ozone layer**. The stratosphere is highly stratified and poorly mixed (the increase in temperature with altitude makes the atmosphere very stable).


Ozone max.

Vertical Structure (Troposphere)

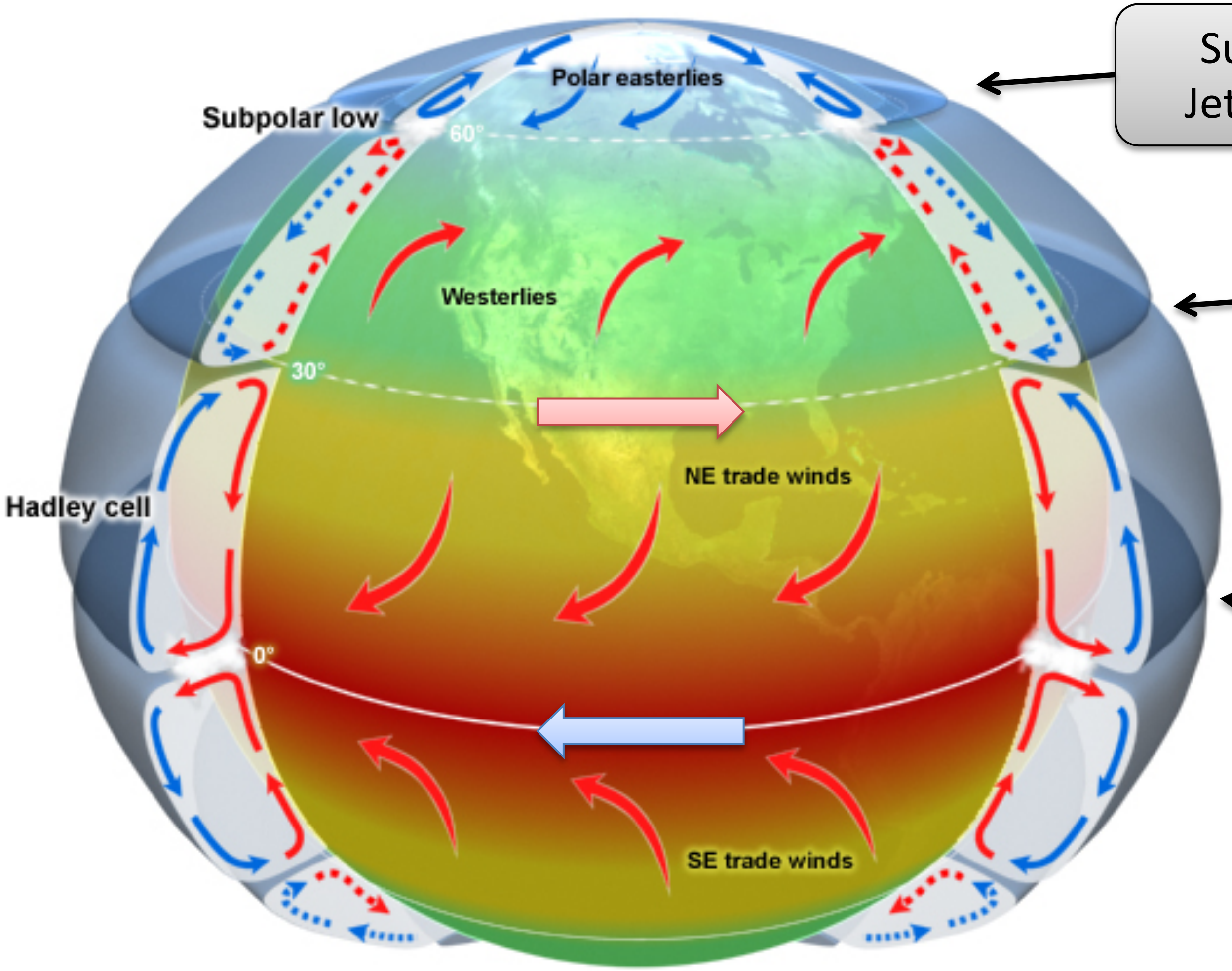
Troposphere: Below the tropopause (typically located between 8-16km depending on latitude and season), temperature increases strongly towards the surface. It contains about **85% of the atmosphere's mass** and essentially **all the water vapor**.



Vertical Structure (Troposphere)

Anvil clouds like these form because rising (buoyant) tropospheric air cannot rise into the stable stratosphere.

Tropospheric General Circulation



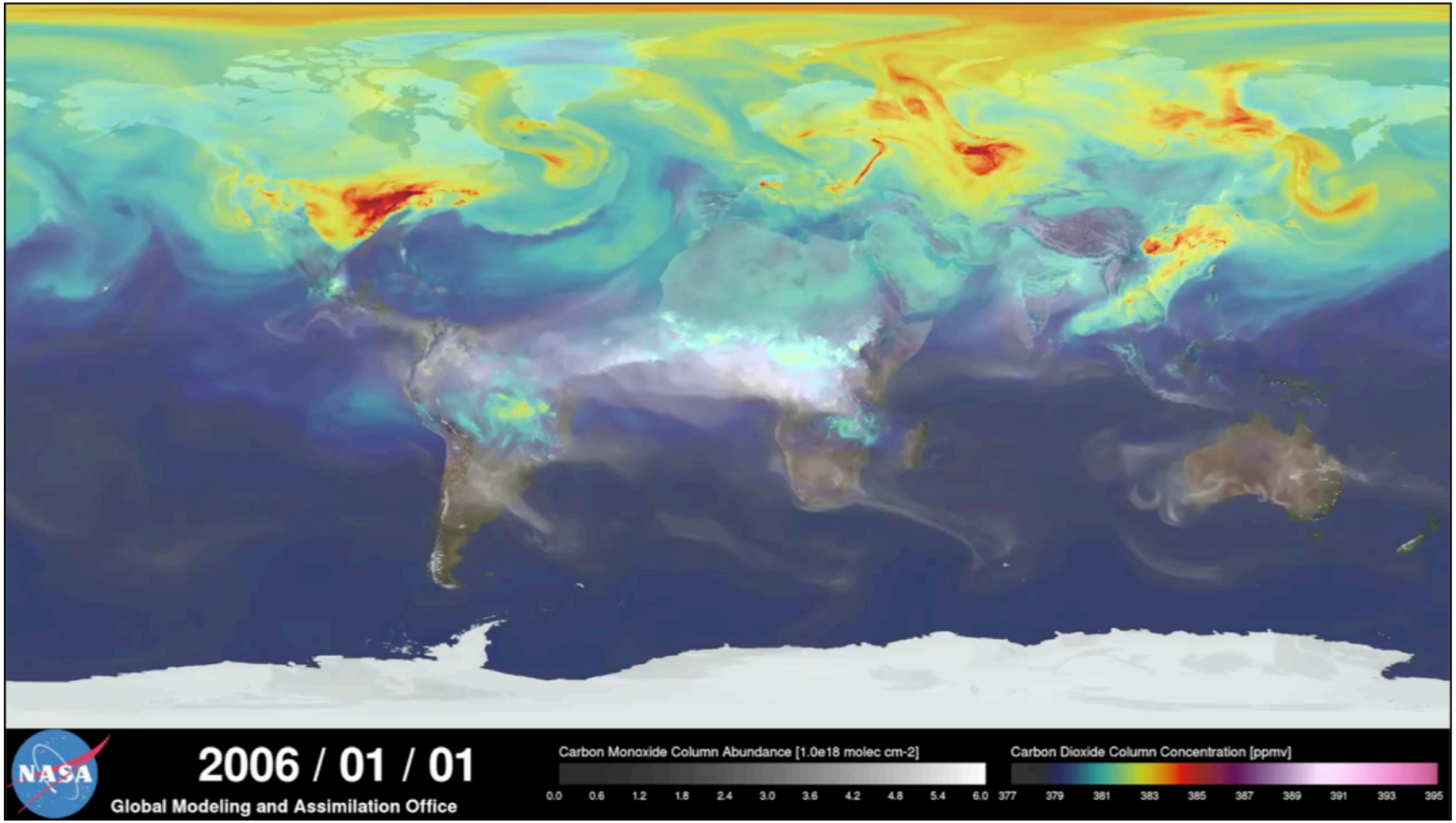
Subpolar
Jet Stream

Subtropical
Jet Stream

Intertropical
Convergence Zone
(ITCZ, rising motion)

Coriolis force directs winds “to the right” in the Northern hemisphere and “to the left” in the Southern hemisphere.

Global Atmospheric Dynamics



https://www.youtube.com/watch?v=x1SgmFa0r04

Water Vapor in the Atmosphere

Properties of Dry Air

(at standard temperature and pressure)

Specific heat at constant pressure	c_p	$1005\ \mathrm{J\ kg^{-1}\ K^{-1}}$
Specific heat at constant volume	c_v	$718\ \mathrm{J\ kg^{-1}\ K^{-1}}$
Ratio of specific heats	γ	1.40
Density at 273K, 1013 mbar	ρ_0	$1.293\ \mathrm{kg\ m^{-3}}$
Viscosity at STP	μ	$1.73 \times 10^{-5}\ \mathrm{kg\ m^{-1}\ s^{-1}}$
Kinematic Viscosity at STP	$\upsilon=\mu/\rho_0$	$1.34 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$
Thermal conductivity at STP	K	$2.40 \times 10^{-2}\ \mathrm{W\ m^{-2}\ K^{-1}}$
Gas constant for dry air	R_d	$287.05\ \mathrm{J\ kg^{-1}\ K^{-1}}$

Thermodynamics of Dry Air

Governed by **ideal gas law**:

$$p_d = \rho_d \frac{R_g}{m_a} T = \rho_d R_d T$$

Ideal gas constant

$$R_g = 8.3143 \text{ J K}^{-1} \text{ mol}^{-1}$$

Specific gas constant for dry air

$$R_d = \frac{R_g}{m_a} = 287 \text{ J kg}^{-1} \text{ K}^{-1}$$

Where m_a is the molecular mass of dry air

$$m_a = 28.9647 \text{ g mol}^{-1}$$

Thermodynamics of Moist Air

Governed by **ideal gas law**:

$$e = \rho_v R_v T$$

Partial pressure of water vapor

$$p_d = \rho_d R_d T$$

Partial pressure of dry air

$$p = e + p_d$$

Total pressure of air

$$(e \ll p_d \implies p \approx p_d)$$

Specific gas constant for water vapor

$$R_v = \frac{R_g}{m_v} = 461.5\ \mathrm{J\,kg^{-1}\,K^{-1}}$$

Where m_v is the molecular mass of water vapor

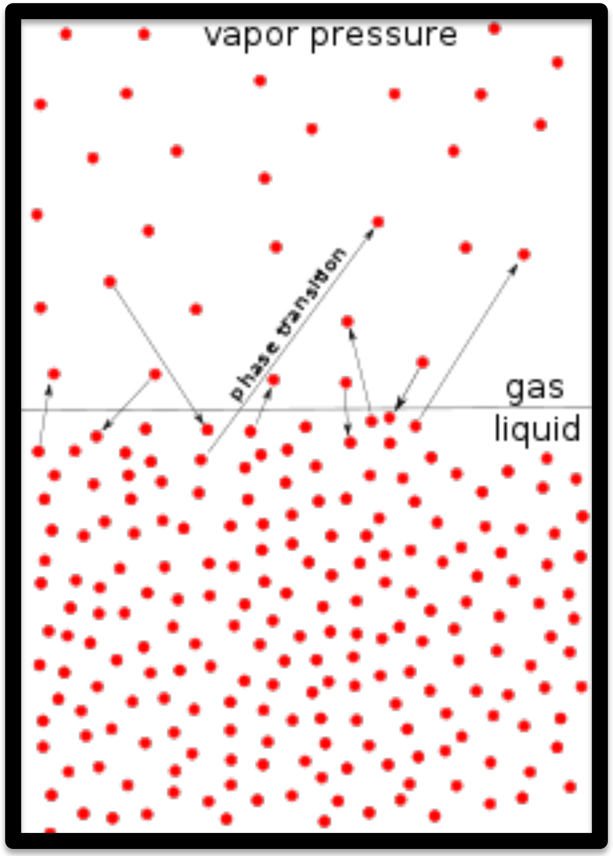
$$m_v = 18.0153\ \mathrm{g\,mol^{-1}}$$

Thermodynamics of Moist Air

When both liquid water and water vapor are present in a closed system, it will tend to equilibrate so that the number of water molecules **leaving the liquid phase (evaporation) equals the number of water molecules entering the liquid phase (condensation).**

When this equilibrium occurs the air is said to be **saturated with water vapor**.

If more water vapor is then added, or if the temperature of the system is reduced, then the condensation rate will be greater than the evaporation rate until equilibrium is returned.



https://en.wikipedia.org/wiki/Vapor_pressure

Thermodynamics: Clausius-Clapeyron

Definition: The partial pressure of water vapor that can exist at a given temperature is determined by the **Clausius-Clapeyron relationship.**

$$\frac{de_s}{dT} = \frac{L_v(T)e_s}{R_v T^2}$$

Specific latent heat of vaporization of water

$$L_v \approx 2.5 \times 10^6 \text{ J kg}^{-1}$$ at 0°C

Typically temperature dependence of latent heat of vaporization cannot be ignored, and empirical relations are often used. In practice this equation is approximated by

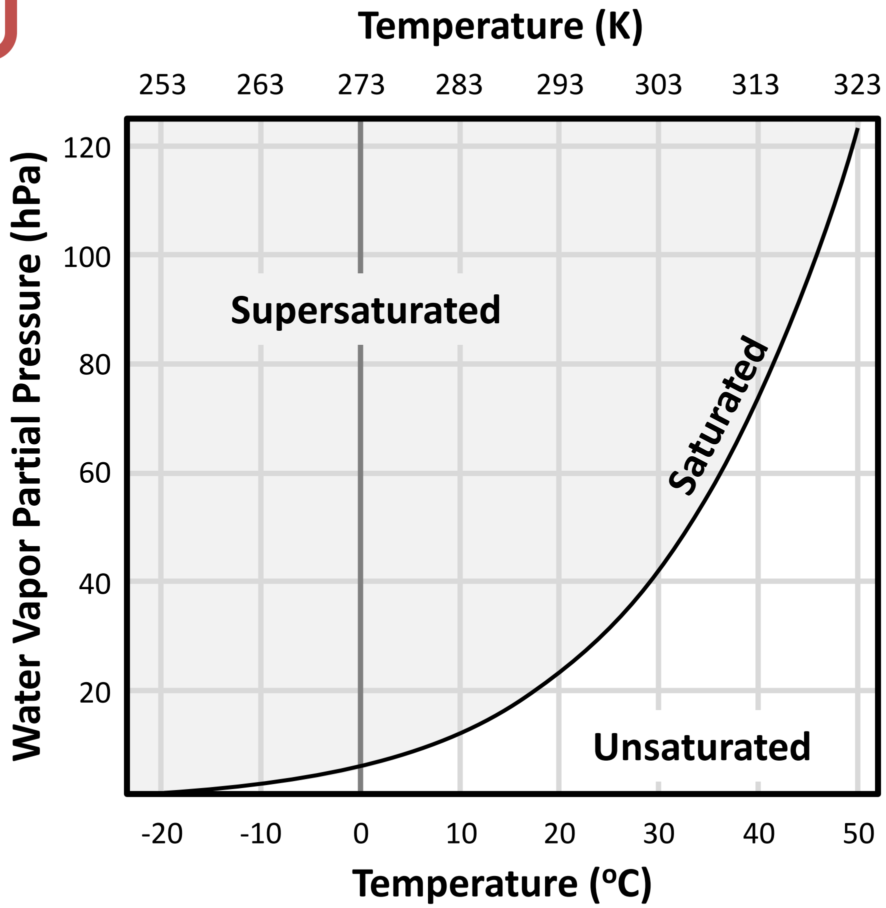
$$e_s(T) = 6.1094 \text{ hPa} \times \exp\left(\frac{17.625T}{T + 243.04}\right)$$ T in °C

Note that Marshall and Plumb use an even simpler expression.

Thermodynamics: Clausius-Clapeyron

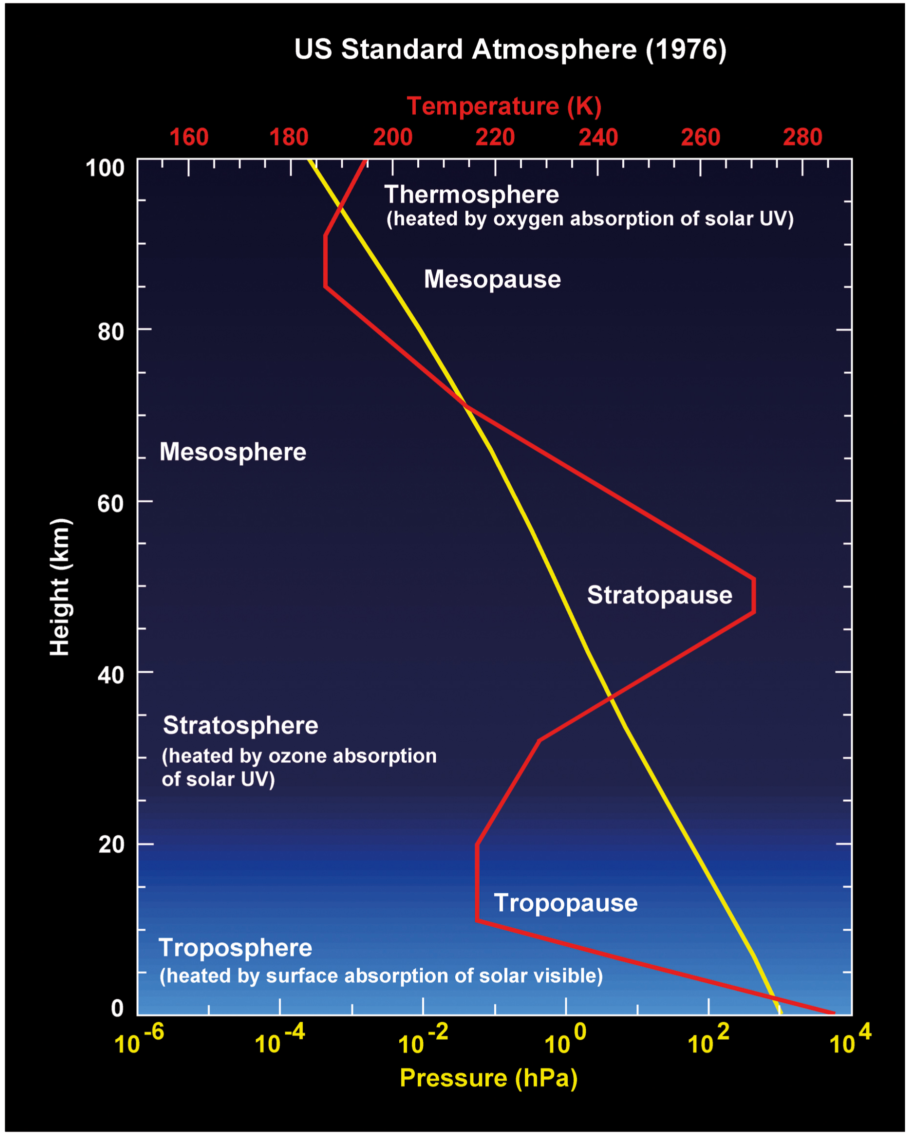
$$e_s(T) = 6.1094\ \mathrm{hPa} \times \exp\left(\frac{17.625T}{T+243.04}\right) \quad T \text{ in °C}$$

In the atmosphere vapor pressure is constrained by $e \leq e_s(T)$ since additional water vapor would immediately condense out in the form of liquid. Namely, air is either unsaturated or saturated – supersaturated air is not observed in nature.



Consequences of Clausius-Clapeyron

- Moisture in the atmosphere decays rapidly with height. Why?
- Air in the tropics tends to be much more moist than air over the poles. Why?
- Precipitation occurs when moist air is cooled by convection. How? What is the temperature decrease associated with adiabatic lifting?



More on Condensation

- Condensation typically requires the presence of condensation nuclei (sulfates, dust, smoke from fires, ocean salt). These provide surfaces for water to stick to and initiate the condensation process.

Definition: The dew point temperature is the temperature to which air must be cooled (at constant pressure and constant water vapor concentration) to reach saturation.

- Clouds consist of liquid water droplets that are formed by condensation of water onto condensation nuclei (when T falls below the dew point).

- Overnight cooling due to radiation can drop the temperature to the dew point. How would we see the effects of this phenomena?

Cloud in a Bottle

Cloud condensation “within a bottle” can be observed by adding warm water and condensation nuclei to the bottle, allowing the air above the water to come to saturation, and then pumping out air from within the bottle.

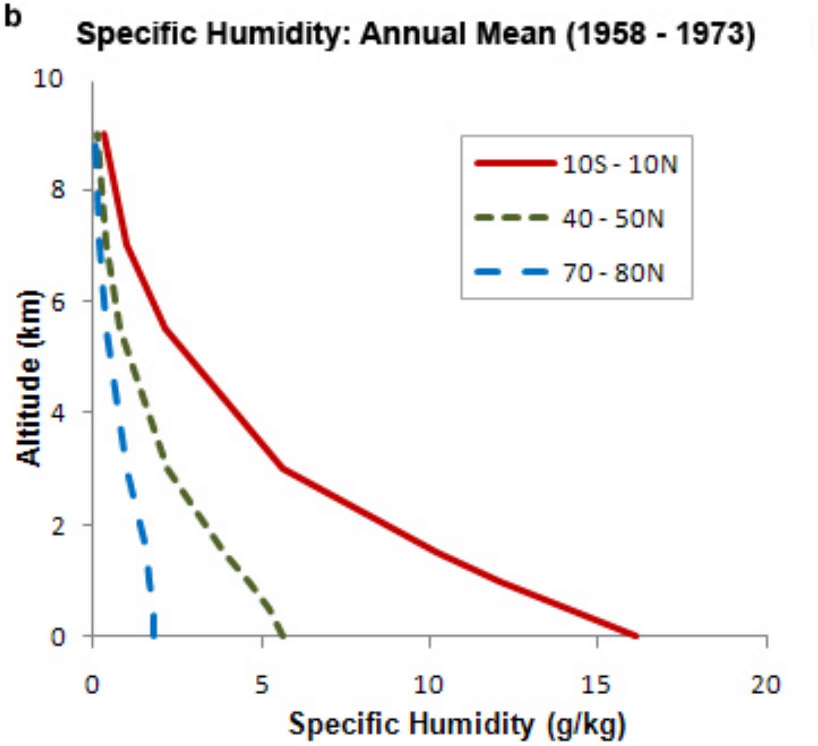
Can you explain why this process occurs?

Vertical Distribution of Water Vapor

As explained by the Clausius-Clapeyron relationship, warm air has greater capacity to “hold” moisture than cold air.

Consequently water vapor in the atmosphere (specific humidity) tends to drop off rapidly with altitude.

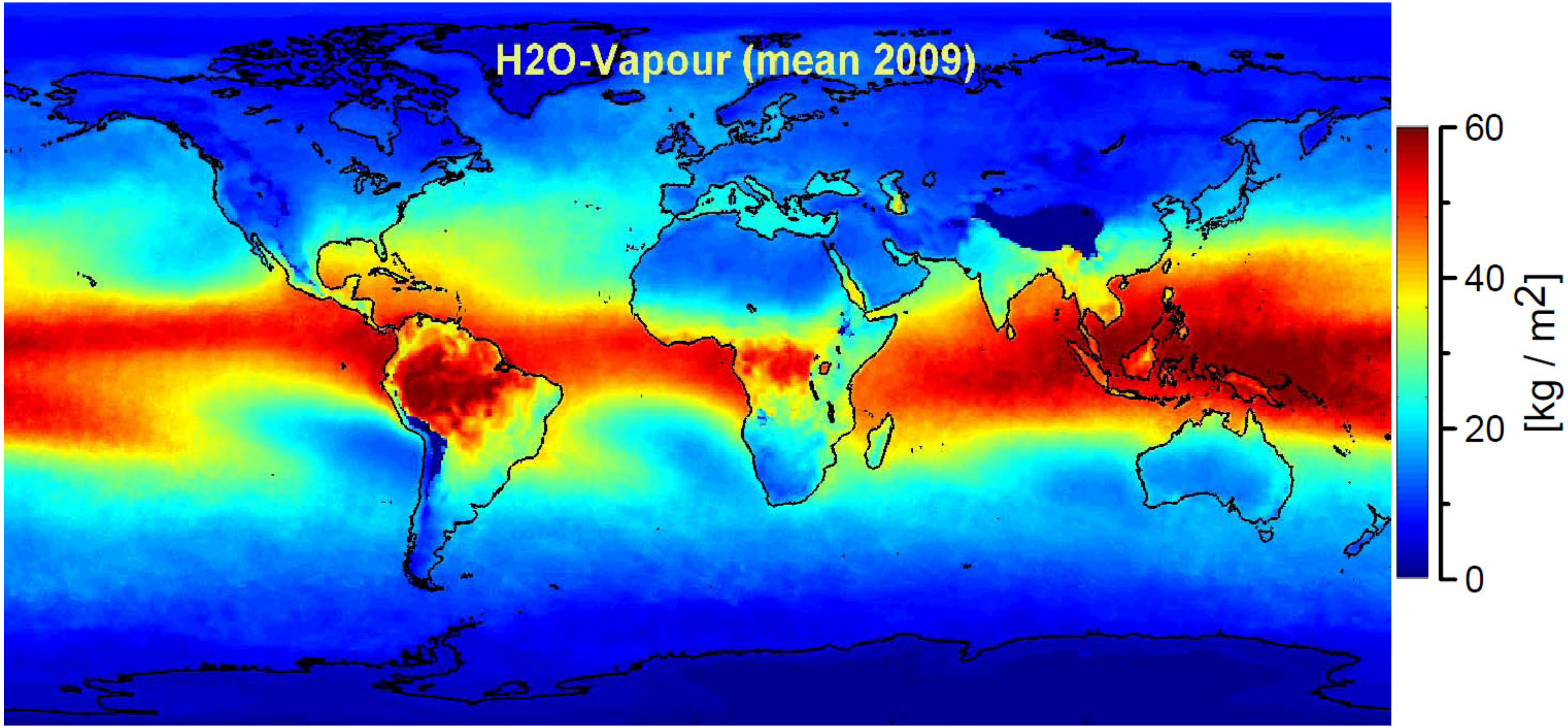
With sufficient water availability, this makes the tropical near-surface the most humid area on Earth.



Data courtesy Oort, 1983 / The COMET Program

Figure: Annual mean water vapor content (in g/kg) plotted against altitude.

Meridional Distribution of Water Vapor



Global mean water vapor column for 2009 derived from GOME-2 measurements

(Thomas Wagner (MPI-C), Steffen Beirle (MPI-C), Diego Loyola (DLR), Kornelia Mies (MPI-C), Sander Slijkhuis (DLR))

ATM 241 Climate Dynamics
Lecture 3
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Thank You!