Fundamentals of Earth's Atmospheric Structure & Circulation (with some comments on the Global Ocean)

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2024
https://umd.instructure.com/courses/1367293

Goals:

1) Barometric law (pressure vs height)
2) Thermal structure (temperature vs height)
3) Geostrophy (balance of pressure force & Coriolis Force ⇨ storms)
4) Ferrel circulation (mean circulation Earth's atmosphere ⇨ climate regimes)
5) Features of the global ocean temperature and circulation

Lecture 3

5 September 2024

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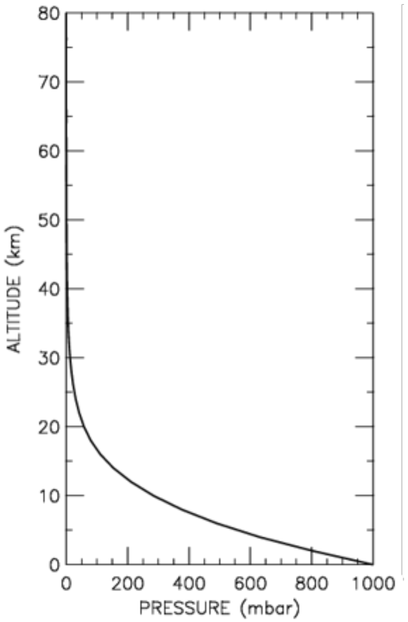
Pressure versus Altitude



- **Pressure = Force per unit area**
- **Graph shows how "force" of atmosphere varies as a function of altitude**
- **Pressure shown in units of mbar : 1 mbar = 10^3 dynes/cm^2**
- **1 dyne = gm cm / sec^2; therefore 1 mbar = 10^3 gm / cm sec^2**
- **Also:**
  - **European community prefers to write hPa; 1 hPa is exactly equal to 1 mbar**
  - **1 atmosphere = $p/p_{STANDARD}$, where $p_{STANDARD}$ = 1013.25 mbar (or 1013.25 hPa)**

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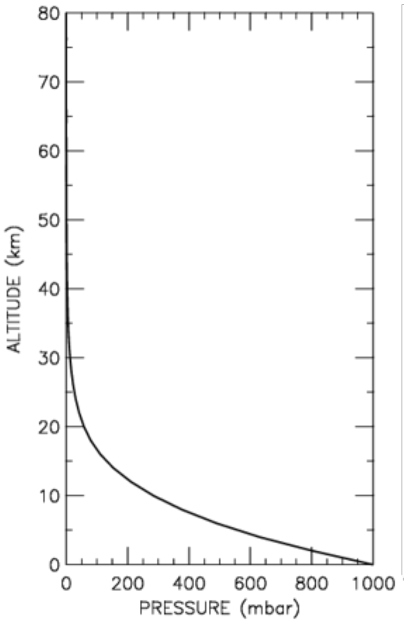
Pressure versus Altitude



Derivation of the Barometric Law involves use of the Ideal Gas Law:

$$p\ Vol = n\ R\ \mathrm{T}$$

where p is pressure, Vol is volume, n is the number of moles of a gas,

R is the gas constant ($8.3143 \times 10^7\ \frac{\text{ergs}}{\text{K mole}}$), and T is temperature

as shown on Extra Slide 1 at end of Class Notes (you will not be tested on this!)

- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

Pressure (z) = Pressure (surface) $\times\ e^{-z/H}$

where H is called the "scale height"

Can show H = R_{EARTH} T (z) / *grav* ,

Since R_{EARTH} = 2.88×10^6 ergs / K gm

***grav* = 981 cm sec^{-2} and T(lower trop) ≈ 272 K**

then H (z=0) = 8.0×10^5 cm = 8 km

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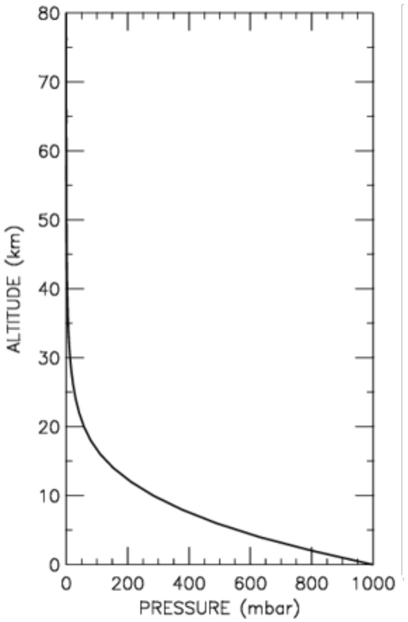
Pressure versus Altitude



In modern atmospheric sciences, the most handy version of the Ideal Gas Law is:

$$p = M\ k\ \mathrm{T}$$

where p is pressure (force per unit area), M is number density (molecules/volume), k is Boltzmann's constant (1.38×10^{-16} ergs/K), and T is temperature.

If p is given in units of mbar (or hPa), M is in units of $\frac{\text{molecules}}{\text{cm}^3}$, and T is in K, then can show k must be $1.38 \times 10^{-19}\ \frac{\text{mbar cm}^3}{\text{K molecules}}$

- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

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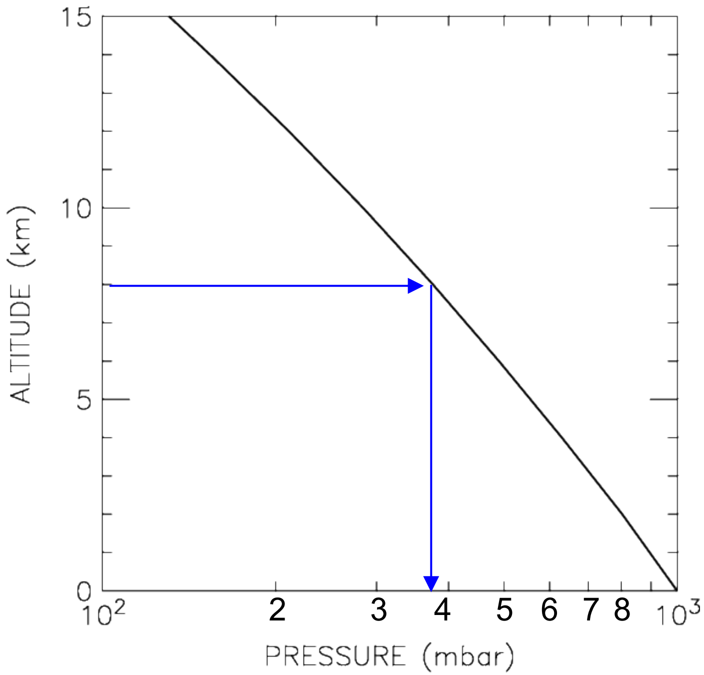
Pressure versus Altitude



p (z=0) = 1013.25 mbar

p (z=8 km) =

- **Barometric law describes the variation of Earth's pressure with respect to altitude:**

Pressure (z) = Pressure (surface) × $e^{-z/H}$

Let's take a closer look at log pressure versus altitude, in the troposphere

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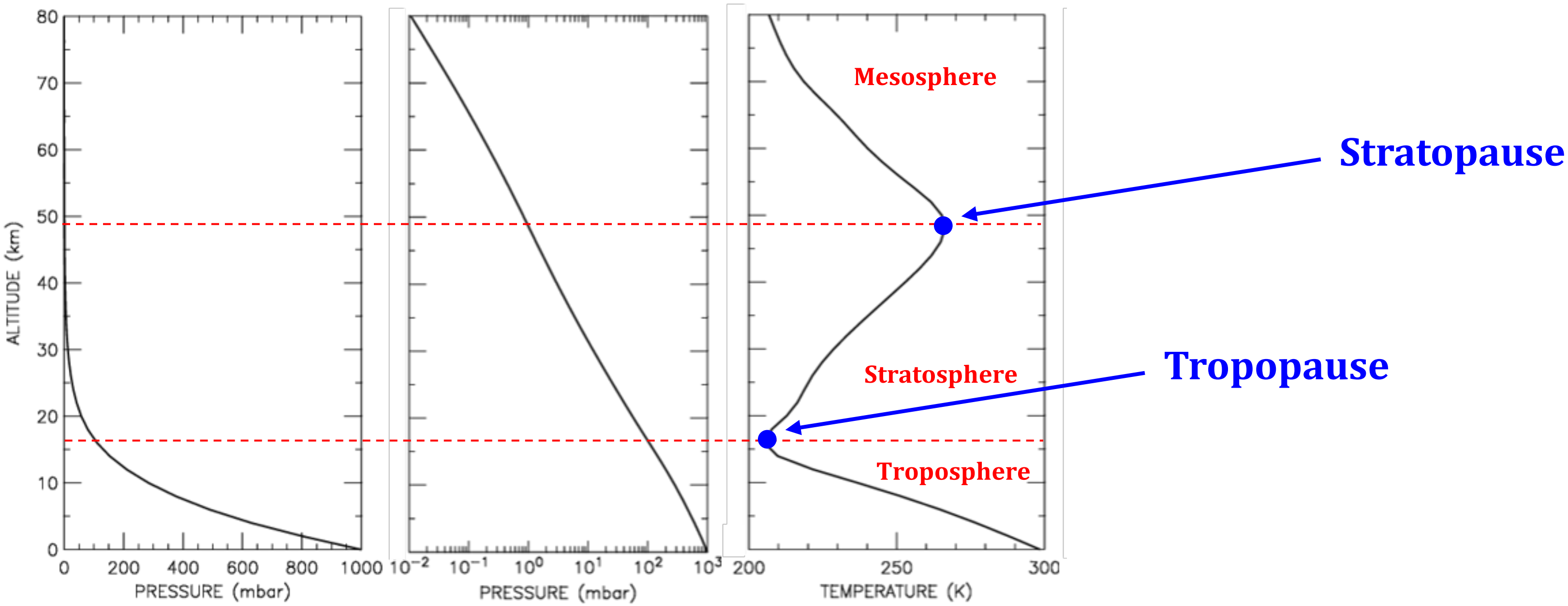
Temperature versus Altitude



- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

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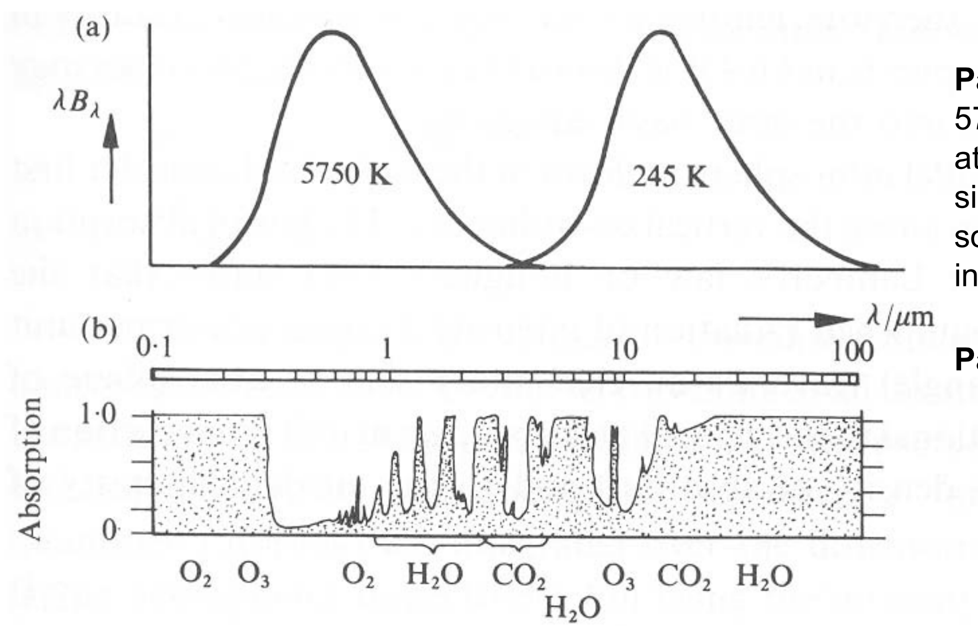
Atmospheric Radiation

- Solar irradiance (downwelling) at top of atmosphere occurs at wavelengths between ~200 and 2000 nm (~5750 K "black body" temperature)
- Thermal irradiance (upwelling) at top of the atmosphere occurs at wavelengths between ~5 and 50 μm (~245 K "black body" temperature)



Panel (a): Black-body energy versus wavelength for 5750 K (Sun's approx T) and 245 K (Earth's mean atmospheric T). Curves are drawn with equal area since integrated over entire Earth, at top atmosphere, solar downwelling and terrestrial upwelling fluxes are in close balance.

Panel (b): absorption by atmospheric gases: 1.0 represents complete absorption.

From Houghton, *Physics of Atmospheres*, 1991

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Atmospheric Radiation

THE GREENHOUSE EFFECT 23

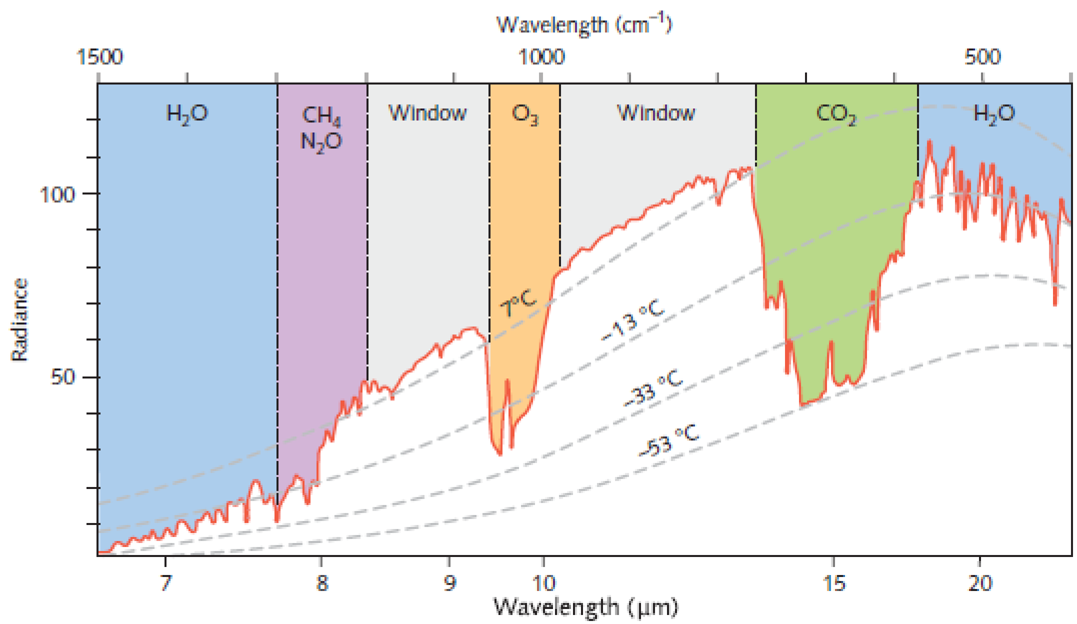

Figure 2.5 Thermal radiation in the infrared region (the visible part of the spectrum is between about 0.4 and 0.7 μm) emitted from the Earth's surface and atmosphere as observed over the Mediterranean Sea from a satellite instrument orbiting above the atmosphere, showing parts of the spectrum where different gases contribute to the radiation. Between the wavelengths of about 8 and 14 μm, apart from the ozone band, the atmosphere, in the absence of clouds, is substantially transparent; this is part of the spectrum called a 'window' region. Superimposed on the spectrum are curves of radiation from a black body at 7°C, −13°C, −33°C and −53°C. The units of radiance are milliwatts per square metre per steradian per wavenumber.

Fig 2.5, *Global Warming (5th Edition)*, Houghton

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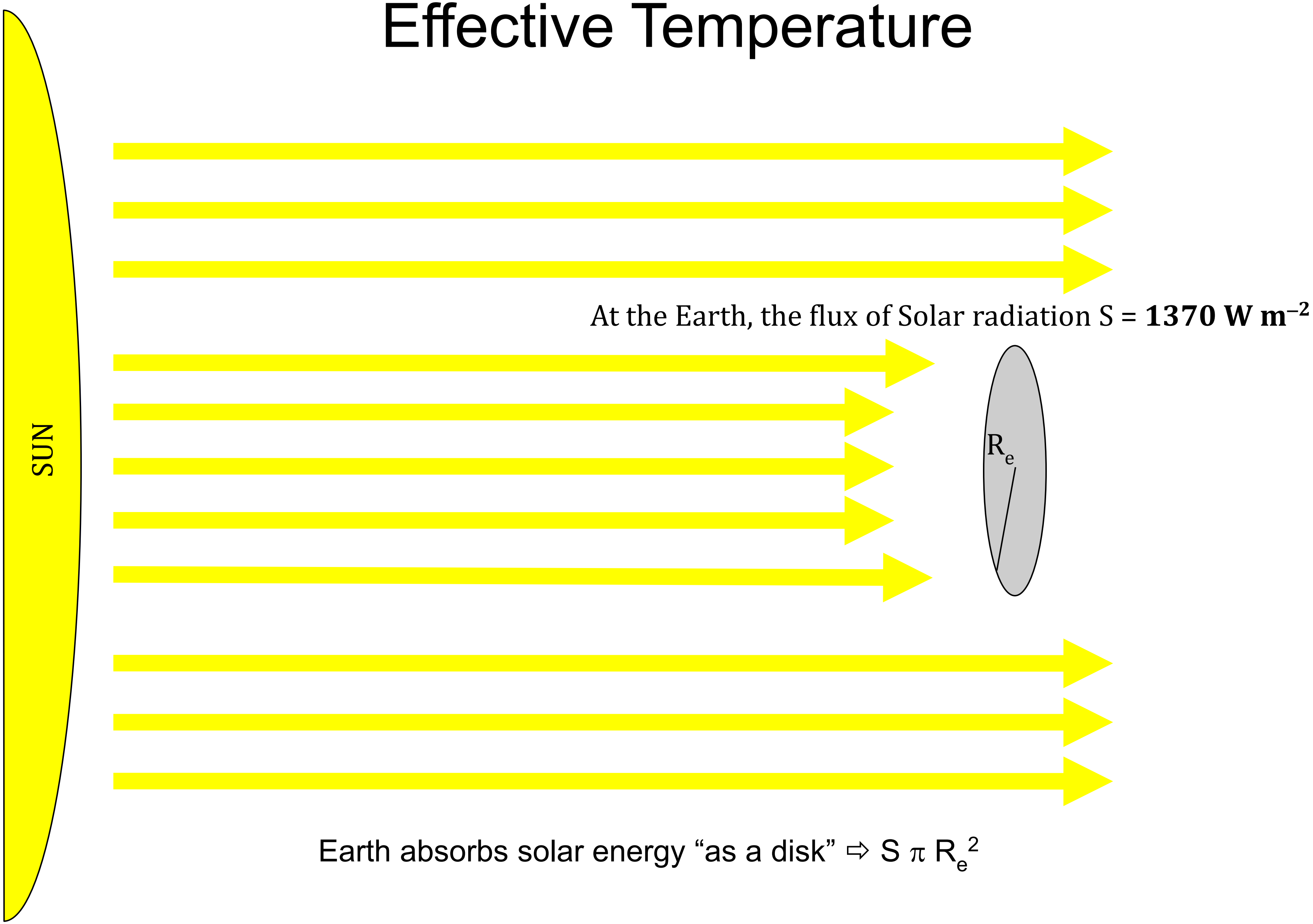
Effective Temperature



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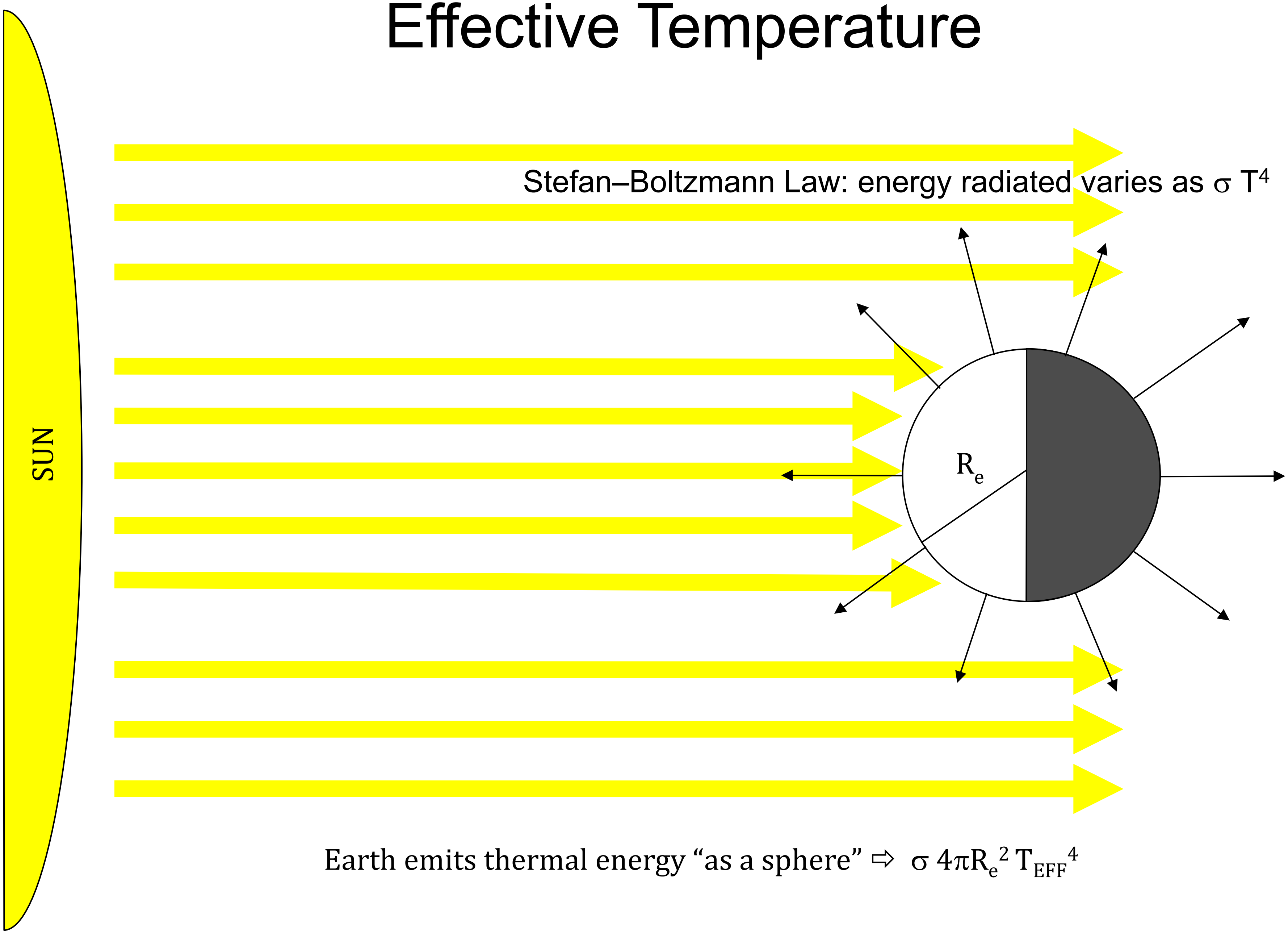
Effective Temperature



Earth emits thermal energy "as a sphere" ⇨ $\sigma 4\pi R_e^2 T_{EFF}^4$

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Effective Temperature

Earth absorbs solar energy "as a disk" ⇨ $(1 - \text{Albedo}) \times S \, \pi \, R_e^2$

Earth emits thermal energy "as a sphere" ⇨ $\sigma \, 4\pi R_e^2 \, T_{EFF}^4$

$$(1 - \text{Albedo}) \times S = 4 \, \sigma \, T_{EFF}^4$$

or

$$T_{EFF} = \{ (1 - \text{Albedo}) \times S \; / \; 4 \, \sigma \}^{1/4}$$

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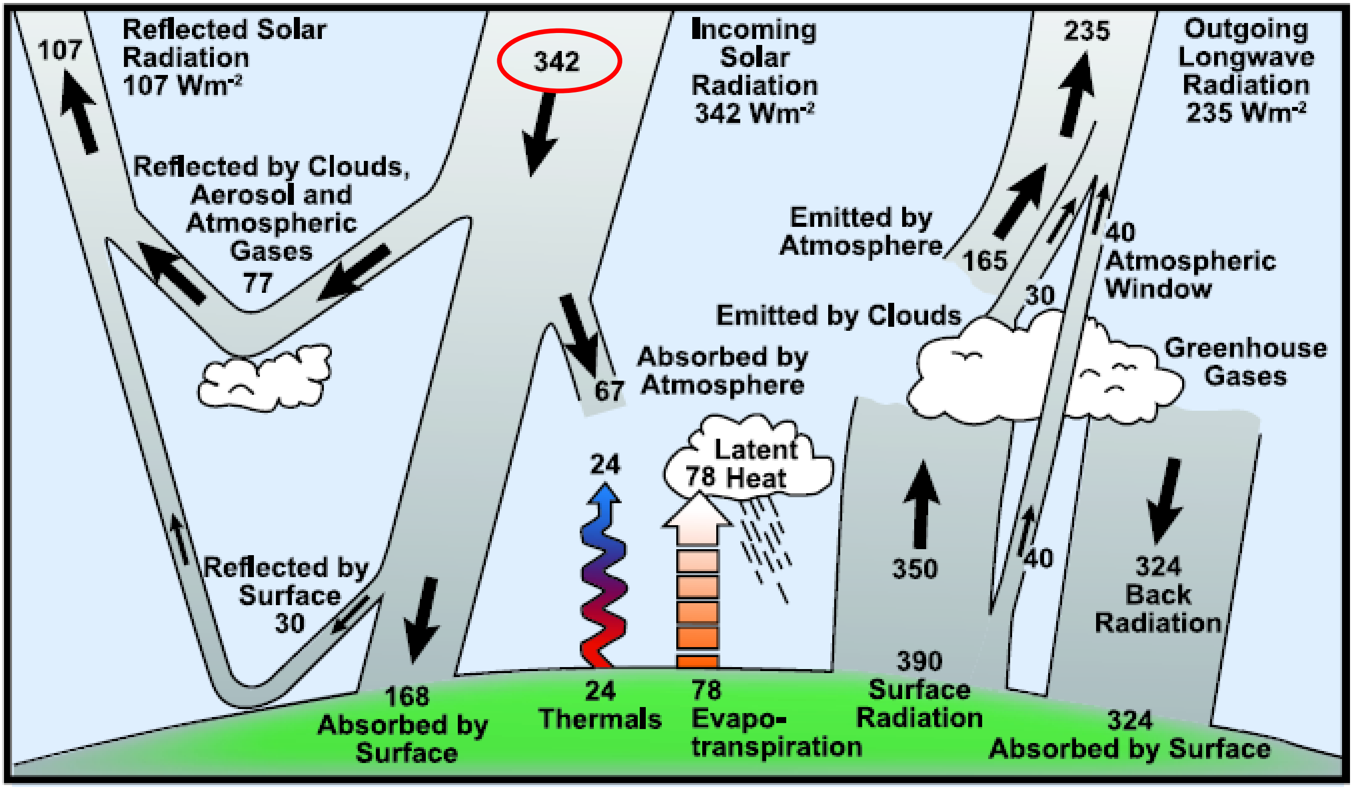
Effective Temperature

Let's take a closer look at S = $1370\ \mathrm{W\ m^{-2}}$



FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

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Effective Temperature

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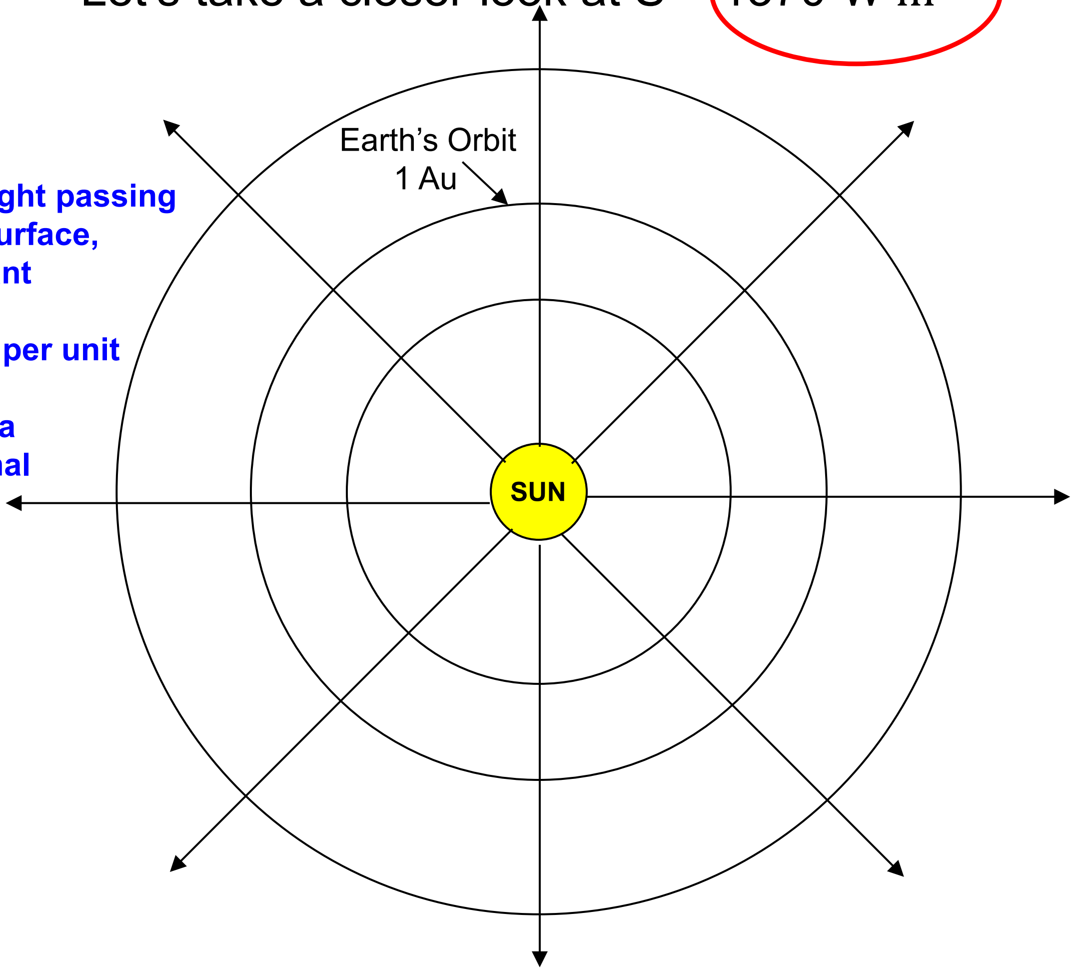

The total amount of sunlight passing through each spherical surface, of various radii, is constant

Therefore the energy (W) per unit area (m^{-2}) decreases wrt distance from the Sun in a manner that is proportional to: ______________

Notes: 1) Au, or Astronomical Unit, is a measure of the distance of a planet from the Sun, normalized by the mean distance of Earth from the Sun. So by definition, **Earth's orbit is 1 Au from the Sun**

2) The diagram above represents orbits as perfect spheres, which is suitable for our study of effective temperatures. In reality, of course, planets orbit the Sun in an elliptical manner.

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$$T_{EFF} = \{ (1 - \text{Albedo}) \times S \ / \ 4\,\sigma \}^{1/4}$$

Fi

Those with "Earth": find T_{EFF} for Earth, using:

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

$S = 1370$ W m^{-2}

Albedo = 0.3

Fi

Those with ""Mars": find T_{EFF} for **Mars** using:

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

$S = 1370$ W m^{-2}

Albedo = 0.17

Distance from Sun = 1.5 AU

Fi

Those with "Venus": find T_{EFF} for **Venus** using:

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

$S = 1370$ W m^{-2}

Albedo = 0.75

Distance from Sun = 0.72 AU

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Effective Temperature

My Favorite Planets

Venus:	Earth:	Mars
$T_{SURFACE} \approx 753$ K	$T_{SURFACE} \approx 288$ K	$T_{SURFACE} \approx 217$ K
$T_{EFFECTIVE} \approx$???	$T_{EFFECTIVE} \approx$???	$T_{EFFECTIVE} \approx$???

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Geological Evolution of Earth's Atmosphere: *Earth, Mars, and Venus*

	Earth	Venus	Mars
Radius (km)	6400	6100	3400
Mass (10^{24} kg)	6.0	4.9	0.6
Albedo	0.3	0.8	0.22
Distance from Sun (A.U.)	1	0.72	1.52
Surface Pressure (atm)	**1**	**91**	**0.007**
Surface Temperature (K)	~15 °C	~ 460 °C	–140 °C to 20 °C
N_2 (mol/mol)	0.78	3.4×10^{-2}	2.7×10^{-2}
O_2 (mol/mol)	0.21	6.9×10^{-5}	1.3×10^{-3}
CO_2 (mol/mol)	3.7×10^{-4}	**0.96**	0.95
H_2O (mol/mol)	1×10^{-2}	3×10^{-3}	3×10^{-4}
SO_2 (mol/mol)	1×10^{-9}	1.5×10^{-4}	Nil
Cloud Composition	H_2O	H_2SO_4	Mineral Dust

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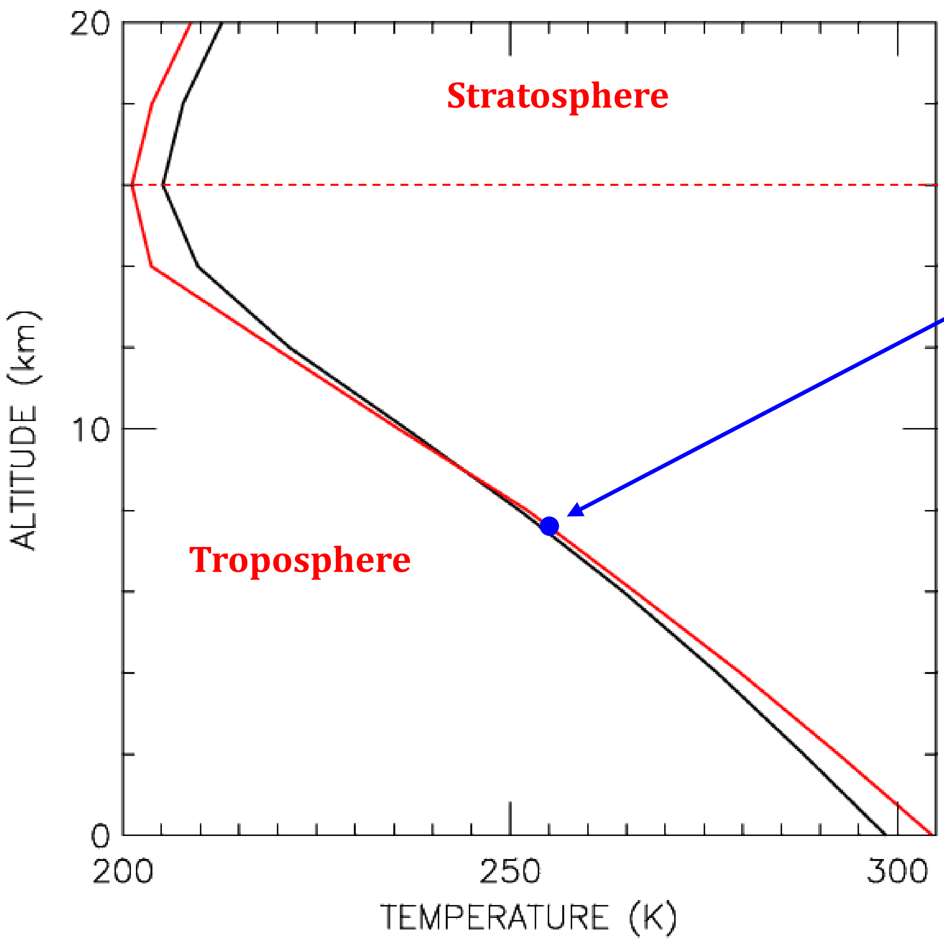
Temperature versus Altitude

Let's take a closer look at T_{EFF} = 255 K



Altitude in troposphere where T = 255 K

Termed Earth's mean radiating altitude to space

As Earth warms in response to rising GHGs, the lower troposphere will warm, the stratosphere will cool, and the mean radiating level will likely rise slightly higher in altitude

Regardless, the temperature of the mean radiating altitude will not change unless

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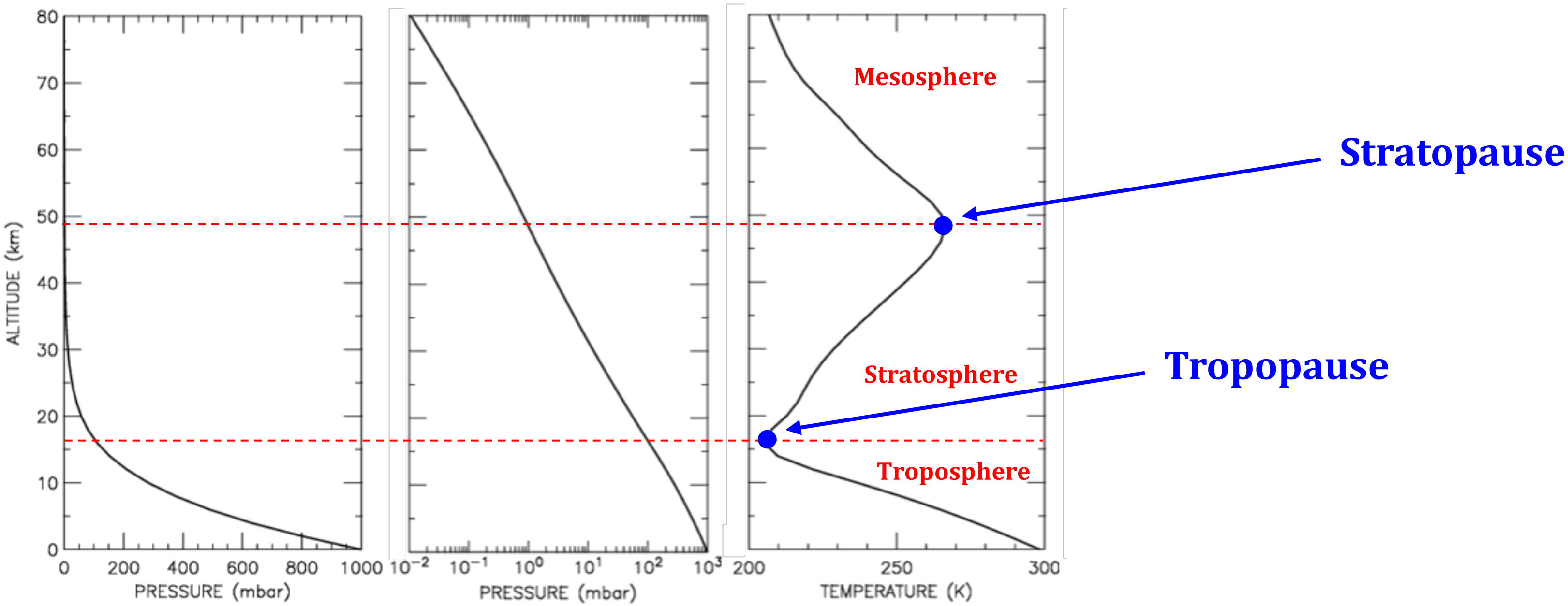
Temperature versus Altitude



- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

If the troposphere is dry, dT/dz = – *grav* / c_p

where c_p is specific heat of air at constant pressure = 1×10^7 erg gm^{-1} K^{-1}

Note: 1 erg = 1 dyne cm = gm cm^2 sec^{-2}

⇨ $dT/dz^{DRY} = -\,981$ cm sec^{-2} / (10^7 cm^2 sec^{-2} K^{-1}) × 10^5 cm/km = 9.8 K / km

Dry adiabatic lapse rate

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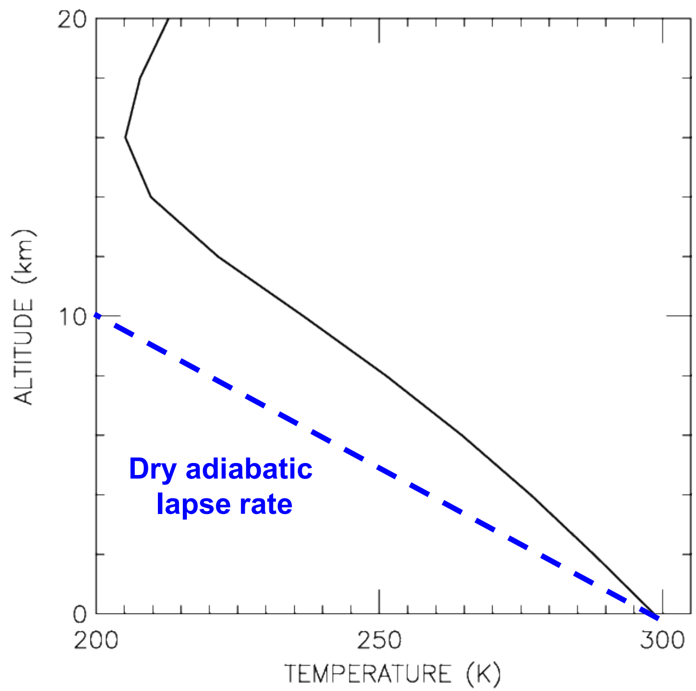
Temperature versus Altitude



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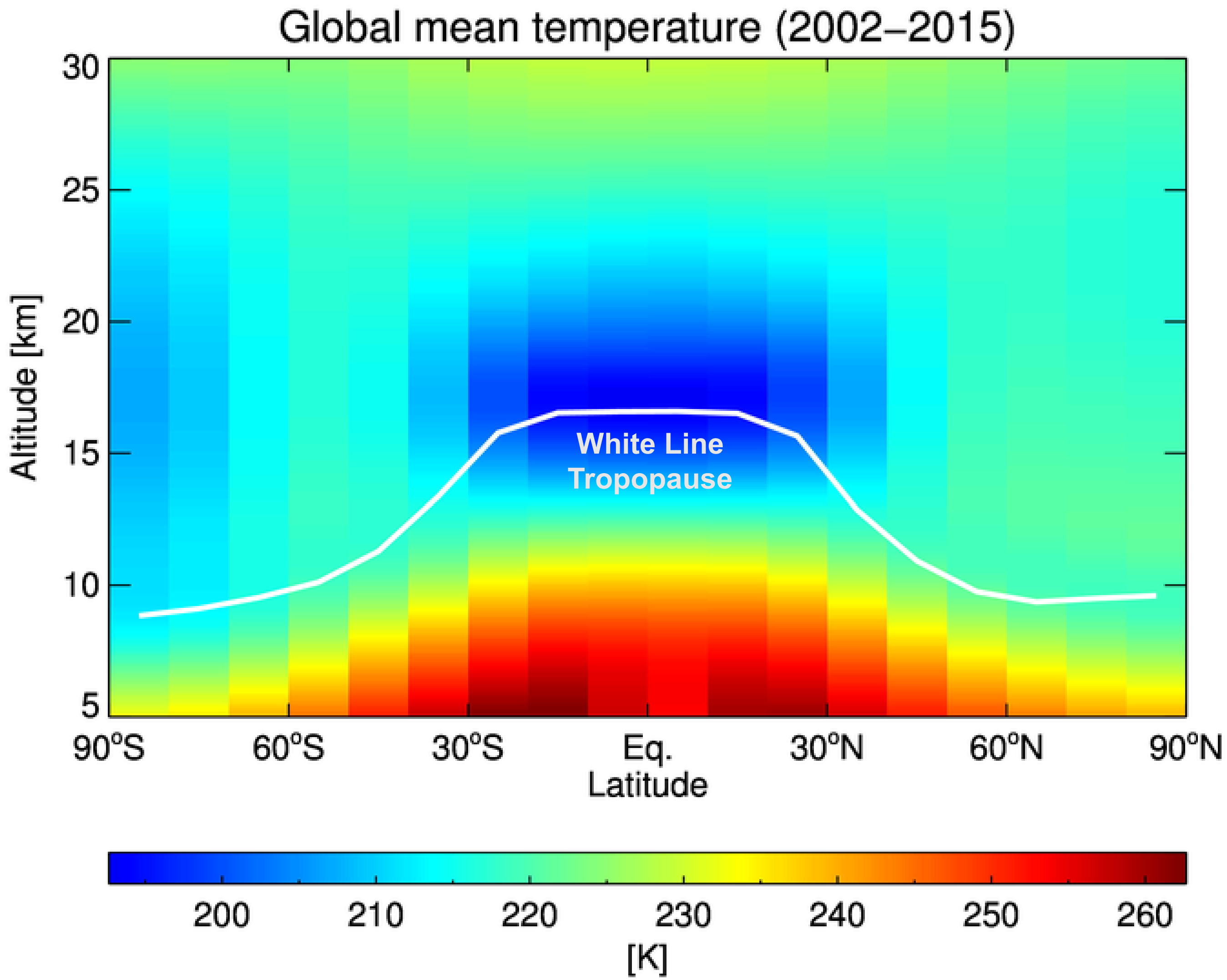
Temperature versus Altitude & Latitude



http://www.tschmidt.eu/ro/ENG/klima.html

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Temperature versus Altitude, Ocean

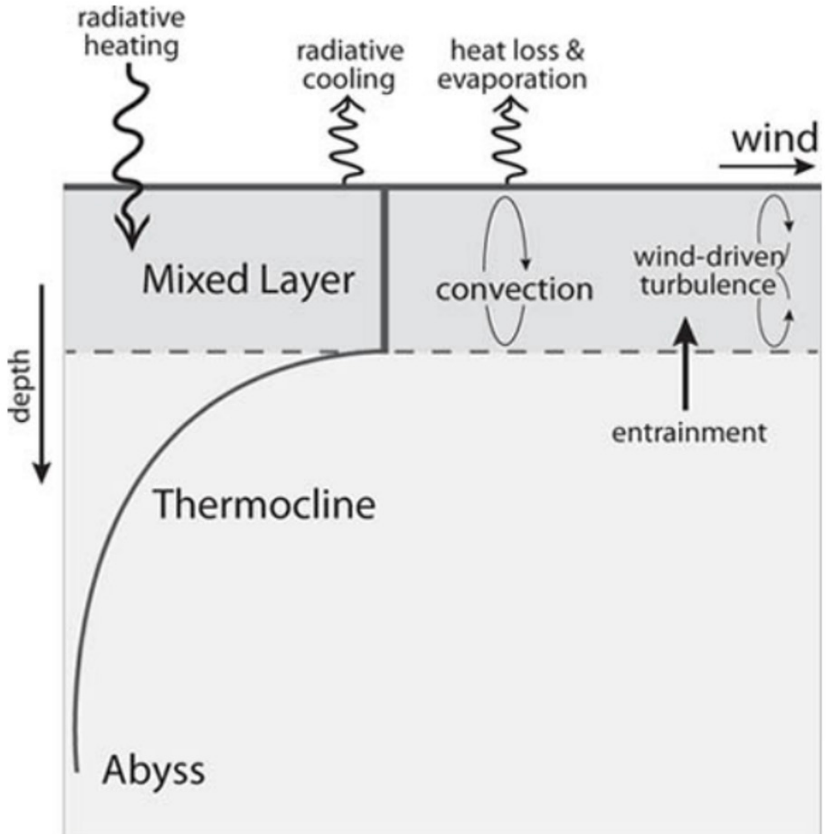

Figure 2.5. Schematic of the vertical structure of the ocean, emphasizing the mixed layer. In the mixed layer, typically 50–100 m deep, turbulence and convection act to keep the temperature relatively uniform in the vertical. Below this layer, temperature changes over a depth of a few hundred meters, in the *thermocline*, before becoming almost uniform at depth, in the *abyss*. Adapted from Marshall and Plumb, 2007.

***Climate And The Oceans*, Vallis**

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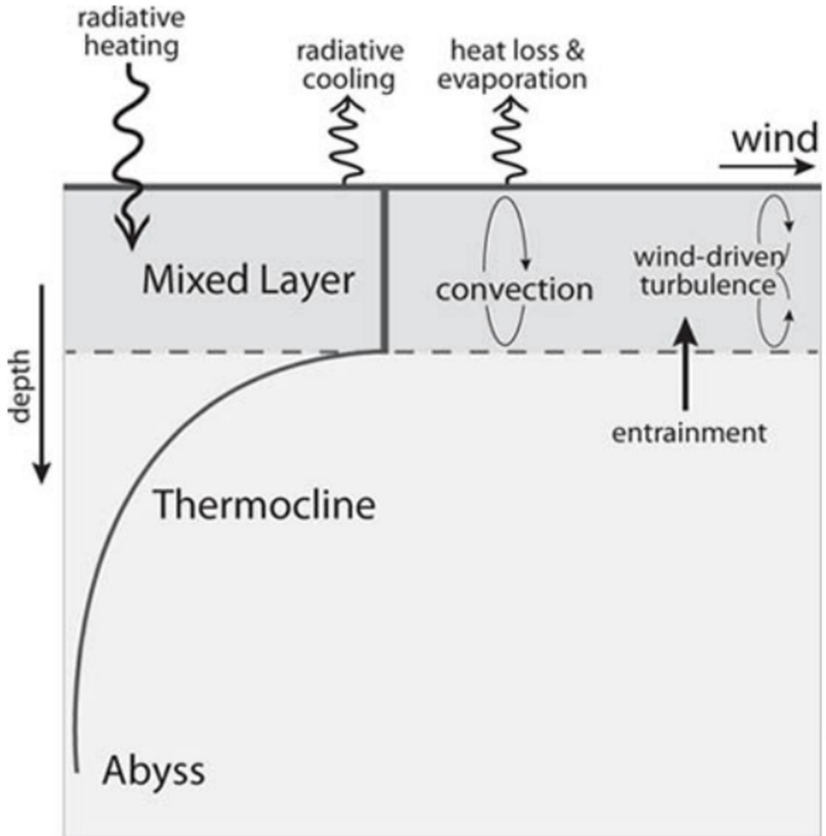
Temperature versus Altitude, Ocean



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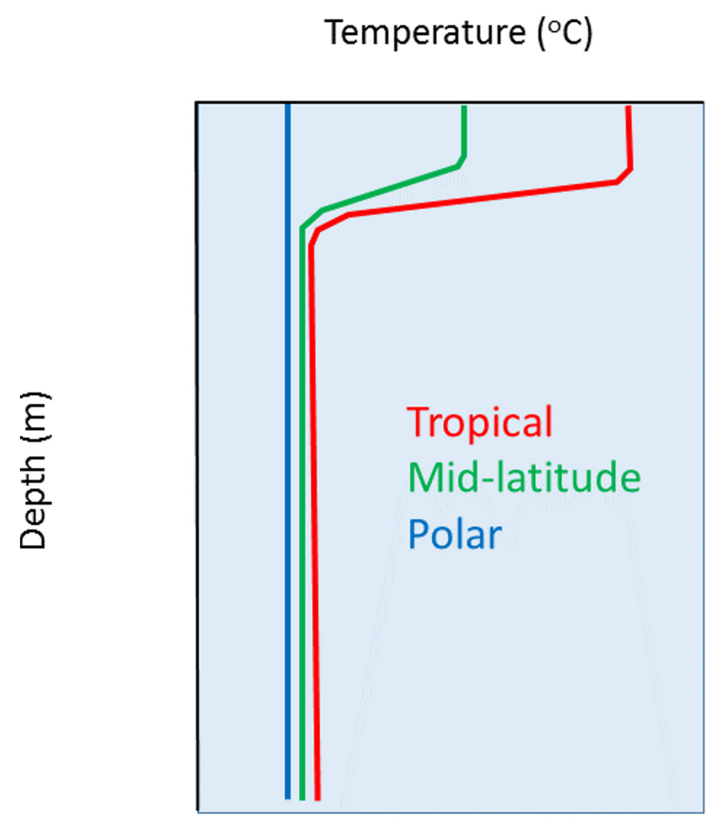
***Climate And The Oceans*, Vallis**

THE ENHANCED GREENHOUSE EFFECT 27

. The amount of water vapour in our atmosphere depends mostly on the temperature of the surface of the oceans; most of it originates through evaporation from the ocean surface and is not influenced directly by human activity. Carbon dioxide is different. Its amount has changed substantially – by nearly 40% so far – since the Industrial Revolution, due to human industry and also because of the removal of forests (see Chapter 3).



https://rwu.pressbooks.pub/webboceanography/chapter/6-2-temperature

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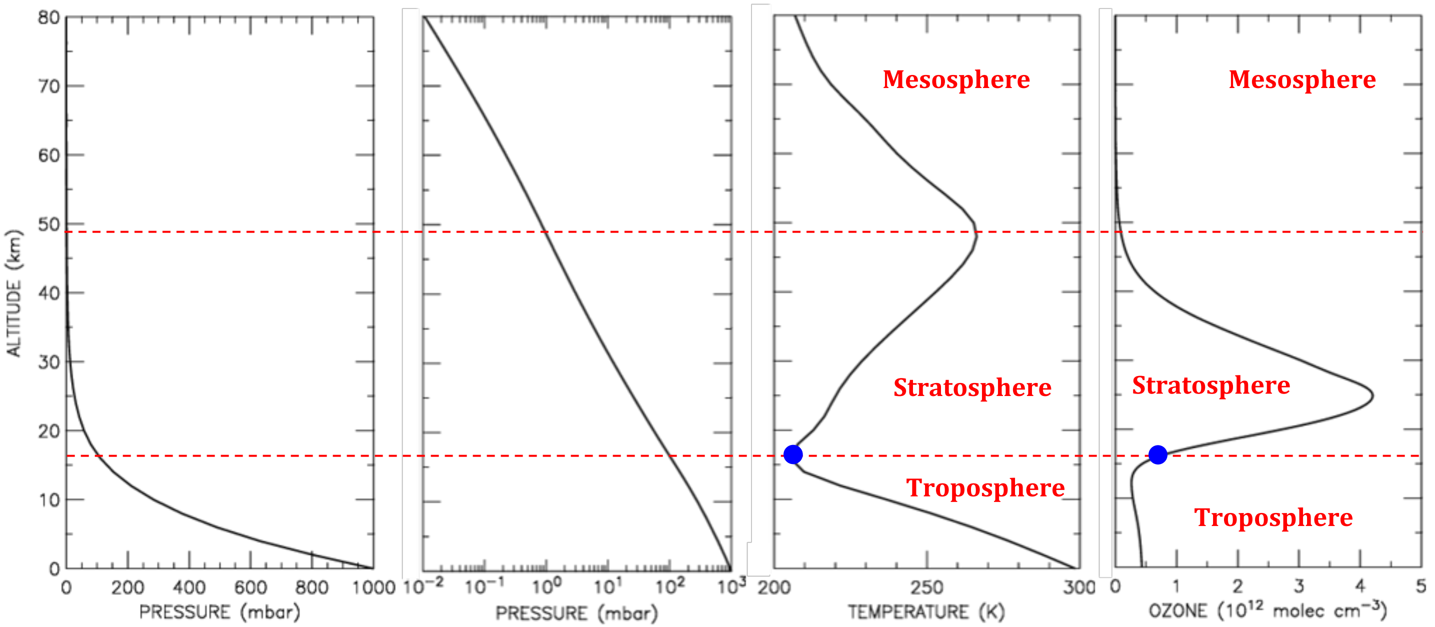
Temperature versus Altitude



- **T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude**

Fourth chart expresses abundance of ozone concentration, or ozone density, or [O_3], in units of molecules / cm^3

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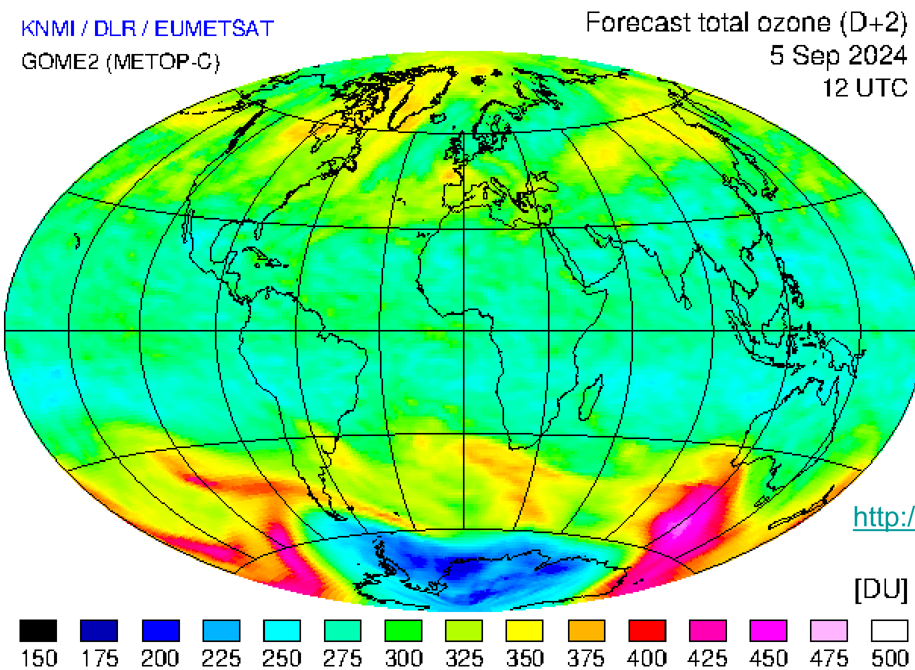
The Ozone Layer

According to *Chemistry in Context*, if all of the ozone in Earth's atmosphere could be isolated and brought to the surface at a pressure of 1 atmosphere and a temperature of 15°C), the resulting gas would have a thickness of **0.25 inch**



http://www.temis.nl/protocols/O3global.html

Mathematically:

$$\text{Ozone Column} = \int_{\text{Ground}}^{\text{Top of Atmosphere}} [O_3(z)]\, dz$$

$$\text{Units}: [O_3(z)] \text{ in } {}^{\text{molecule}}\!/_{\text{cm}^3} \text{ and z in cm, leading to Ozone Column in } {}^{\text{molecule}}\!/_{\text{cm}^2}$$

$$\text{Mathematically, 1 DU} = 2.687 \times 10^{16}\ {}^{\text{molecule}}\!/_{\text{cm}^2}$$

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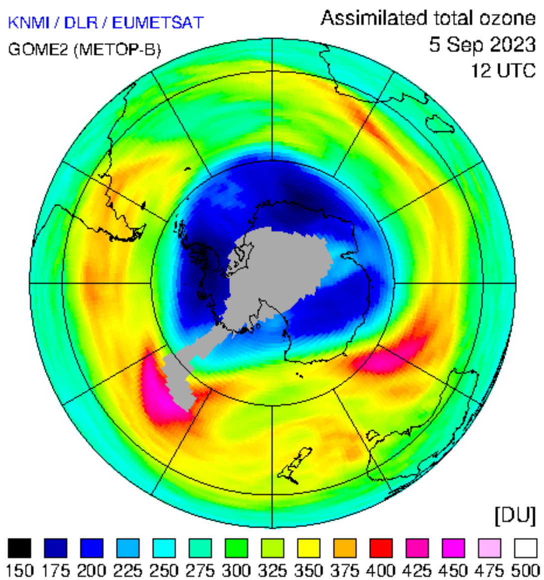
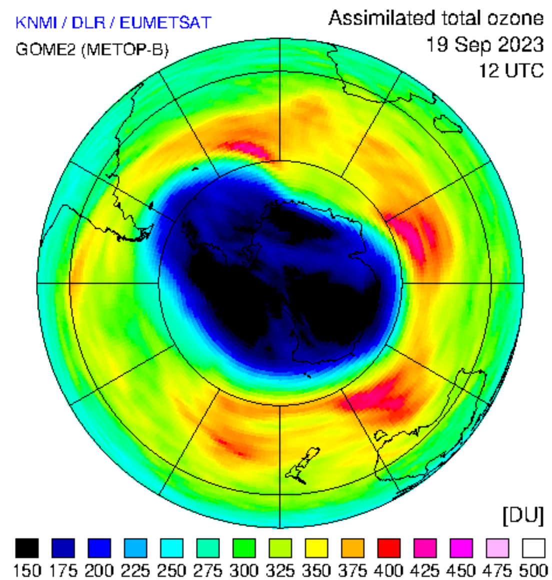
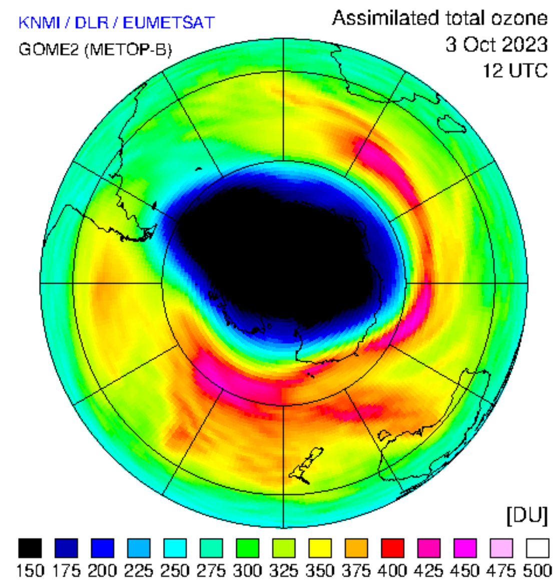
Seasonal Evolution of Ozone Hole

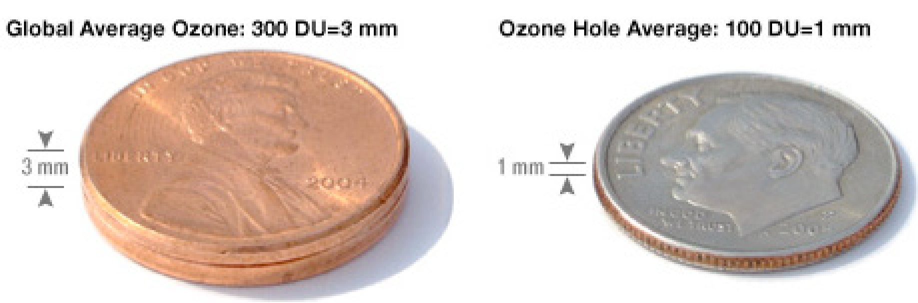






http://www.temis.nl/protocols/O3global.html

1 Dobson Unit is defined to be a 0.01 millimeter thickness of air, at "standard temperature and pressure"
Today we have about 300 Dobson Units (*CC*) = 300 x 0.01 millimeter = 3 millimeter or 0.3 cm = 0.12 inch of ozone, isolated and compressed to STP, between us and outer space.



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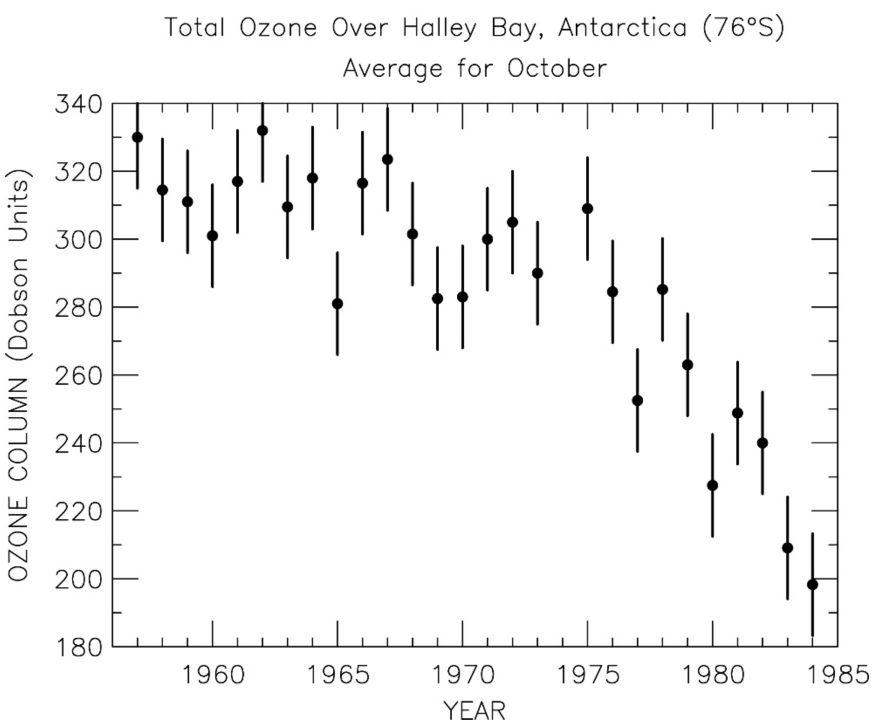
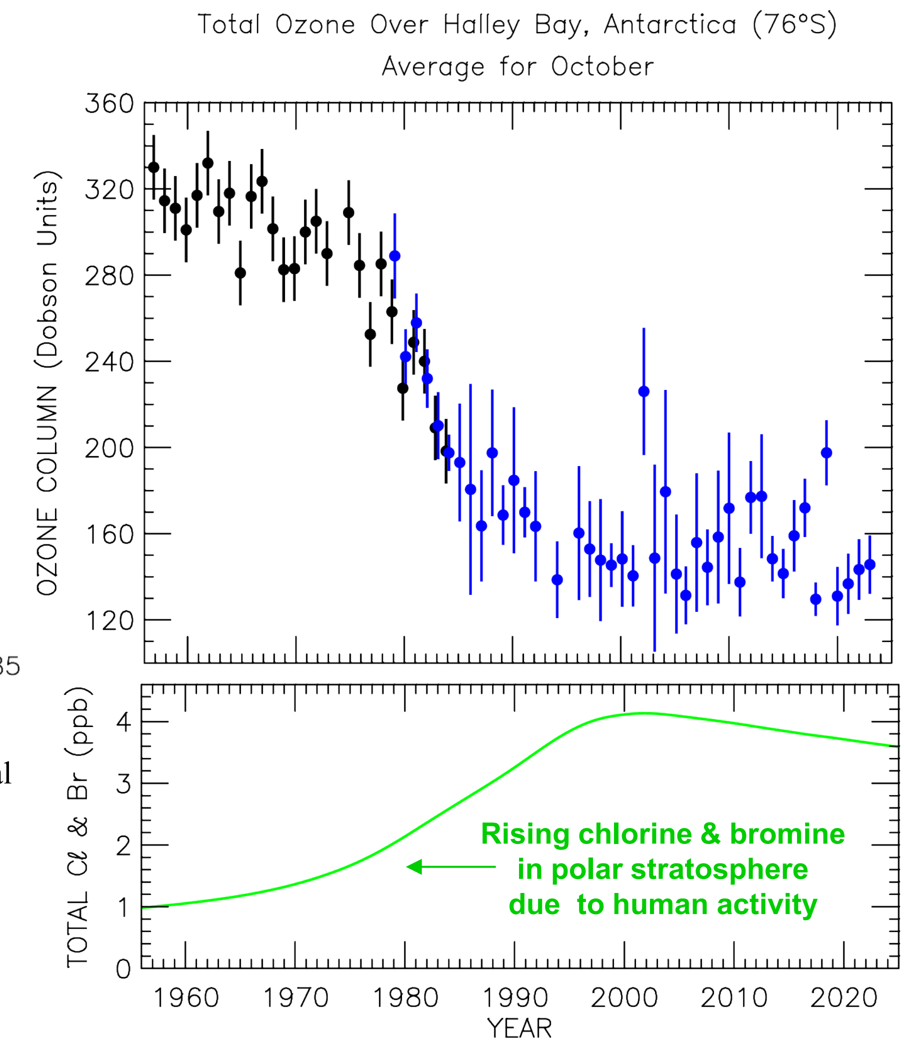
Earth's Atmosphere – Effect of Humans

Stratospheric Ozone – shields surface from solar UV radiation



After Farman *et al*., Large losses of total ozone in Antarctica reveal Seasonal ClOx/NOx interaction, Nature, 315, 207, 1985.

Update



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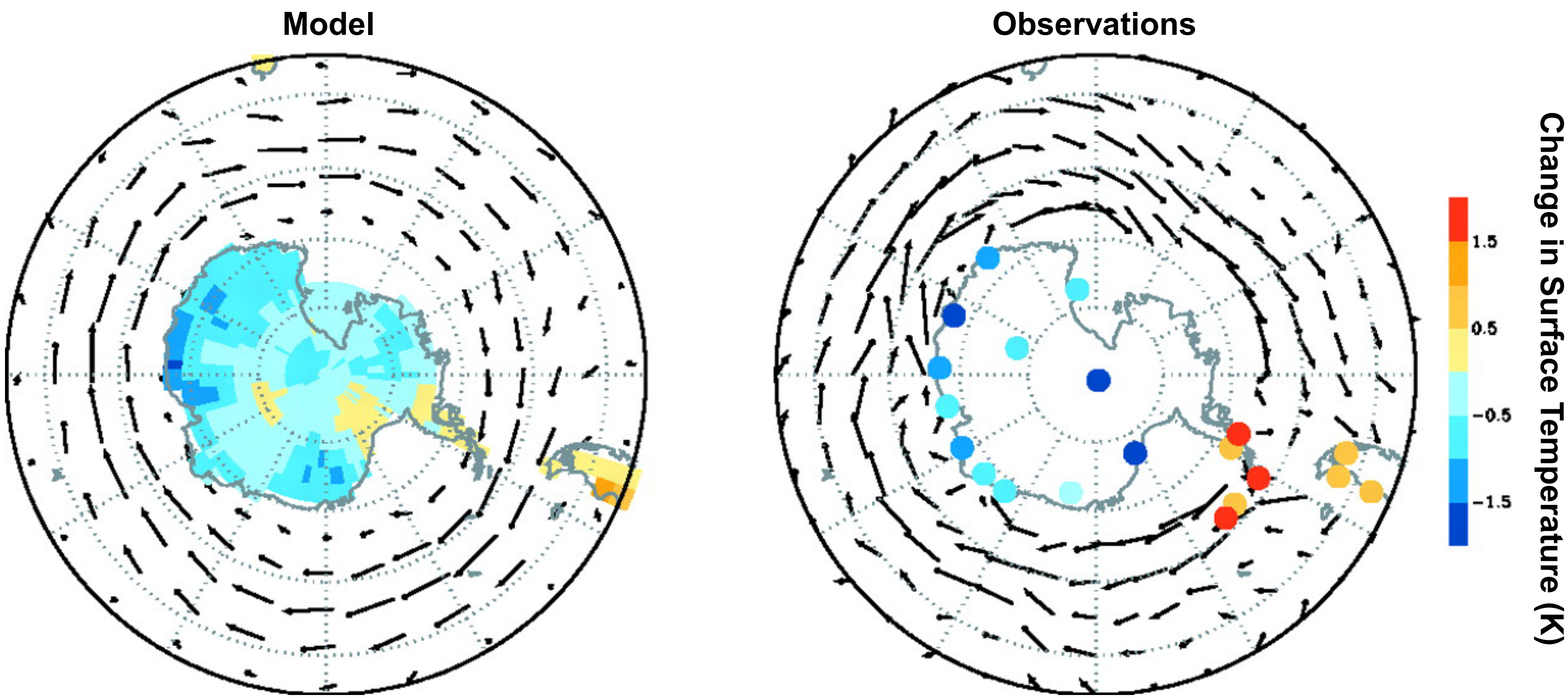
The Ozone Hole may have shielded the Antarctic surface from warming!



Simulated and observed changes in surface temperature (K) and wind speed,1969 to 2000, averaged over December to May. The longest wind vector corresponds to 4 m/s.

Gillett and Thompson, *Science*, 2003

As ozone depletion occurs:

The positive phase of the southern annular mode (SAM) increases, causing Antarctic surface westerlies to intensify, resulting in cooling of Antarctic continent

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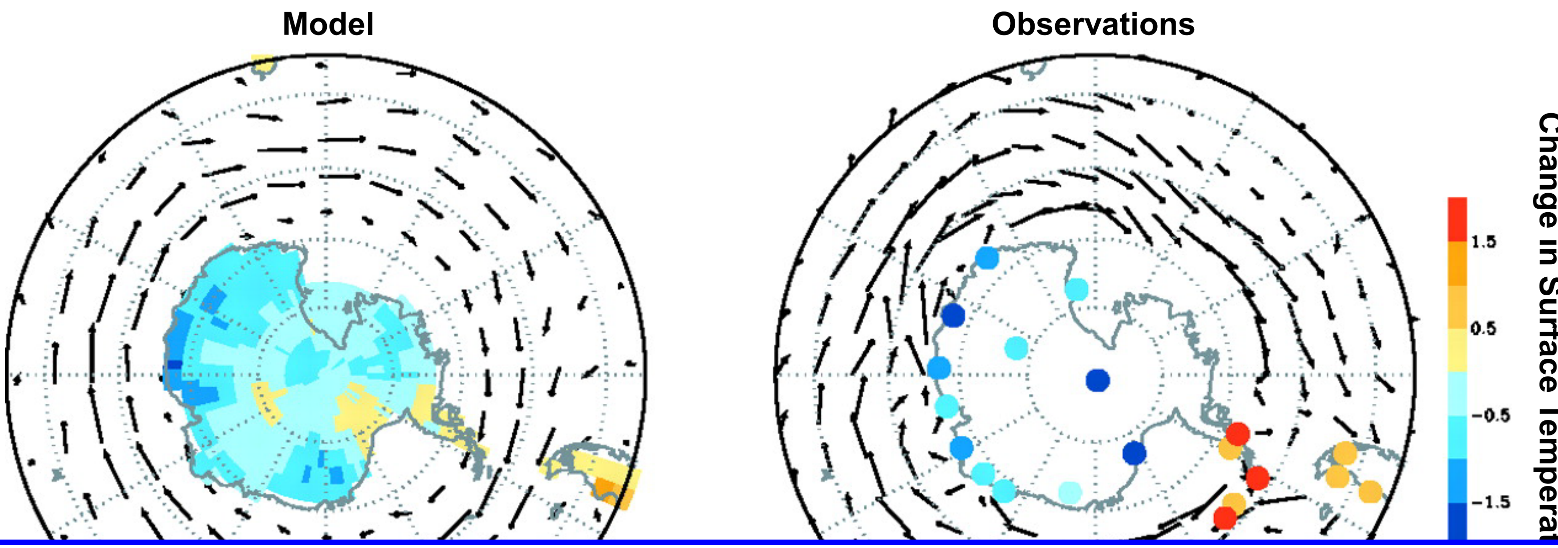

SAM: difference in zonal mean sea-level pressure between 40°S and 65°S. The pattern associated with SAM is a nearly annular pattern with a large low pressure anomaly centered on the South Pole and a ring of high pressure anomalies at mid-latitudes. The SAM effects storm tracks, precipitation patterns, etc.

http://www.climate.be/textbook/chapter5_node6.html

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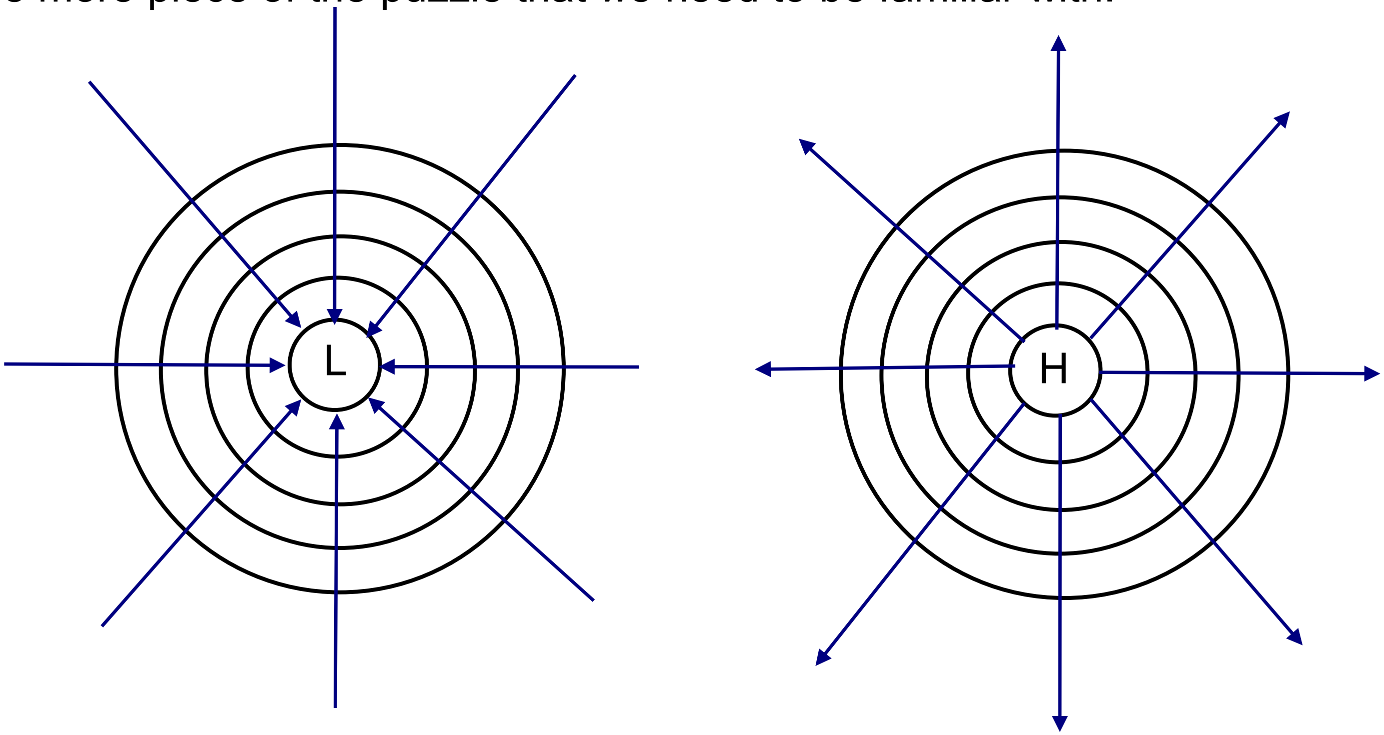
Coriolis Force

So far, we've reviewed temperature, pressure, and the balance between solar energy input to the atmosphere and terrestrial radiation leaving the atmosphere.

There's one more piece of the puzzle that we need to be familiar with.



In general, air moves from areas of high pressure to areas of low pressure. In the absence of external forces, air will move in a straight line, following pressure gradients

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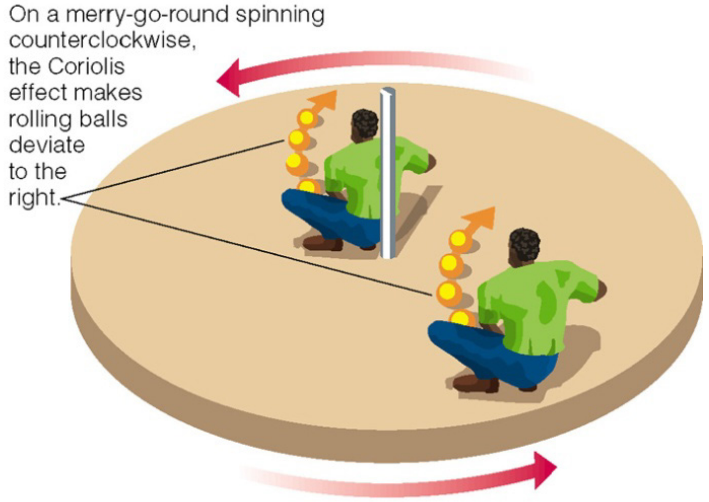
Coriolis Force



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http://lasp.colorado.edu/~bagenal/3720/CLASS15/15EVM-Dyn1.html

Earth's rotation provides an apparent force that deflects air to the right in the Northern Hemisphere, to the left in the Southern Hemisphere.

Force is proportional to sin(latitude), so vanishes at the equator

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Geostrophy

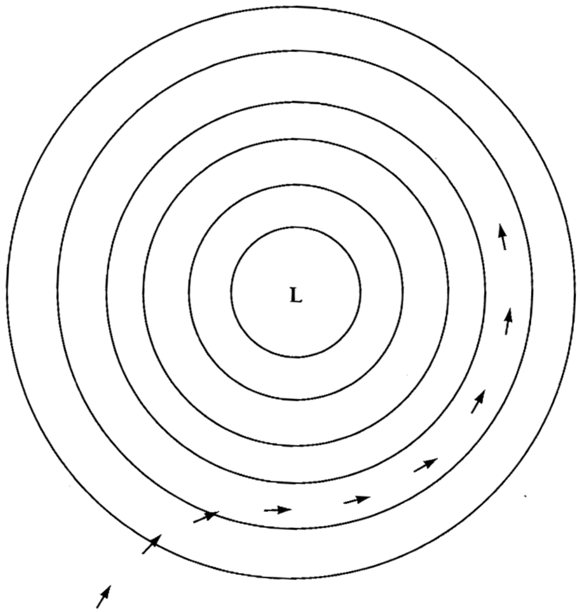

Figure 8.16 Track of an air parcel in the vicinity of a low pressure region in the Northern Hemisphere. The parcel is initially at rest but then adjusts to the pressure gradient force and the Coriolis force to achieve geostrophic balance.

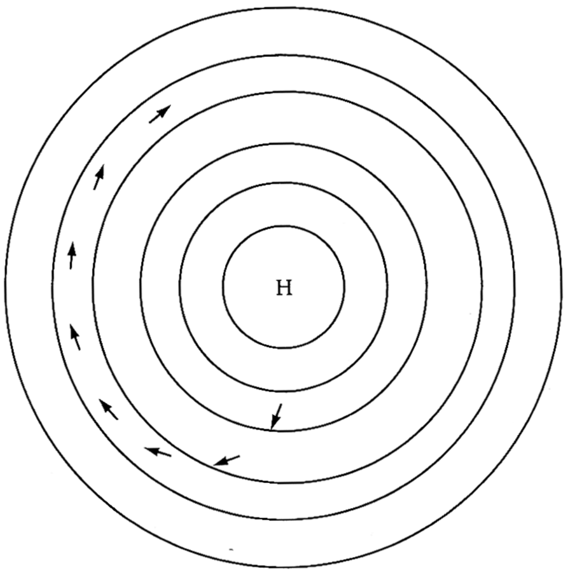

Figure 8.17 Same situation as in 8.16, except that the parcel is in the vicinity of a high pressure region in the Northern Hemisphere.

From "The Atmospheric Environment", M. B. McElroy

Geostrophic balance: balance between Coriolis Force and pressure gradient

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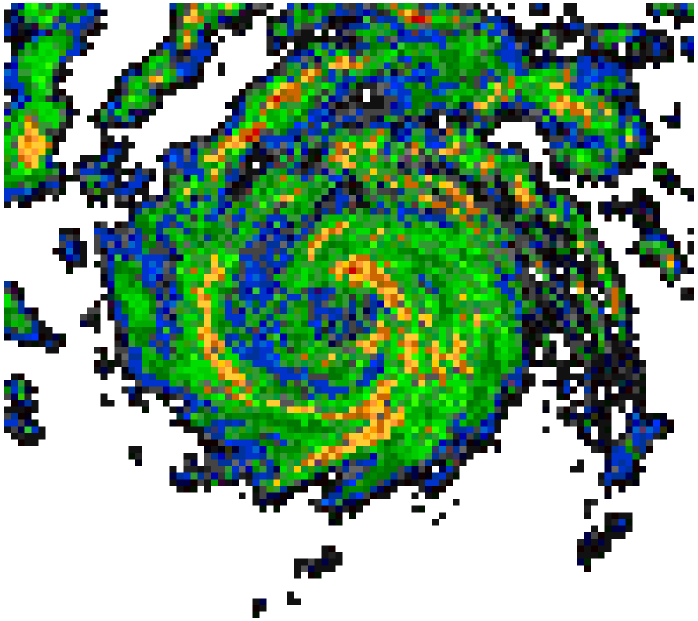
Geostrophy

NH Weather System:



Cyclonic Flow: when the wind swirls
counter-clockwise in the NH

Hurricane: Cyclonic flow occurring in the N Atlantic or NE Pacific Ocean east of the dateline.

Typhoon: Cyclonic flow occurring in the NW Pacific Ocean, west of the dateline.
Cyclones: Cyclonic flow occurring in the South Pacific and Indian Ocean.

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Atmospheric Circulation

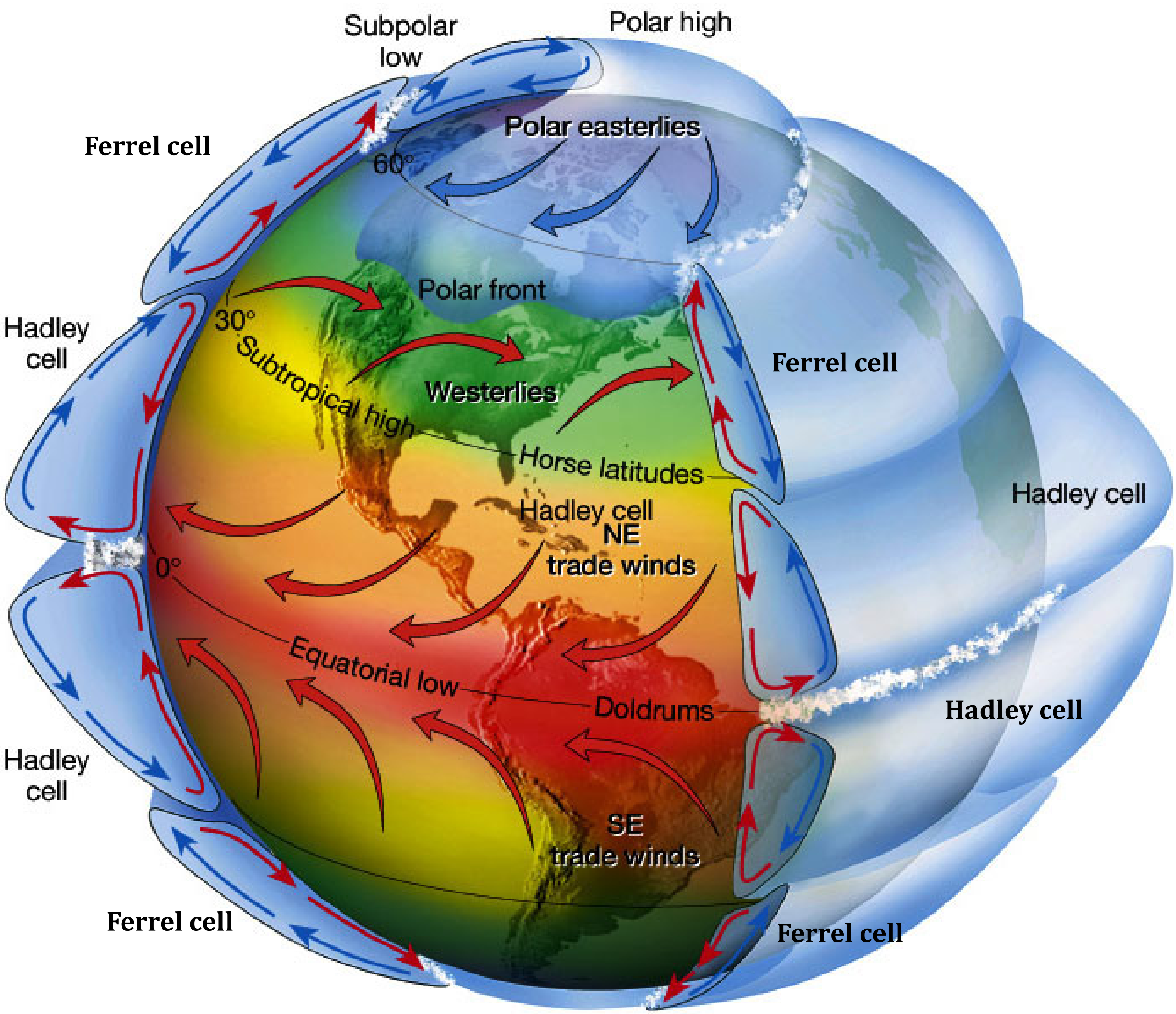

Figure 7.5 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001; http://www.ux1.eiu.edu/~cfjps/1400/circulation.html

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Oceanic Circulation

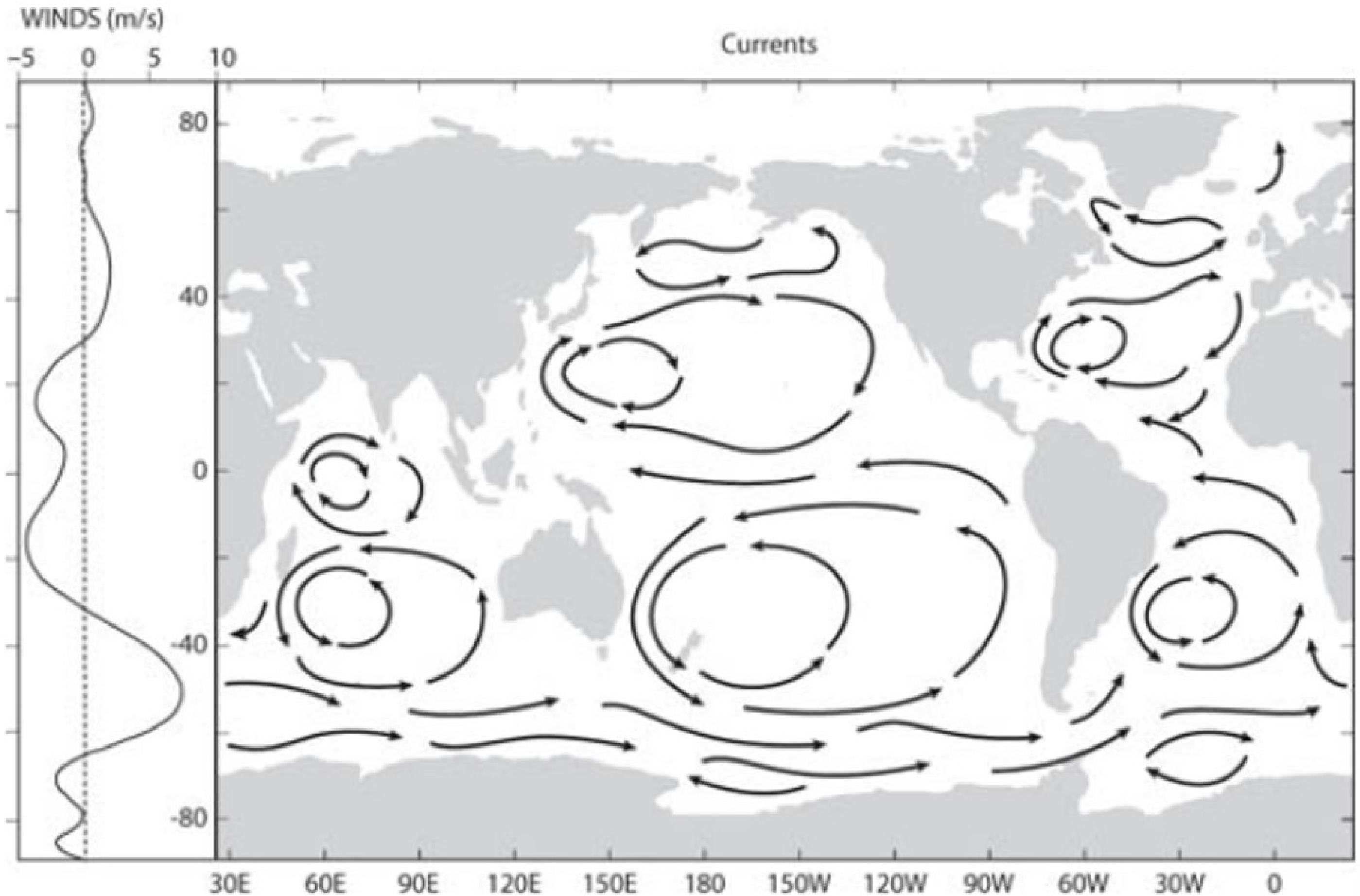

Figure 2.3. A schematic of the main surface currents of the world's oceans. The panel at the left shows the zonally averaged zonal (i.e., east–west) surface winds.

***Climate And The Oceans*, Vallis**

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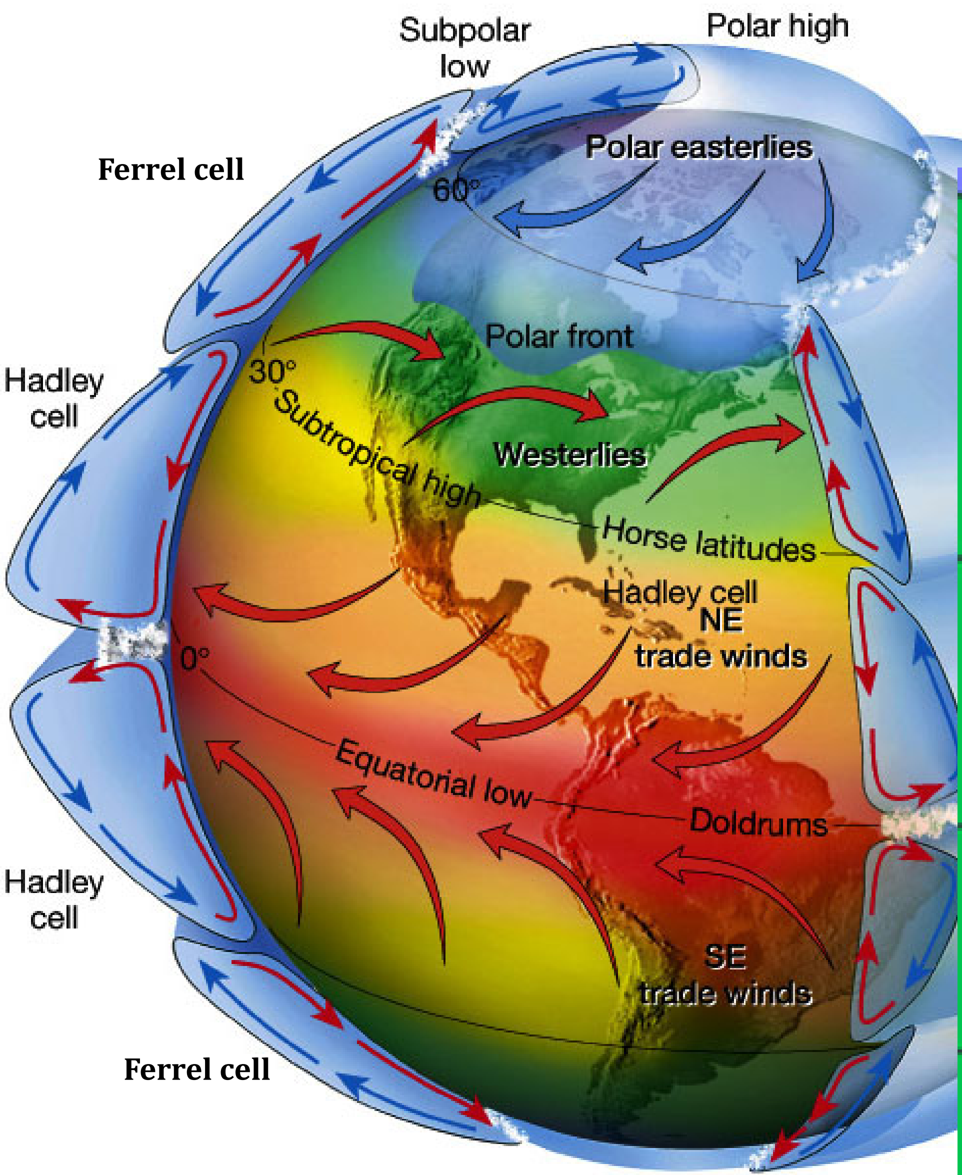
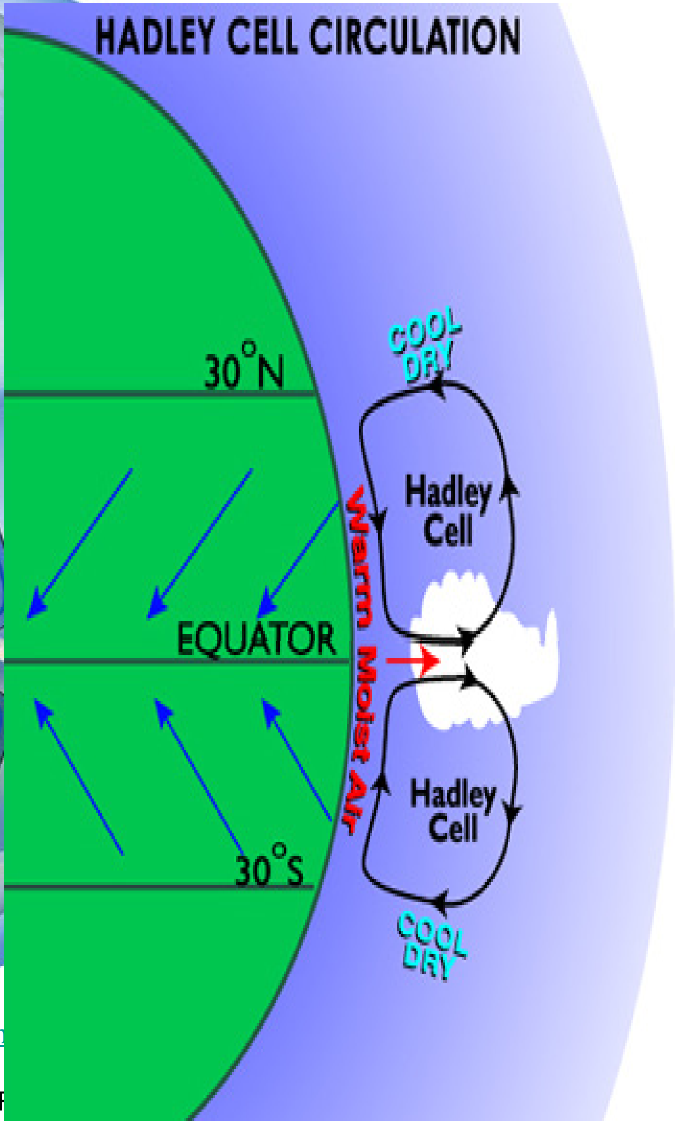
Atmospheric Circulation





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As CO_2 and other GHGs rise:

- Hadley Cell becomes more energetic
- WWDD: Wet gets wetter, dry gets drier
- Deserts expand poleward

REVIEW ARTICLE
https://doi.org/10.1038/s41558-018-0246-2

nature climate change

Re-examining tropical expansion

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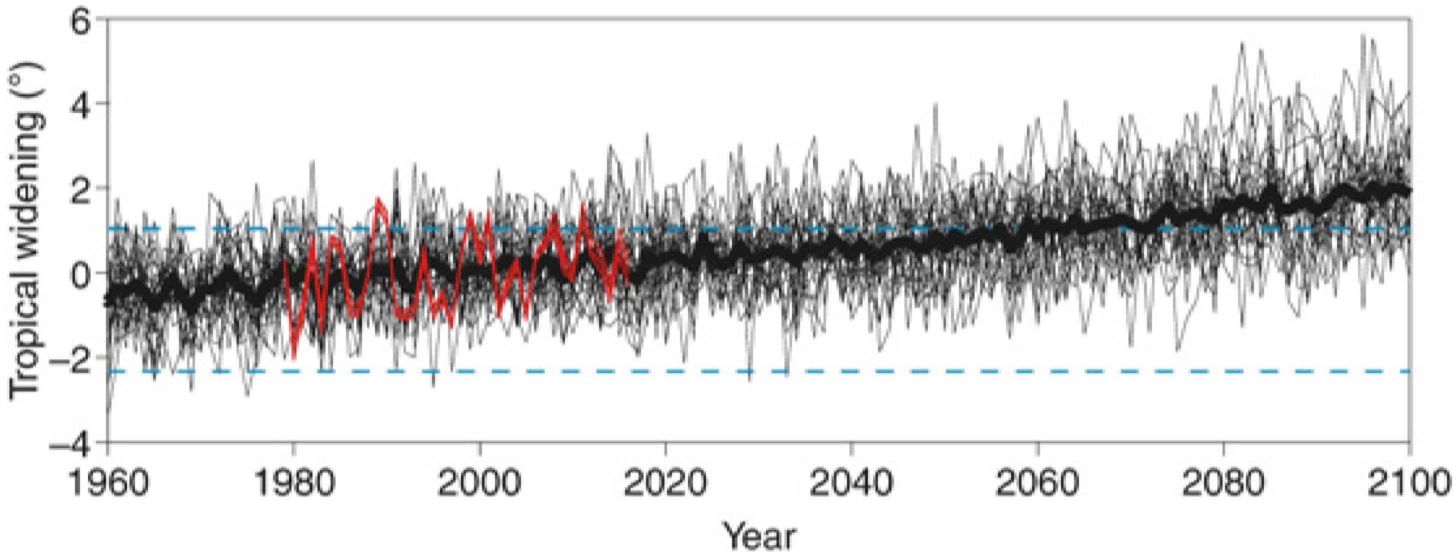

Change in the latitudinal width of the tropics relative to 1981-2010 mean from satellite observations (red) and climate models (thin black lines), along with the multi-model mean (thick black). The blue dashed lines show the 2σ range of the width of the tropics due to natural variability for pre-industrial levels of GHGs.

From Staten *et al.*, *Nature Climate Change*, 2018. https://www.nature.com/articles/s41558-018-0246-2

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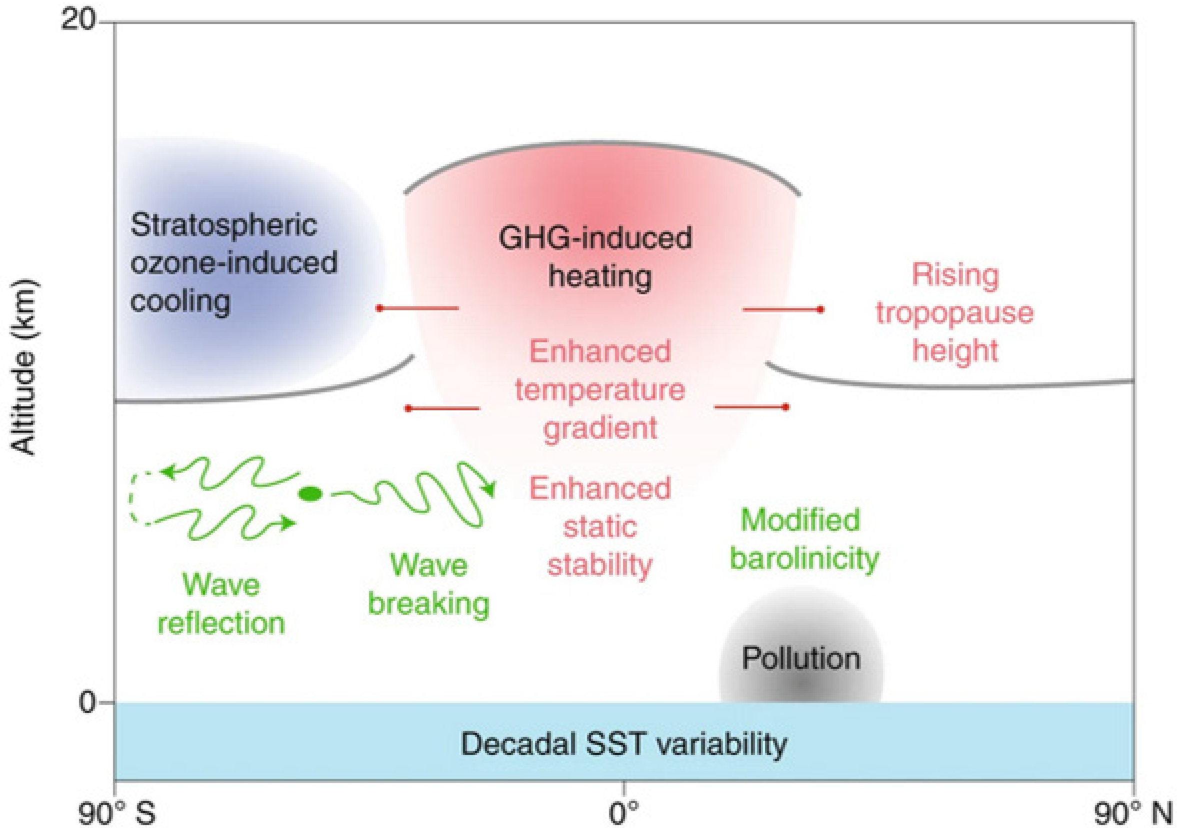
Tropical Expansion: Causal Factors

Fig. 3: Factors and mechanisms for tropical expansion.

From: Re-examining tropical expansion



The key factors hypothesized to be responsible for the recent tropical expansion are tropical upper-tropospheric warming related to GHG forcing, enhanced extratropical stratospheric cooling related to O_3 depletion in the Southern Hemisphere, emissions of black carbon and tropospheric ozone (pollution, primarily over the Northern Hemisphere) and decadal SST variability and trends. A green dot is used to denote the source of Rossby waves.

Staten *et al.*, *Nature Climate Change*, 2018. https://www.nature.com/articles/s41558-018-0246-2

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Tropical Expansion: One Important Consequence

Article | Open access | Published: 11 September 2023

New insights into the poleward migration of tropical cyclones and its association with Hadley circulation

U. Anjana & Karanam Kishore Kumar

Scientific Reports **13**, Article number: 15009 (2023) | Cite this article

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Abstract

Recent investigations have shown a robust signature of poleward migration of the tropical cyclone latitudes using observations and climate model simulations. Most of these studies invoked the role of the Hadley circulation (HC) expansion in the poleward shifting of tropical cyclones. However, none of these studies focused on the dissection of the zonally asymmetric HC into ascending and descending regions at regional scales, which holds the key in establishing the association between these two phenomena. Here, we are reporting the poleward migration of tropical cyclones and their association with ascending region boundaries of the HC at regional scales for the first time. The results emphatically show that the tropical cyclone latitudes as well as latitudes of maximum lifetime intensity vary in tandem with boundaries of the ascending region of the HC as compared to its descending region thus providing a vital clue on processes governing poleward migration of tropical cyclones.

Anjana and Kumar, *Nature Climate Change*, 2023. https://www.nature.com/articles/s41598-023-42323-7

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Next Lecture: Climates of the Past

Next Reading:

Chemistry in Context, Secs 2.2, 3.0, 3.1, 3.2 (~14 pgs)

as well as 8 pages from *Global Warming: The Complete Briefing* by Houghton
7 pages from *Paris Beacon of Hope*

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Derivation of the Barometric Law

Assume a sample volume is at rest with respect to vertical motion :

$$p(z) - p(z+\Delta z) = \rho \;\; grav \;\Delta z$$

in other words, the pressure difference between z and $z+\Delta z$

is equal to the weight of air contained in a volume of unit horiz area.

Using calculus:

$$\frac{dp}{dz} = -\rho(z)\; grav$$

Writing the gas law as $p = R_{\mathrm{EARTH}} \;\rho\; \mathrm{T}$

$$\text{where } R_{\mathrm{EARTH}} = 8.3143\times10^{7}\,\frac{\text{ergs}}{\text{K mole}}\;\times\frac{\text{mole}}{28.8\text{ gm}} = 2.87\times10^{6}\,\text{ergs/ K gm}$$

and substiting gives:

$$\frac{dp}{dz} = -\;\frac{p\; grav}{R_{\mathrm{EARTH}}\;\;\mathrm{T}}$$

Or

$$\frac{dp}{dp} = -\;\frac{dz}{H} \qquad \text{where } H = \frac{R_{\mathrm{EARTH}}\;\;\mathrm{T}}{grav}$$

The solution of this ODE is:

$$p(z) \;=\; p(z=0)e^{-z/H}$$

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