Climate and Ocean Change: Physical Foundations and Impacts Lab

Module 1: Physical foundations

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last review:
2025-06-11

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 "Education and Research" - Component 2: "From research to business" - Investment 3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani

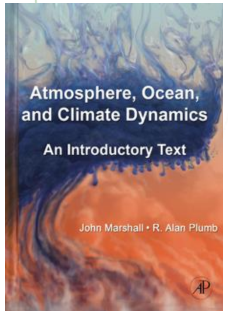
Contents of the course (modules 1-2)

1. Physical foundations
- Greenhouse effect
- Climate feedbacks
- Aerosols
- Convection
- Meridional structure of the atmosphere
- General circulation: atmosphere, ocean
- Natural variability and teleconnections

2. Contemporary changes
- Observations of change
- Overshoot
- Attribution
- Climate projections

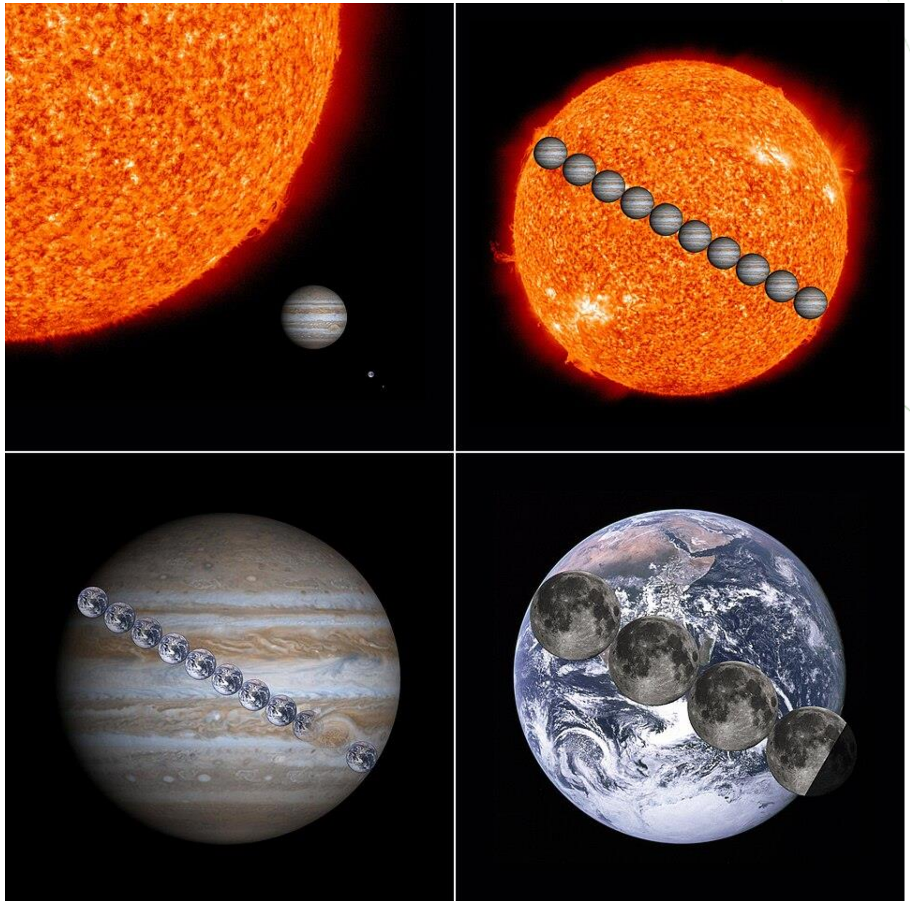
Bibliography

- [MP08] (textbook): J. Marshall, R. Alan Plumb "Atmosphere, Ocean and Climate Dynamics: An Introductory Text", Academic Press (2008)
- [IPCC6] "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change"
- [IPCC5] "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change"
- [H16] (selected figures) D. L. Hartman "Global Physical Climatology, 2nd edition", Elsevier (2016)
- Selected journal papers and websites (as indicated in the slides)



Greenhouse effect

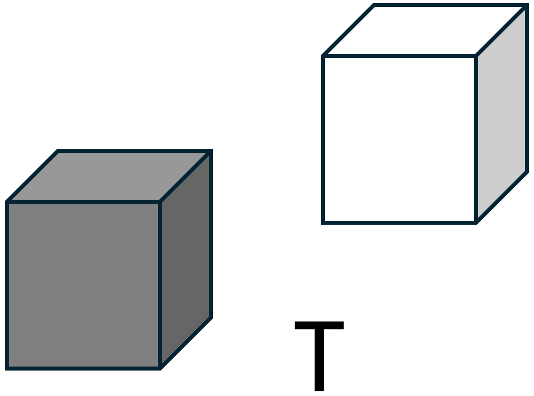
The Sun and the Earth



https://upload.wikimedia.org/wikipedia/commons/0/02/SolarSystem_OrdersOfMagnitude_Sun-Jupiter-Earth-Moon.jpg

Greenhouse effect

Black Body radiation



Definition

- An idealized physical body that absorbs all incident electromagnetic radiation,
- regardless of wavelength or angle of incidence,
- ***and*** re-emits this energy in a continuous spectrum that depends solely on the body's temperature

The spectral distribution of this radiation follows Planck's law, exhibiting a peak at a wavelength inversely proportional to the temperature (Wien's displacement law). The total radiative power emitted per unit area is proportional to the fourth power of the absolute temperature, in accordance with the Stefan–Boltzmann law.

Examples of black bodies:

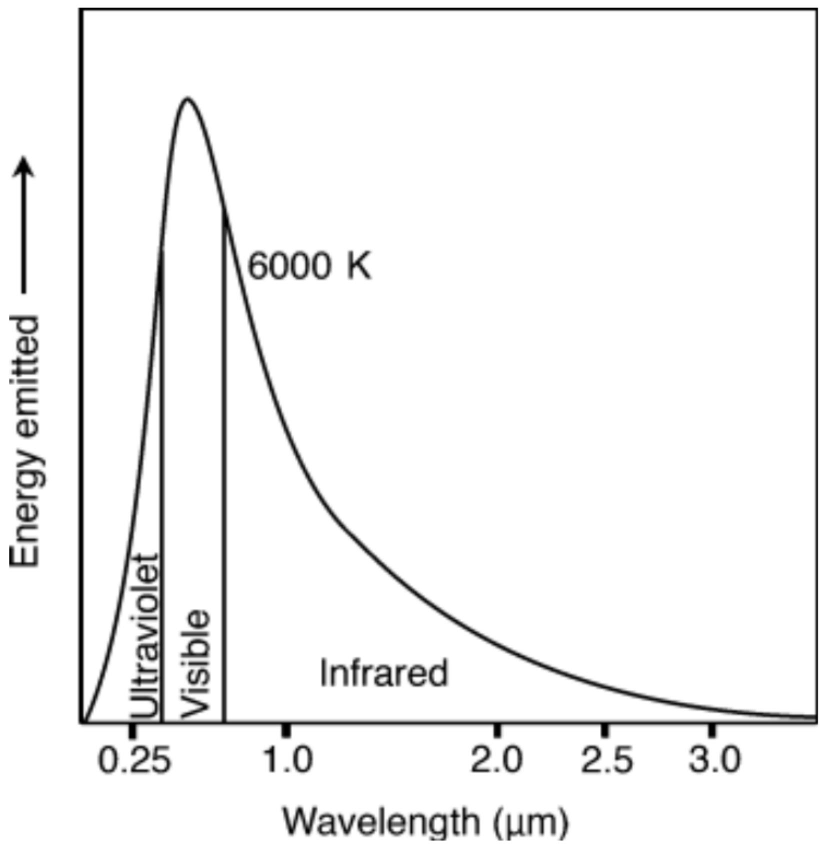
- The Sun
- Rocky planets with thin atmospheres and negligible internal energy sources

Not black bodies:

- Earth's atmosphere: spectral windows and gaps in absorption
- clouds: absorb and emit strongly in infrared, but reflect most visible radiation
- glass: absorb strongly in infrared but not in visible
- polished metal: reflect most radiation, very low emissivity

Greenhouse effect

The Sun is a black body which looks yellow/red but is white



[MP08] 2.2

The solar spectrum is close to a *Black Body* spectrum at a temperature of 5800 K → Peak emissions is in the visible range, at 0.5 μm (green *)

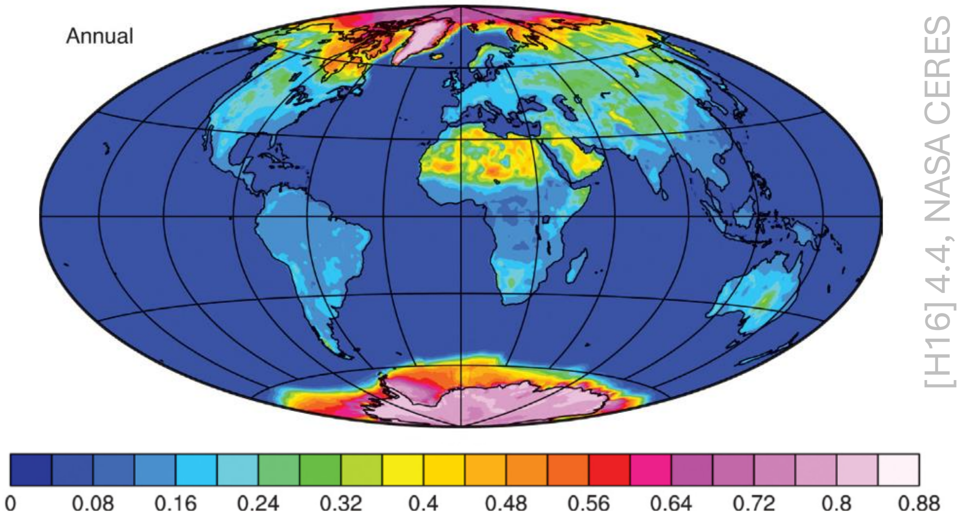
Solar irradiance (total power radiated at the distance of the Earth orbit, per unit area): $S_0 \sim 1360\ W \cdot m^{-2}$

Note: S_0 depends, besides Sun-Earth distance, on both Sun's emission temperature and surface (it's a black body)

*) The Sun looks white from space (due to all visible colours contributing nearly equally) and yellow from Earth surface (due to Rayleigh scattering of blue light). At sunset or sunrise, sunlight passes through a thicker layer of atmosphere, scattering shorter wavelengths even more and allowing more red and orange light to reach the observer. The Sun's stellar classification is G-type main-sequence "yellow-dwarf" just for historical reasons related to ground-based observations.

Earth albedo

The spectrally and directionally integrated fraction of energy reflected by the planet



[H16] 4.4, NASA CERES

Type of surface	Albedo (%)
Ocean	2–10
Forest	6–18
Cities	14–18
Grass	7–25
Soil	10–20
Grassland	16–20
Desert (sand)	35–45
Ice	20–70
Cloud (thin, thick stratus)	30, 60–70
Snow (old)	40–60
Snow (fresh)	75–95

[MP08] 2.2

It mainly arises from ice sheets and deserts, but also from clouds

Average Earth's albedo is α = 0.30 (i.e., 30% of reflection)

Greenhouse effect

0-dimensional model

The Earth as a whole (including its atmosphere) absorbs energy from the Sun and re-radiates it (nearly) as a Black Body at an *emission temperature* T_e:

At balance:

$$S_0 (1-\alpha) / 4 = \sigma T_e^4$$

Earth's albedo (α)

disc-to-sphere surface ratio (4)

Stefan-Boltzmann's constant (σ)

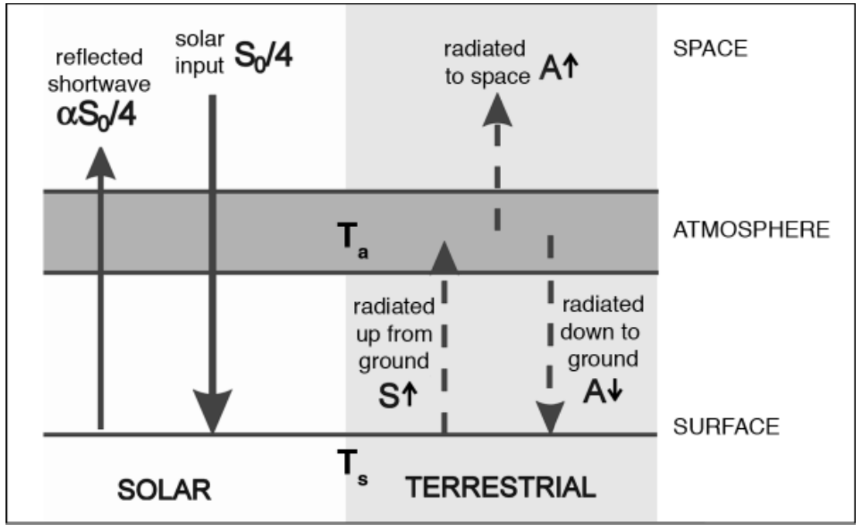
➔This simple model results into a single temperature, T_e = 255 °K (= -18 °C)

Note: as this T_e implies peak emissions in the IR, but visible solar light is partially reflected (α>0), Earth looks black just at night (and far from articial light sources)

Greenhouse effect

Basic 1-dimensional Greenhouse Gas (GHG) model

A single-slab atmosphere absorbs and radiates longwave radiation, while it remains transparent to solar (shortwave) one:



[MP08] 2.7

Surface net energy flux must be zero:

upwelling = downwelling, or:

$S\uparrow = 1/4\,(1-\alpha)\,S_0 + A\downarrow$

It follows than $T_s = 2^{1/4}\,T_e = 303$ °K (= +29 °C) ➔ T_s too large with respect to observations

However, we now have two distinct temperatures: surface's and atmosphere's one

Greenhouse effect

Planets as black bodies

Comparison of computed emission, measured emission, and measured surface temperatures:

	r 10^9 m	S_0 W m^{-2}	α_p	T_e K	T_m K	T_s K
Venus	108	2632	0.77	227	230	760
Earth	150	1367	0.30	255	250	288
Mars	228	589	0.24	211	220	230
Jupiter	780	51	0.51	103	130	134
Moon	as Earth	as Earth	0.11	270	270	270

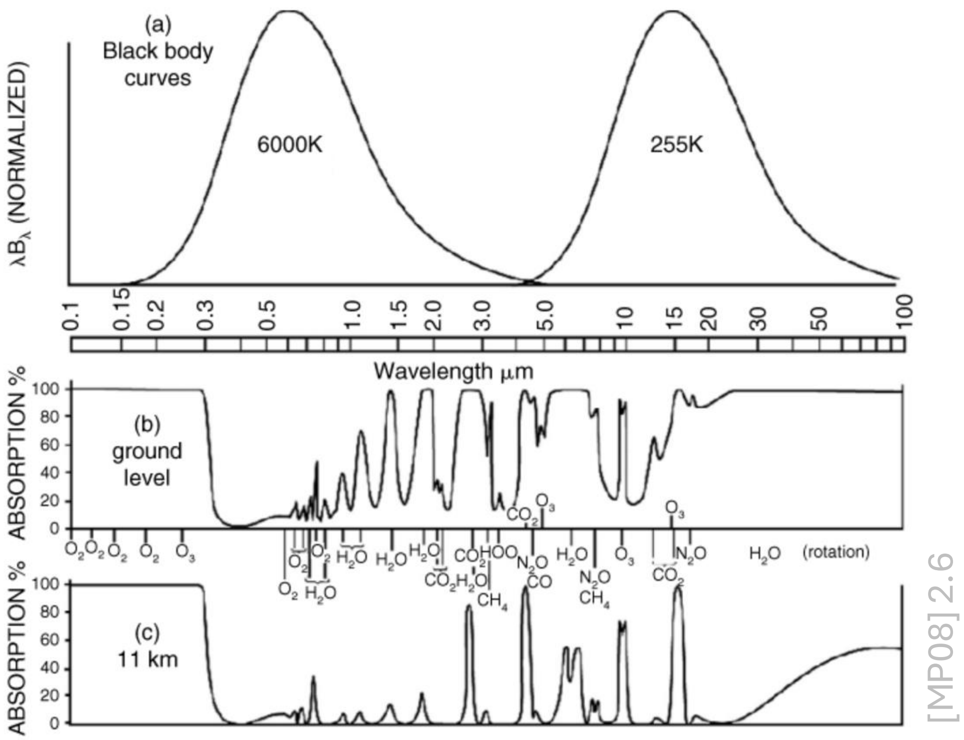
[MP08] 2.1

- Venus has a stronger greenhouse effect, Mars a weaker one than the Earth
- Jupiter has a significant internal source of energy, in addition to the solar one
- Moon is the closest to a black body

ITINERIS

Refining the basic 1D GHG model

The atmosphere is not completely opaque to longwave radiation, it has finite absorbivity ϵ resulting from its band spectrum:



- nearly transparent in the visible range
- opaque in the UV
- selectively transparent in the IR ("window region", absorbtion mainly from tri-atomic molecules such as H_20 and CO_2 – "greenhouse gases")
- opaque in the far IR due to water vapour (this matters for Earth Observation in presence of clouds)
- absorption is higher near the ground than aloft (density decreases with height)

Greenhouse effect

ITINERIS

Refining the basic 1D GHG model

Absorption spectrum depends on rotational and vibrational modes of greenhouse molecules:

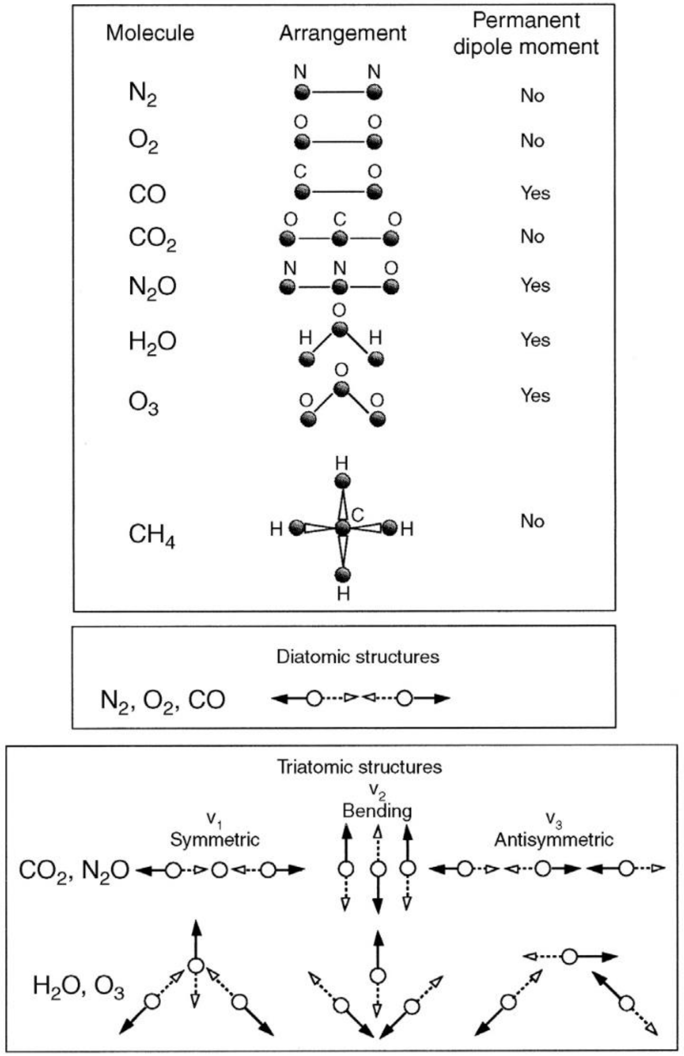
- CO_2 bending mode (ν_2) is near the peak of terrestrial radiation

Species	Vibrational modes v1	v2	v3
CO	4.67		
CO_2		15.0	4.26
N_2O	7.78	17.0	4.49
H_2O	2.73	6.27	2.65
O_3	9.01	14.2	9.59
NO	5.25		
NO_2	7.66	13.25	6.17
CH_4	3.43	6.52	3.31
CH_4	5.25		

Units are in microns (μm).

[H16] 3.1

- H_2O has a permament dipole moment and thus strong rotational absorption bands

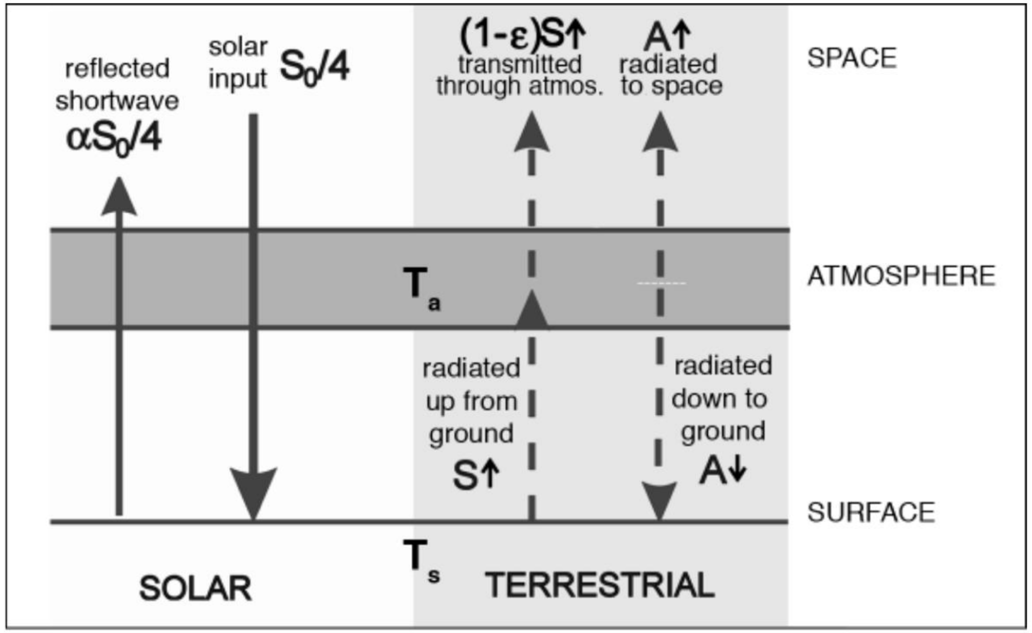


[H16] 3.3

Greenhouse effect

1D GHG model with atmospheric absorption

In this case, the atmospheric slab transmits to space (1- ϵ) of radiation from the ground (so far, ϵ=1):



[MP08] 2.8

- Equilibrium implies that $T_s = (2/(2- \epsilon))^{1/4}\, T_e < 2^{1/4}\, T_e$
- Using Kirchoff's law, the atmospheric temperature is obtained as well:

$T_a = (1/(2-\epsilon))^{1/4}\, T_e = (1/2)^{1/4}\, T_s$

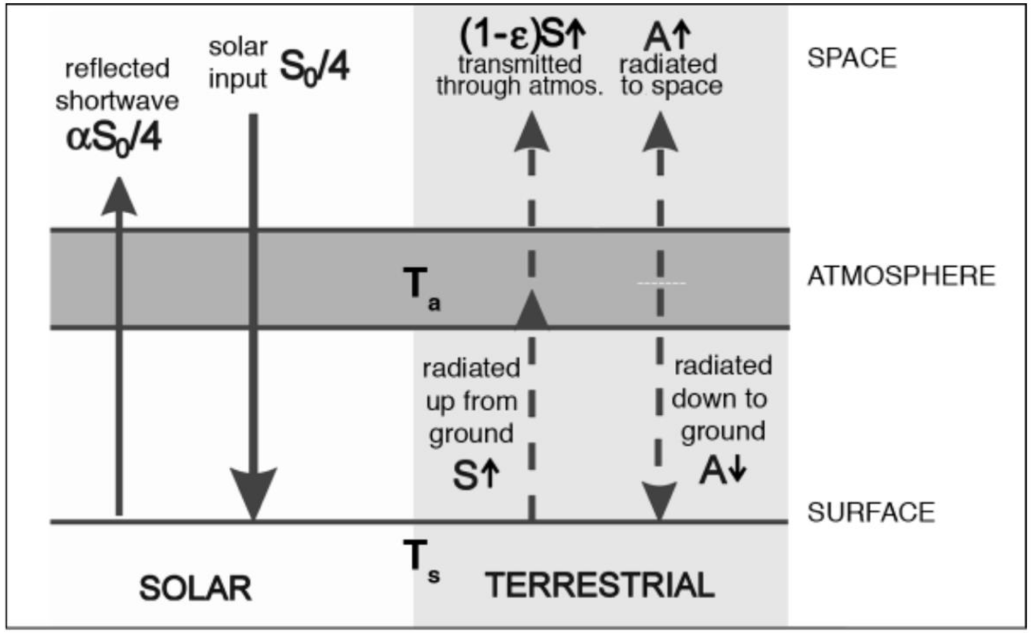
➔ T_a is lower than both T_e and T_s

We now have three distinct temperatures: surface's, atmosphere's, and effective emission layer's one

Greenhouse effect

1D GHG model with atmospheric absorption

In this case, the atmospheric slab transmits to space (1- ϵ) of radiation from the ground:



[MP08] 2.8

- apply with $\epsilon = \epsilon_0 + \epsilon_1 \cdot [CO_2]$

where: $\epsilon_0 = 0.734$, $\epsilon_1 = 1.0 \times 10^{-4}$/ ppm

	$[CO_2]$ /ppm	T_s / °C	T_a / °C
pre-industrial	280	14.3	12.0
today	429	15.2	12.8
doubling pre-industrial*	560	16.0	13.5
2100 with present trend** (+3.3 ppm/yr)	676	16.7	14.0

*) resulting surface warming is termed «climate sensitivity»
**)https://gml.noaa.gov/ccgg/trends/gr.html

Greenhouse effect

Further model improvements

The previous model's outcome is quite satisfactory for Ts.

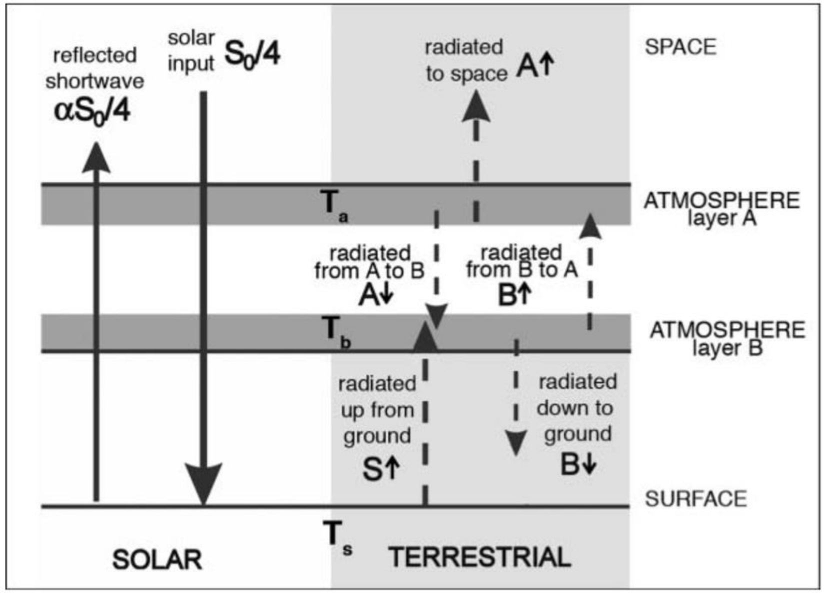
However, it results in:

- one single temperature value for the entire atmosphere (Ta)

which is not observed.

Improve with a multi-layer model, accounting also for vertical distribution of absorbers, spectral dependence of absorption (ϵ), and presence of clouds

Start from a 2-layer model as shown aside (each layer is opaque)→



[MP08] 2.9

We now have four distinct temperatures: surface's, atmosphere's (Ta and Tb), and the emission layer's one

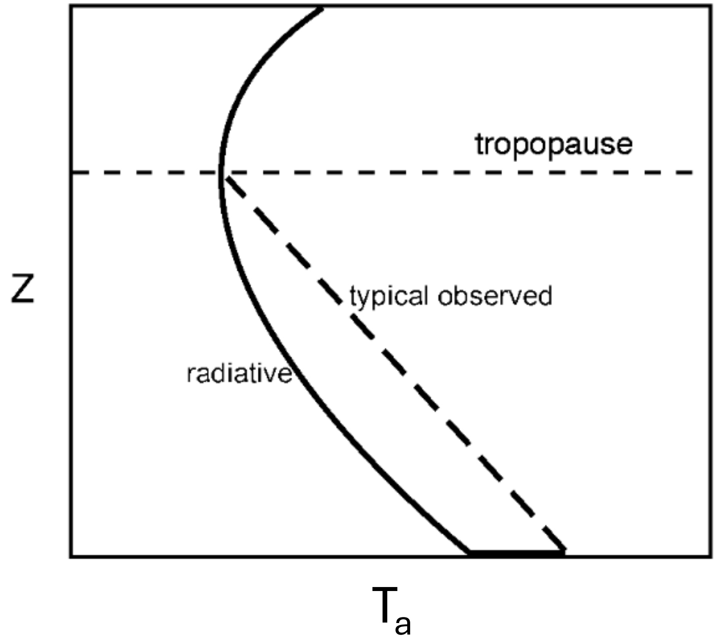
Multi-layer, radiative-only GHG model

It results in a vertically-dependent profile of atmospheric temperature $T_a=T_a(z)$

It exhibits a discontinuity at surface, with ground much warmer than air above → (due to surface absorption dominating on tropospheric one)

In presence of convection (air density depending on temperature), this profile would be unstable

➔ we need a radiative-convective model

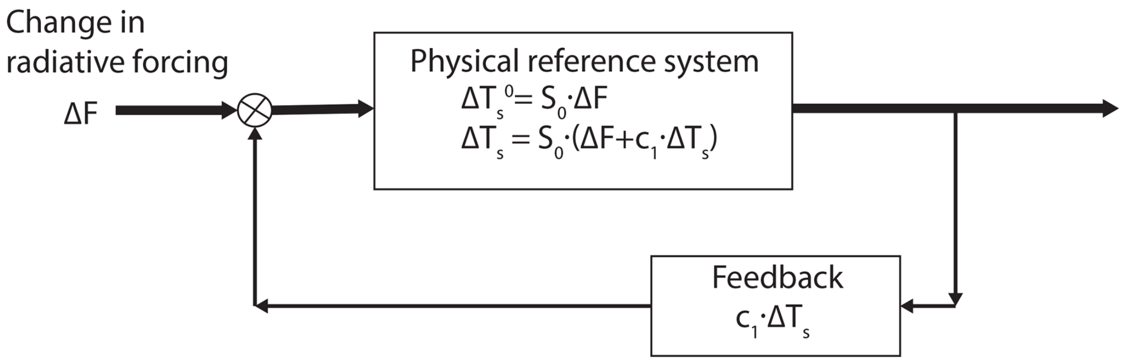


[MP08]3.4

Climate feedbacks

Modifying the response to a forcing

How changes in atmospheric properties (e.g. water vapor or clouds) respond to surface temperature increases ΔT_s and affect the radiative balance of the Earth, which in turn changes T_s (Manabe and Wetherald, 1967)



	Thermal SW - reflectivity/albedo	Thermal LW - heat re-distribution including water vapour and moisture	Atmospheric composition - greenhouse gases without water vapour	Atmospheric composition - non-GHG and particles
Fast physical climate feedbacks				
3.1 Atmospheric thermodynamic feedbacks				
3.1.1 Planck response		■		
3.1.2 The combined water vapour lapse rate feedback		■		
3.2 Cloud feedbacks				
3.2.1 Rise of cloud top feedback		■		
3.5 Sea ice feedbacks				
3.5.1 Sea ice albedo feedback	■	■		
4.5 Aerosol-climate feedbacks				
4.5.1 Feedbacks between marine aerosol emissions and climate change	■	■		■
4.5.2 Feedbacks between dust mobilization and climate, including fertilizing effects	■	■	■	■
4.5.3 Secondary aerosol feedbacks	■	■	■	■
4.5.4 Aerosol-cloud feedbacks	■	■	■	■

➔ A feedback mechanism can either amplify (positive, $c_1 > 0$) or reduce (negative, $c_1 < 0$) the change

Heinze et al. (2019), Earth System Dynamics

Climate feedbacks

Negative feedback: Planck response

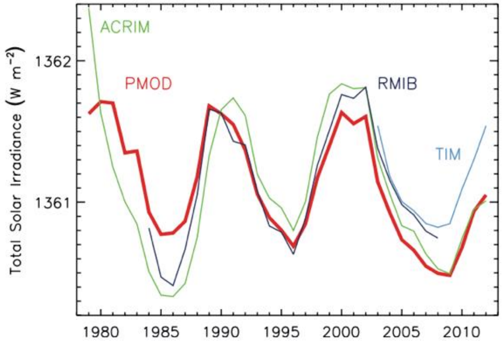
As more energy is added to the planet, it radiates at a higher temperature, but not so high.

From Planck's black body law <u>and</u> assumption that Ts and Te differ by a constant:

$$\frac{\partial T_s}{\partial Q_{BB}} = \left(4\sigma T_e^3\right)^{-1} = 0.26 \frac{\mathrm{K}}{\mathrm{W\,m^{-2}}}$$

Note: a ΔQ_{BB}=1 $W \cdot m^{-2}$change demands a 4/(1-α) ΔQ_{BB} =6 $W \cdot m^{-2}$ change in solar forcing

During the 11-year sunspot cycle, Sun's irradiance varies by 1 $W \cdot m^{-2}$ (s. figure aside)
→ Ts changes by about 0.26K /6 ~ 0.04 K in response to Sun's cycle.



[IPCC5] Fig.8.10

➔ A negative feedback, as it prevents a runaway warming

Note: on Venus the "<u>and</u>" condition is not valid due to strong GHG effect between surface and the higher atmosphere, where the Outgoing Longwave Radiation (OLR) originates from

Climate feedbacks

Positive feedback: water vapour

Water vapour saturation pressure increases exponentially with temperature (➔)
Thus, changes in specific saturated humidity are linear in temperature changes:

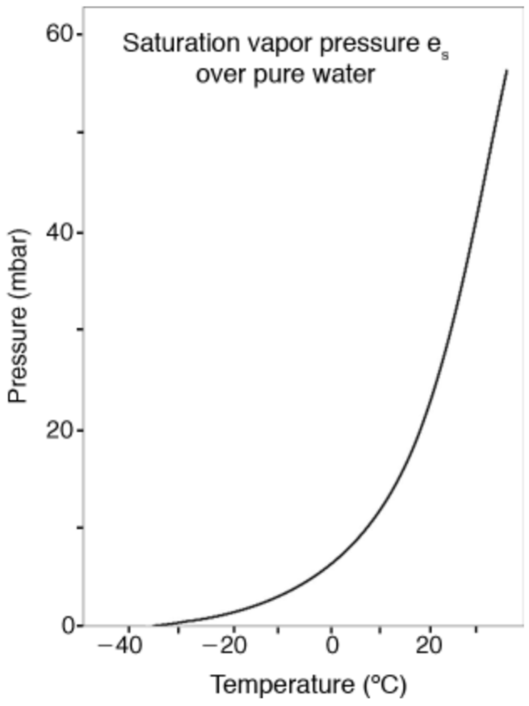
$$\frac{de_s}{e_e} = \beta dT,$$

with β = 0.067 °C^{-1} :

1°C change in air T. implies a 7% change in specific saturated humidity (Clausius-Clapeyron)
As relative humidity is nearly constant, absolute humidity would also grow at this rate
This implies a stronger greenhouse effect (H_2O is a large absorber in the longwave spectrum)

➔ A positive feedback, as it doubles the climate sensitivity:

$$\frac{\partial T_s}{\partial Q}_{\text{BB and H}_2\text{O}} = 0.5 \frac{\text{K}}{\text{W m}^{-2}}$$



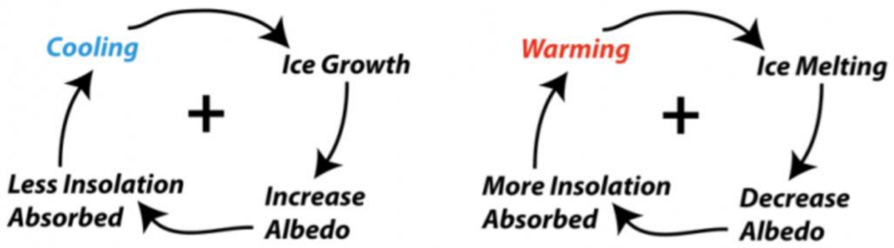
[MP08] 1.5

Climate feedbacks

Positive feedback: ice albedo

Ice-covered surface has a higher-than-average albedo (α ~ 0.2-0.7)

https://www.e-education.psu.edu/earth103/node/668



As energy is added to the planet:

ice sheets melt,

planetary albedo is reduced,

absorbed shortwave radiation (1- α) increases

➔ A positive feedback, as it amplifies global mean temperature changes (of both signs)

Aerosols

Properties

both natural and anthropogenic sources

wide range of sizes (.001 – 10 μm)

both primary (emitted at source) and secondary (formed from gaseous precursors)

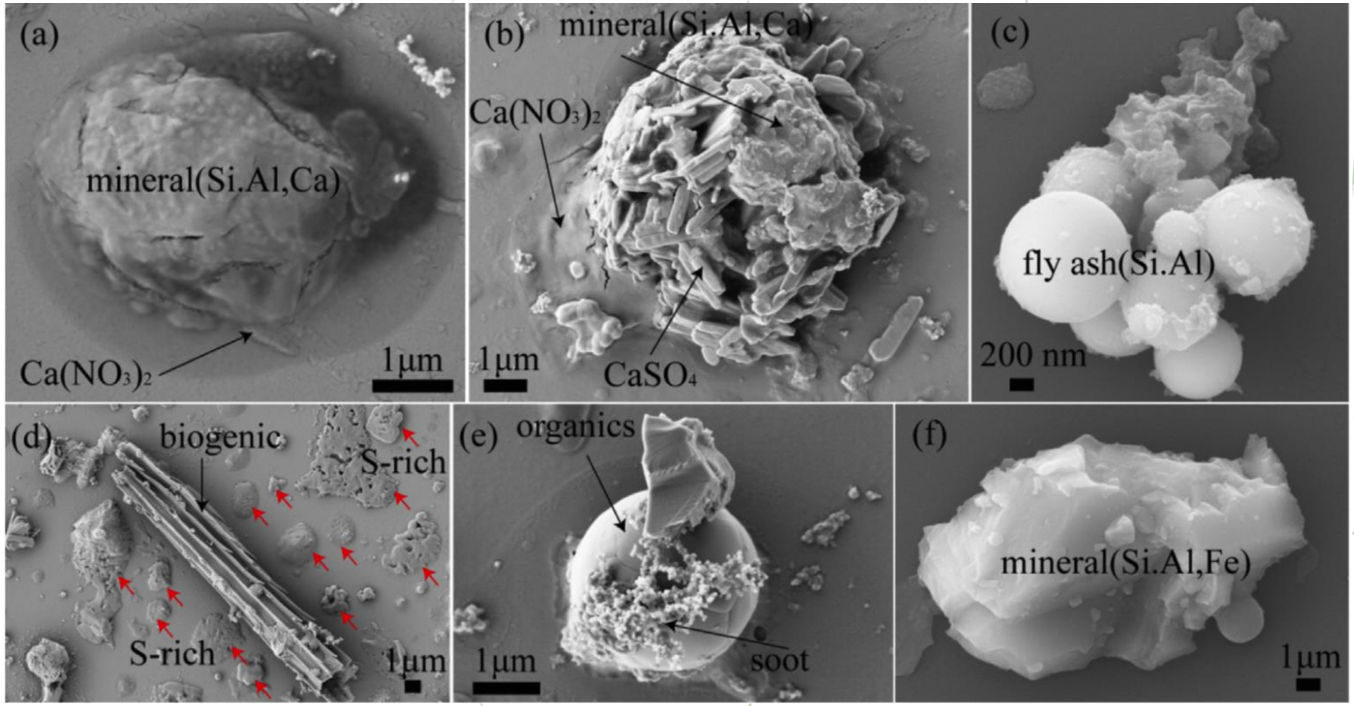
can be externally or internally mixed

atmosphere removal via either dry or wet deposition→ lifetime from minutes to weeks

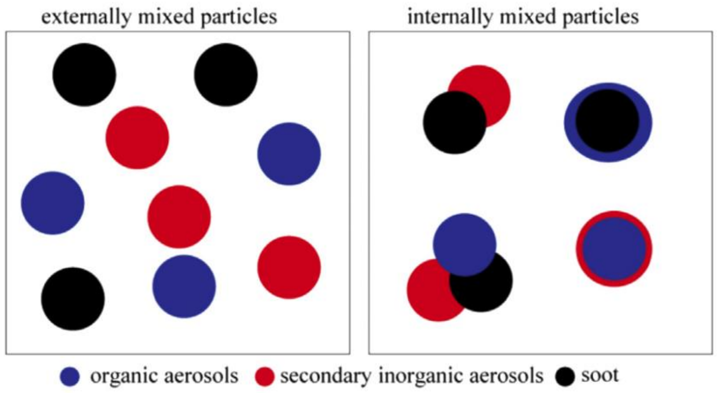
four main types:

- sulfate
- black carbon (BC) and organic carbon
- dust
- sea salt

cf. Haywood and Boucher (2000), Review of Geophysics



pictures from: Li et al. (2016), Journal of Cleaner Production



Aerosols

Physical interactions

- **Direct effect**: absorption and Mie scattering of (mainly) solar radiation

○ [*planetary albedo*] aerosol extinction (absorption + reflection) → reduction in surface albedo

Single Scattering Albedo (SSA = scattering/extinction):

SSA ~1 for sulfate aerosols, 0.2 for BC

Net Top Of Atmosphere (TOA) forcing of aerosols:

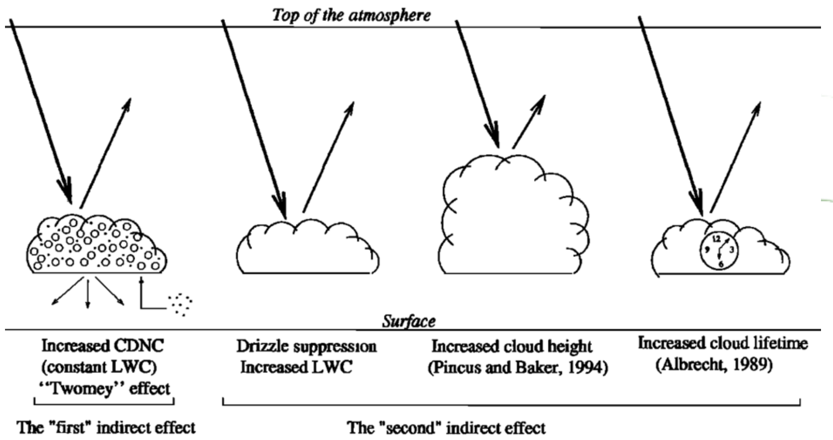
- negative, if SSA> 0.95
- positive, if SSA < 0.85

→ TOA aerosol forcing is negative, unless >19% of BC

- **Indirect effect**(s): modify microphysical and radiative properties of clouds:

○ I [*cloud albedo*]: more cloud condensation nuclei (CCN) and ice nuclei → decrease in droplet size → brighter cloud (Twomey effect) → planet cooling

○ II [*cloud lifetime*]: smaller droplets → less coalescence → less precipitation → cloud lifetime increase → more cloudiness and albedo



Ramanathan et al. (2001), Science

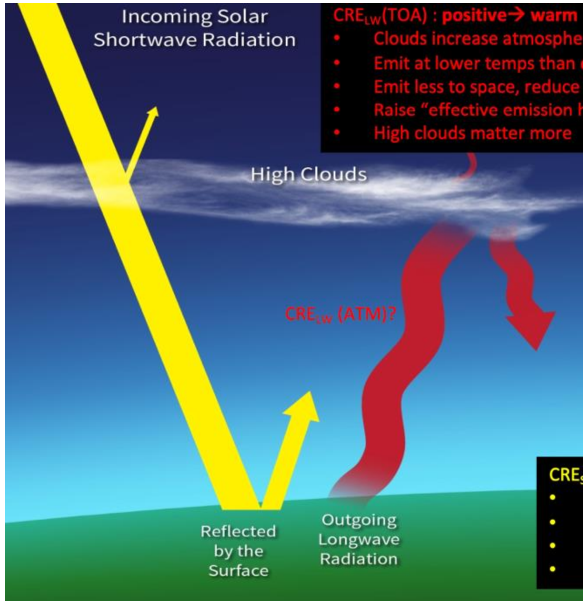
Haywood and Boucher (2000), Review of Geophysics

Aerosols

Cloud Radiative Effect (CRE)

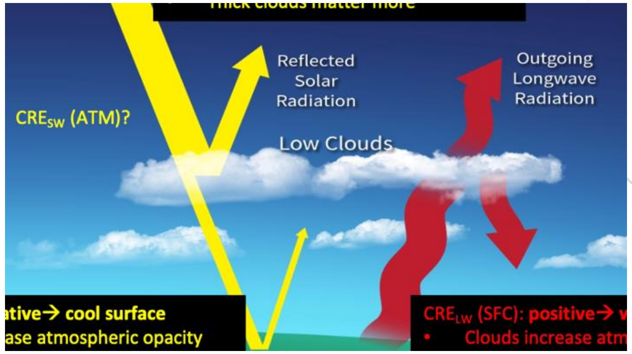
https://ntrs.nasa.gov/ - L. Oreopoulos

High Clouds (e.g. cirrus)



- thin → reflect little solar radiation
- cold → emit less than what they absorb
- net warming effect

Low Clouds (e.g. stratus, stratus cumulus)



- thick → reflect more solar radiation
- warm → emit more → limited GHG effect
- net cooling effect

The real situation is much more complicated
(
- more cloud classes
- more surface types
- latitudinal variations
- seasonal variations

)

→ need a numerical model to explore the global impact

cf. Lee et al. (2024), Geosci. Model Dev.
DOI: 0.5194/gmd-13-673-2020

Aerosols

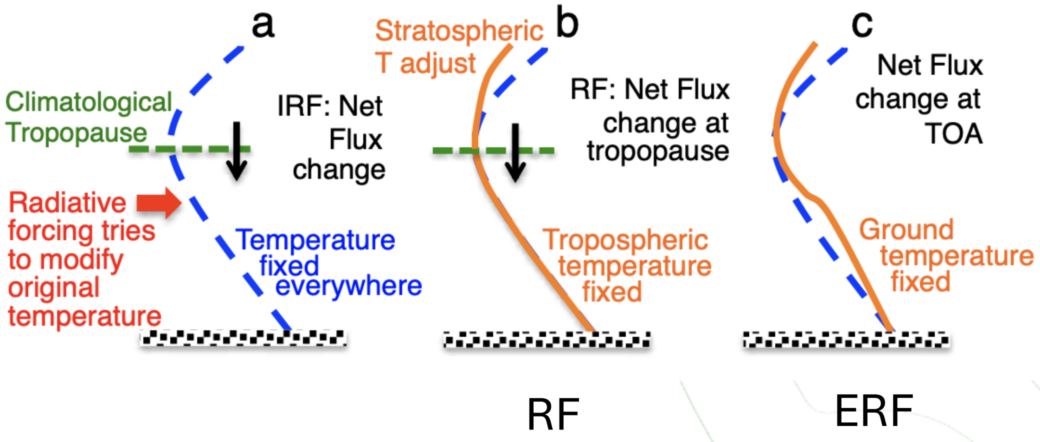
Radiative Forcing

Computationally prohibitive to to simulate the response to every individual factor of interest

→ Modelers tend to reuse simulations, with limited changes

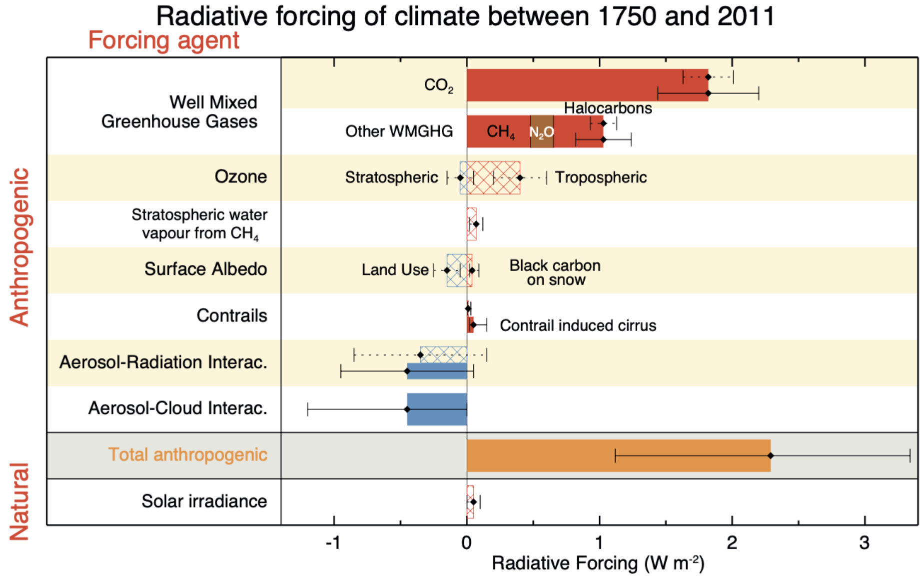
Radiative forcing is estimated from the change in TOA net (down-up) radiative flux due to an imposed change

- RF: just stratospheric adjustment is allowed (done offline through a radiative-only model)
- ERF (*effective* RF): also tropospheric adjustment, but with fixed Ts



[IPCC5] Fig. 8.1

Note: ERF from aerosol direct (indirect) effect is also called ERFari (ERFaci)



[IPCC5] Fig. 8.15

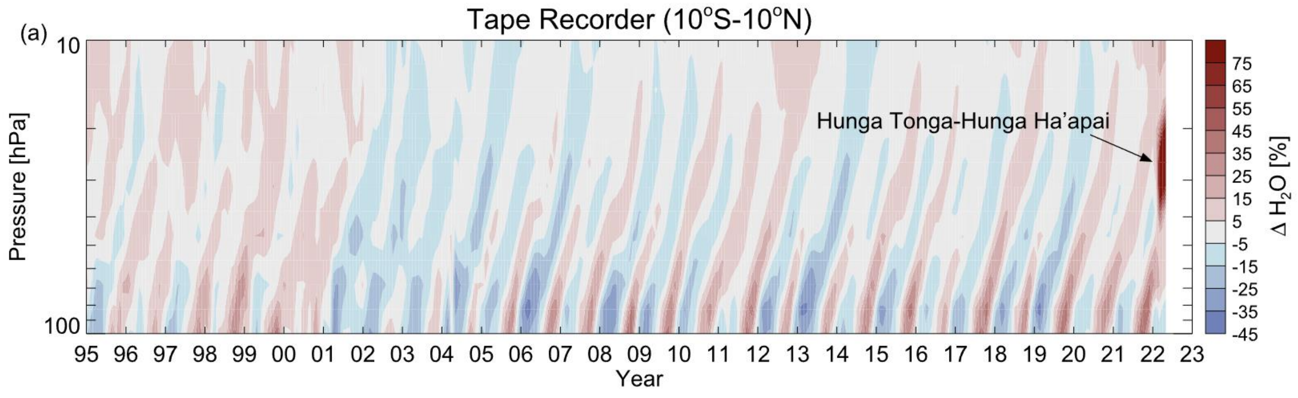
RF: hatched, ERF: solid bars

Global Warming Potential (GWP): time-integrated RF due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2

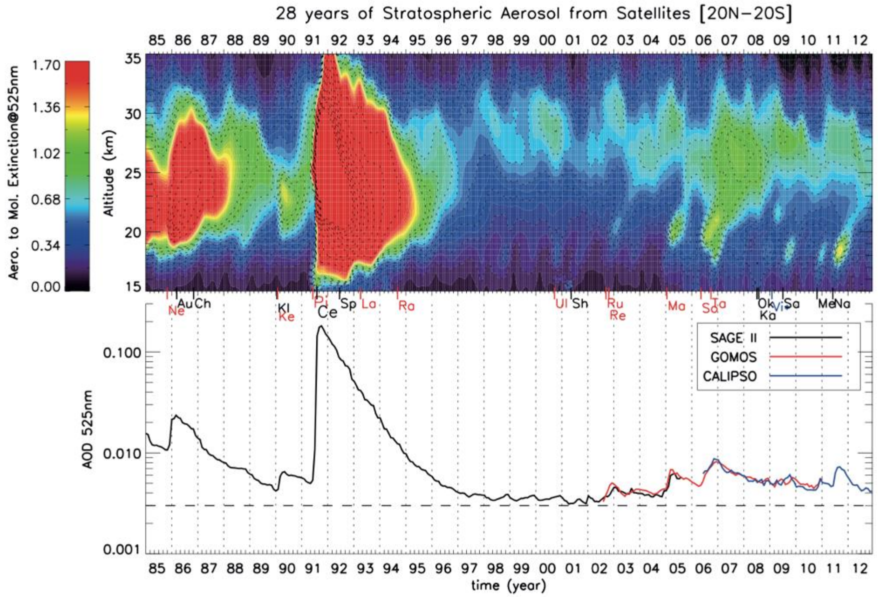
Aerosols

Volcanic radiative forcing

- Eruptions can inject substantial amounts of SO_2 into the stratosphere
- in the stratosphere, at tropical latitude, lifetime of about one year (and not days as in troposphere)



Millàn 2022, GeoPhys. Res. Letters



[IPCC5] Fig.8.13

- ❑ Pinatubo 1991 : 17 Tg SO_2 → negative RF
- ❑ Hunga Tonga 2022: 146 Tg H_20 → positive RF

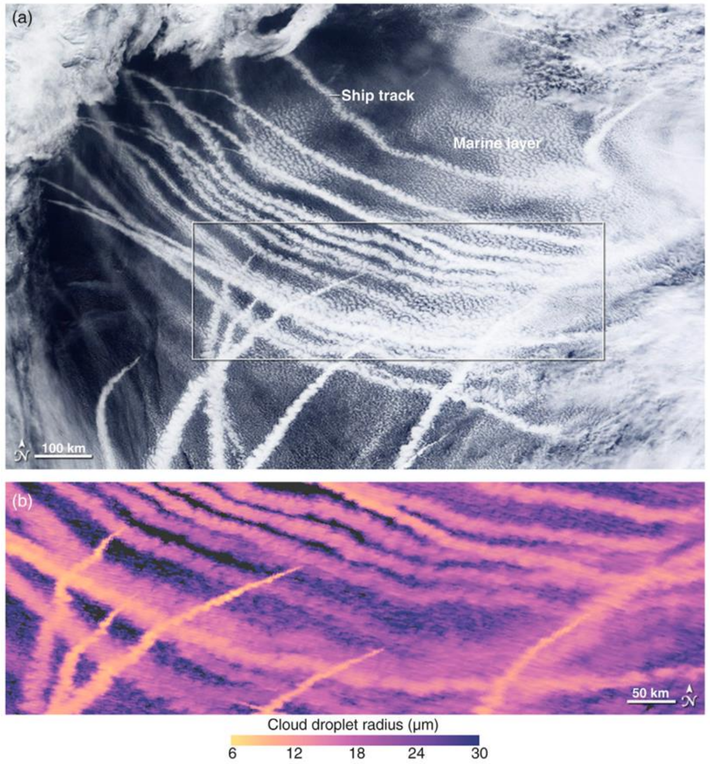
➔ Volcano eruptions as a natural experiment of a stratospheric aerosol injection.

Note: the Scientific Advice Mechanism to the EU recommended (Dec.2024) a Europe-wide moratorium on using solar radiation modification technologies https://scientificadvice.eu/advice/solar-radiation-modification/

Aerosols

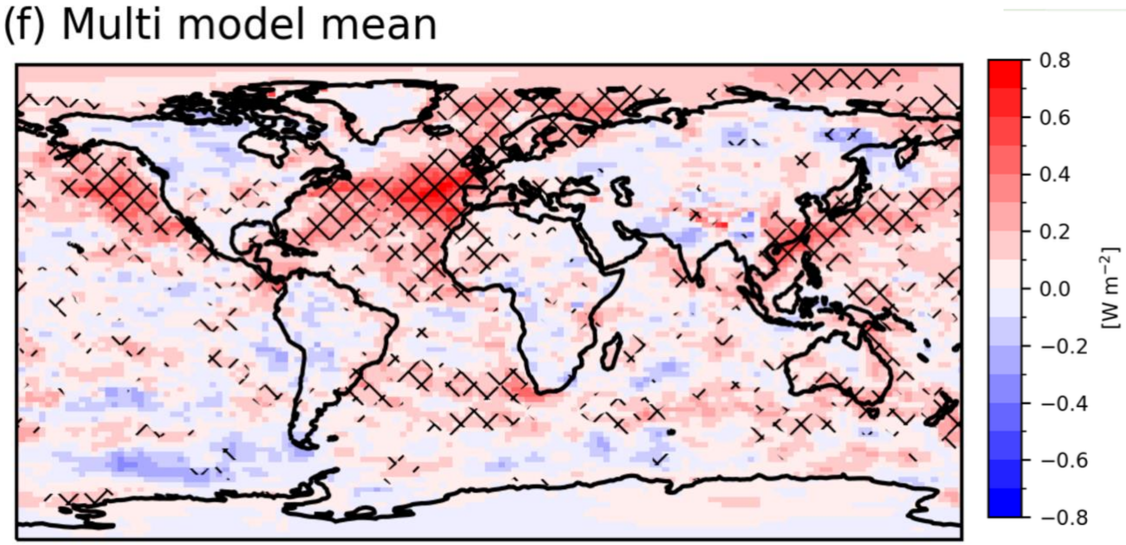
Shipping ERF

Large emissions of sulfates from ships → more CCN → more low clouds (with small droplets *) along the tracks



[H16] Fig.12.7

*) For effective radius < 14 μm, precipitation usually does not occur → cloud persistance→ feedback



Skeie et al. (2024), Atmospheric Chemistry and Physics

For protecting human health, the International Maritime Organization imposed a "sulfur cap", effective since 2020:

→ sulfate contents of fuels reduction by ~80%

→ sudden reduction in sulfate emissions

→ less along-track low clouds

→ positive change in TOA forcing

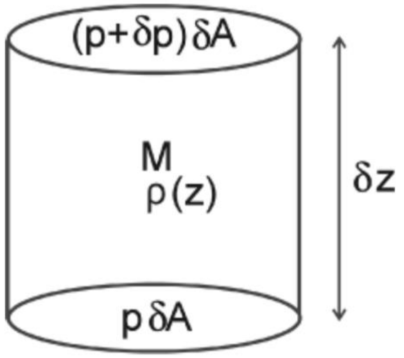
→ additional global warming (*climate penalty* of air quality)

Convection

Hydrostatic balance

Forces exerted on a column of fluid:

- pressure on upper side
- pressure on lower side
- gravity



[MP08] 3.5

setting the net force to zero implies:

$$\frac{\partial p}{\partial z} + g\rho = 0.$$

(equation of hydrostatic balance)

➔ pressure *decreases* with height in proportion to the weight of the overlying fluid (exponentially for air, linearly for water)

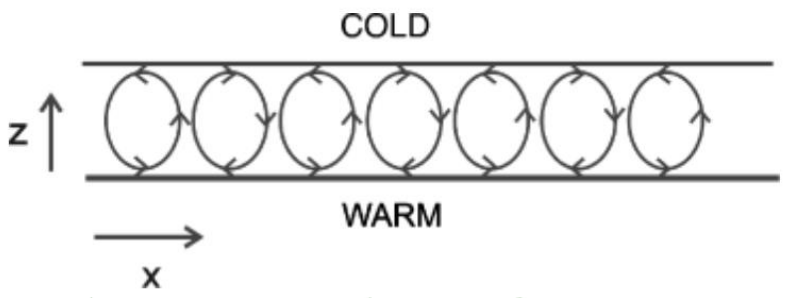
Note: density must be provided through the fluid's equation of state

Convection

Homogeneous fluid heated from below

In this case, despite hydrostatic balance, motions develop.
Two questions arise:

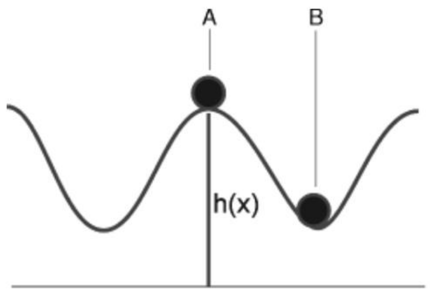
1. why?
2. why horizontal inhomogeneity?



[MP08] 4.2

Key fact: the vertical configuration is in equilibrium, but an instable one:

if a perturbation triggers motion, its amplitude increases ➔



[MP08] 4.3

in A, potential energy is reduced and converted into kinetic one;

In B, energy must be supplied to mantain a higher potential energy state

Convection

In Water

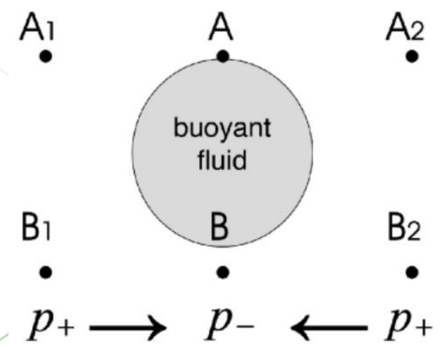
Lighter objects immersed in water bounce up («Archimede's principle»): how to extend this to parcels of fluid?

Horizontal pressure gradient force restores pressure deficit at B ➔

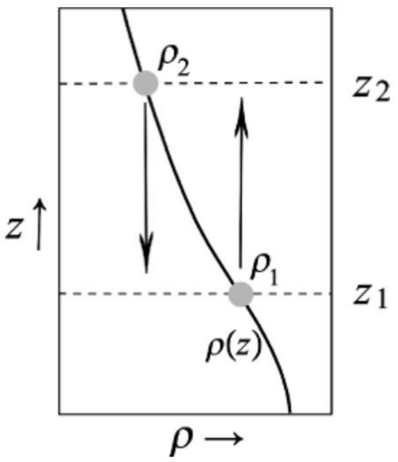
excess of fluid at B exerts an upward force on the lighter fluid above

Buoyancy b>0 develops with: $$b = -g\frac{(\rho_P - \rho_E)}{\rho_P}$$

➔ not even unstable equilibrium is possible!



[MP08] 4.4



[MP08] 4.5

Adiabatic displacement of a parcel of fluid from 1 to 2 ➔

Buoyancy depends just on ambient density ρ_E:

$$\left.\begin{array}{c}\text{positively}\\\text{neutrally}\\\text{negatively}\end{array}\right\}\text{buoyant if}\left(\frac{d\rho}{dz}\right)_E\left\{\begin{array}{l}>0\\=0\\<0\end{array}\right. .$$

This is a "top-heavy" criterium of instability.

→ Note: if density independent of salinity, ρ_E and T gradients are opposite in sign

Convection

In dry air

Unlike water, air is compressible.
In adiabatic rise, it expands and cools: $$\frac{dT}{dz} = -\frac{g}{c_p} = -\Gamma_d,$$ with $\Gamma_d \simeq 10\,\mathrm{K\,km^{-1}}$

This leads to a stability condition:

$$\left.\begin{array}{c}\text{unstable}\\ \text{neutral}\\ \text{stable}\end{array}\right\} \text{ if } \left(\frac{dT}{dz}\right)_E \left\{\begin{array}{l} < -\Gamma_d \\ = -\Gamma_d \\ > -\Gamma_d \end{array}\right.$$

replacing the simple "top-heavy" condition that applies to water.

Let us check if the atmosphere can sustain convection (use tropical values):

$$\left(\frac{dT}{dz}\right)_E \simeq \frac{T(500\text{mbar}) - T(1000\text{mbar})}{Z(500\text{mbar}) - Z(1000\text{mbar})} = \frac{(270-295)\ \text{K}}{(5.546-0.127)\ \text{km}} \simeq -4.6\,\mathrm{K\,km^{-1}},$$

This rate is larger than $-\Gamma_d$, so atmosphere is typically stable to dry convection (stratification).

Convection

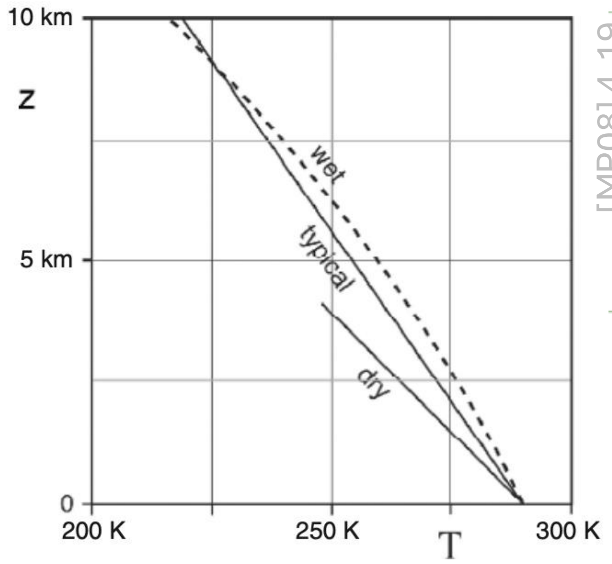
In moist air

Condensation of water vapour releases latent energy to the air parcel, which favours its convection.

Thermodynamic analysis shows that the condition for instability now reads: $\frac{dT}{dz} < -\Gamma_s$,
with the saturated adiabatic lapse rate:

$\Gamma_s \simeq 3\,\mathrm{K\,km^{-1}}$ tropical, moist lower troposphere

$\Gamma_s \simeq \Gamma_d = 10\,\mathrm{K\,km^{-1}}$ upper troposphere

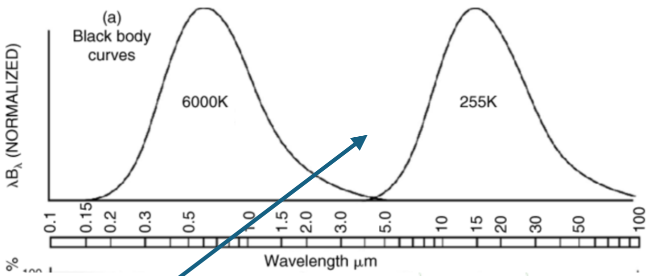


[MP08] 4.19

This rate can be easily exceeded (in magnitude) under typical tropical conditions

Convection

Radiative-convective equilibrium

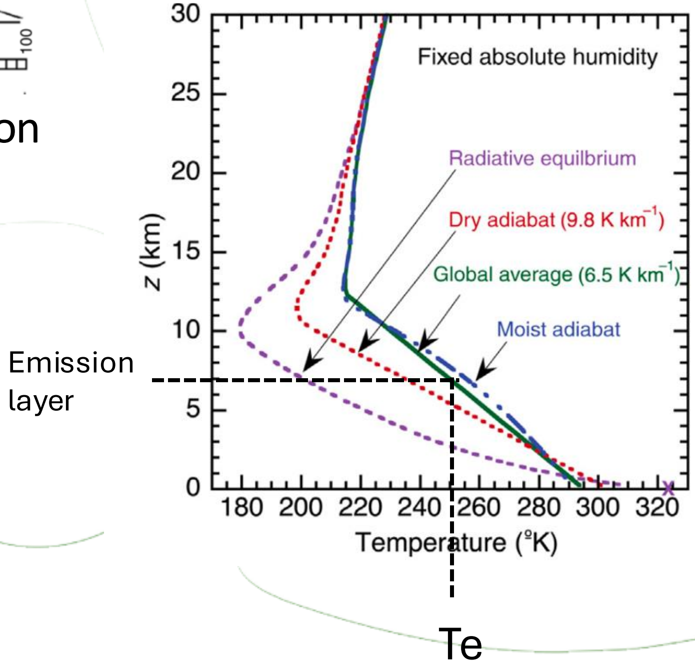


Convection mainly occurs in moist conditions, leading to saturation and cloud formation

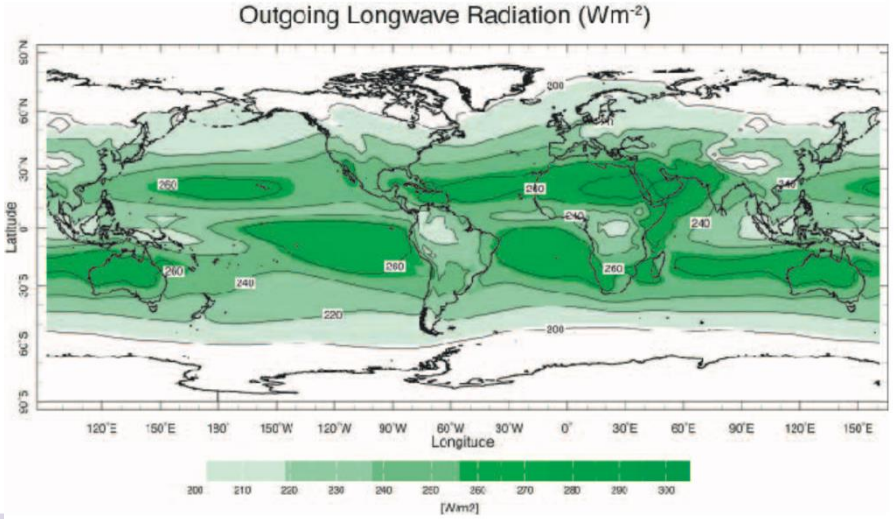
Monitor via OLR, which is (because of spectral separation) a proxy of Te.

From 0-D balance, OLR = 239 $W \cdot m^{-2}$

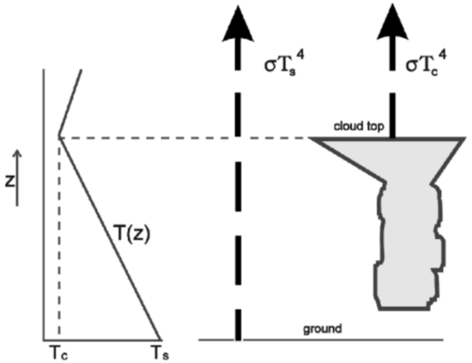
OLR is low in both polar regions (cold) and the equatorial regions (cloud tops).



[H16] 3.16



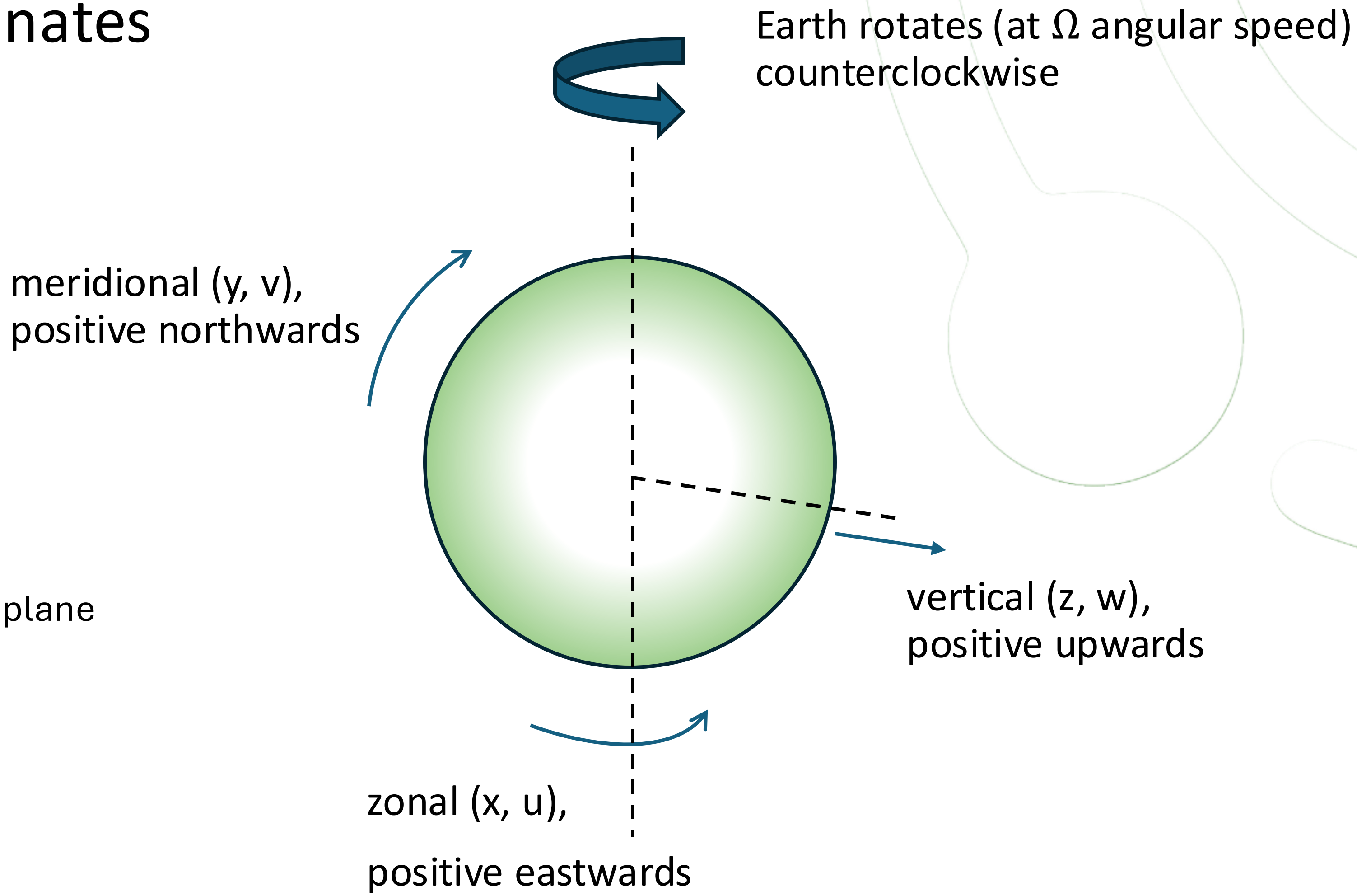
[MP08] 4.26



[MP08] 4.27

Meridional structure of the atmosphere

System of coordinates

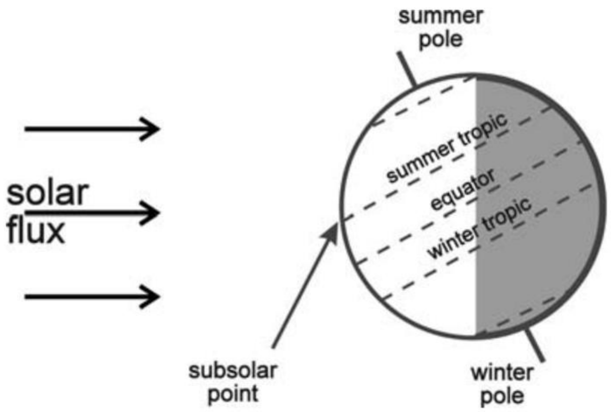


the locally tangent plane (x,y) is also called "horizontal"

Meridional structure of the atmosphere

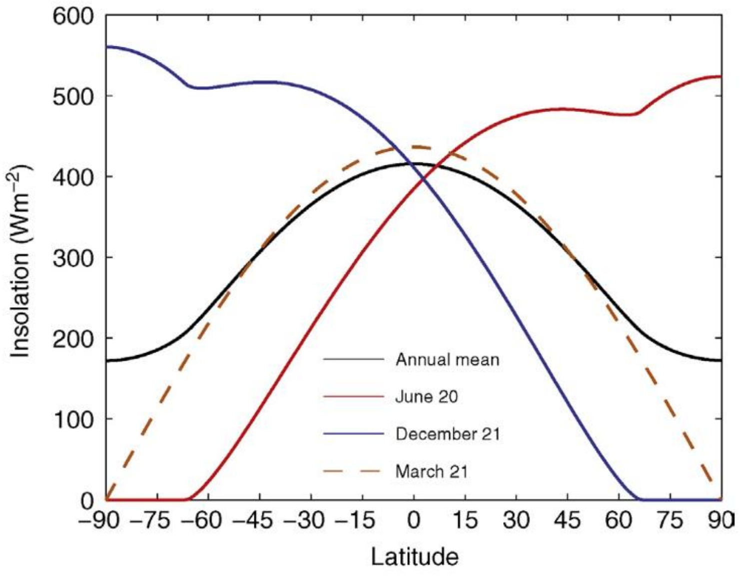
Geometry of insulation

- Earth axis is tilted by 23.5° with respect to the orbital plane
- Earth-Sun distance reaches a minimum (3.3% below maximum) on January 3rd



[MP08] 5.3

The equinox curve shows what would occur on annual average if orbital tilt were zero:



[H16] 2.7

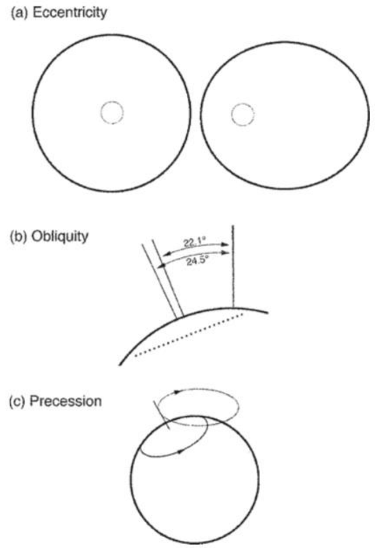
Consequences: day length varies trough the year (seasons); polar regions receive solar radiation during summer; the annual mean equator-to-pole difference is reduced; the December solstice insolation at the South pole exceeds the one at North pole by ~10%

Curiosity: tilting is presently decreasing a rate of 0.013°/century

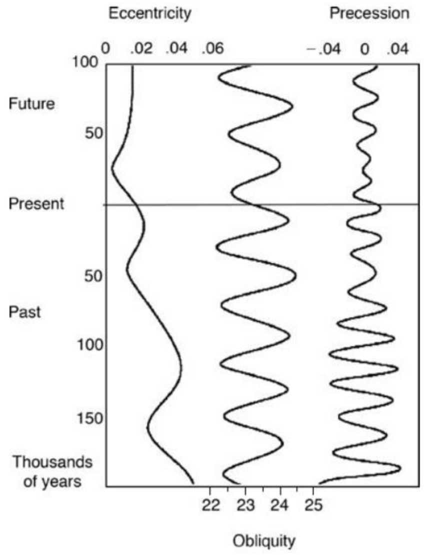
Meridional structure of the atmosphere

Geometry of insulation

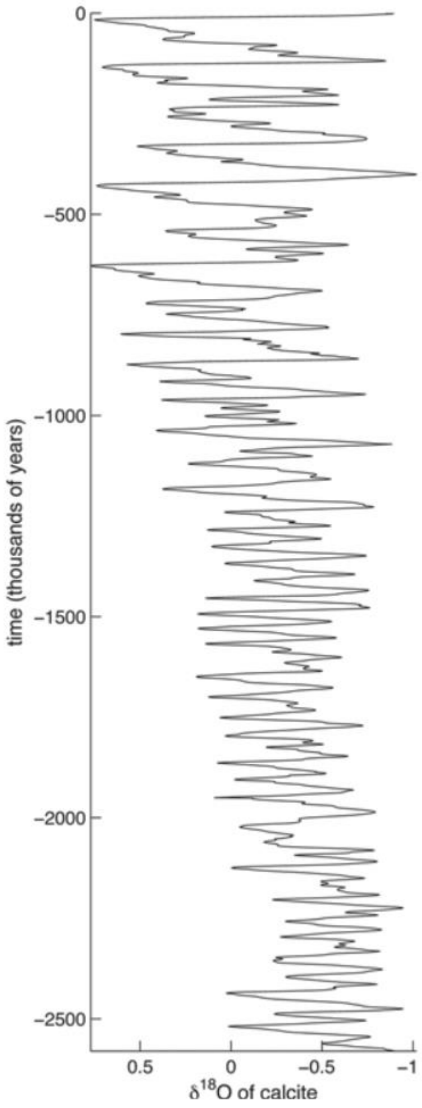
- Earth axis tilting varies in [22.1-24.5]° on a timescale of 41 ky
- This oscillation correlates well with $\delta^{18}O$ in the shells of foraminifera, a proxy of ocean temperature
- Other motions (eccentricity change and axis precession) have less clear relation to palaeoclimatic fluctuations



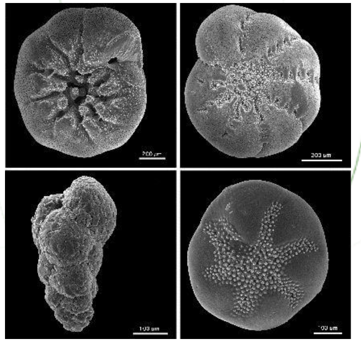
[MP08] 12.20



[MP08] 12.21



[MP08] 12.18



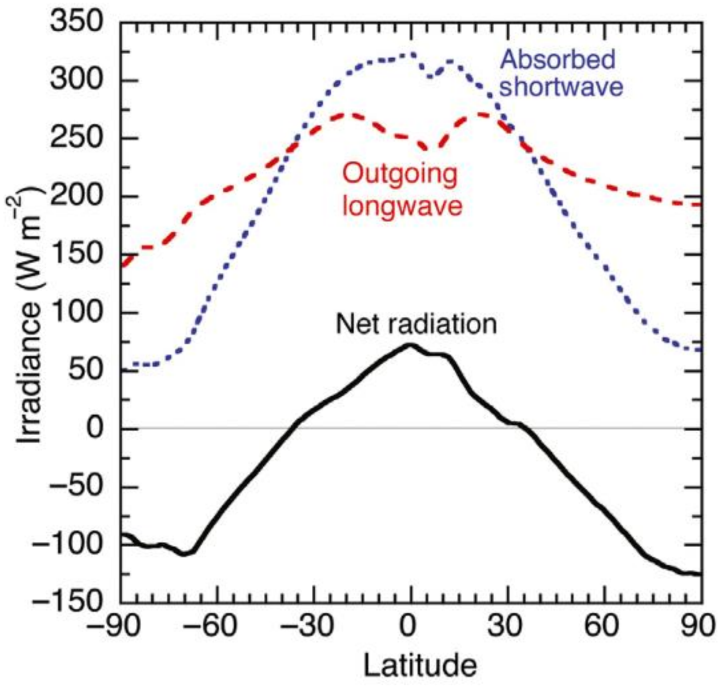
Foraminifera, https://en.wikipedia.org/wiki/%CE%9418O

animations: https://science.nasa.gov/science-research/earth-science/milankovitch-orbital-cycles-and-their-role-in-earths-climate/

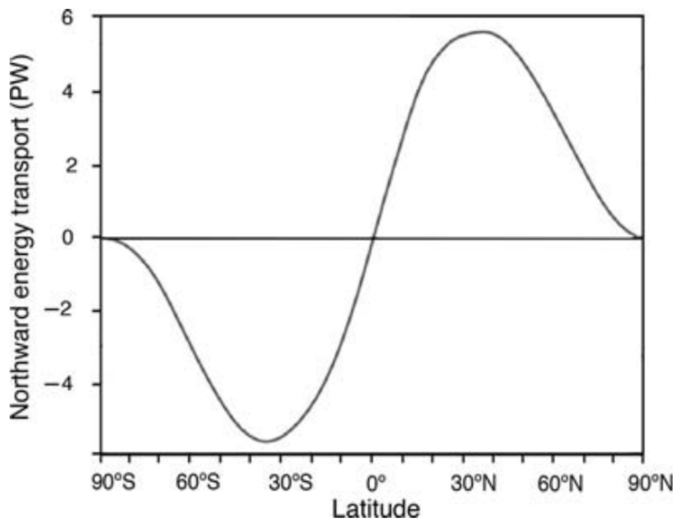
Meridional structure of the atmosphere

Heat balance and meridional transport

- Absorbed: incoming – reflected
- Outgoing: weaker meridional dependence (tip at equator due to cold tops of deep convective clouds)
- Net inbalance at the tropics



[H16] 2.12



[MP08] 5.6

Local energy balance➔

a poleward energy transport mechanism(s) must be in place

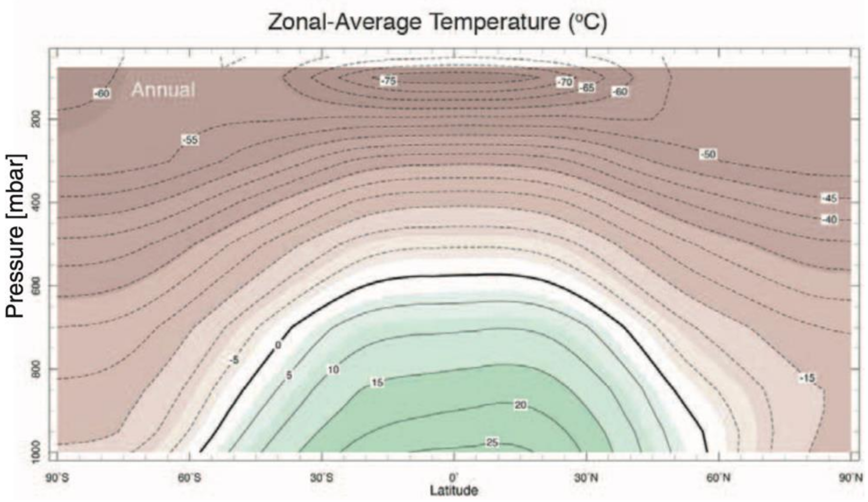
Meridional structure of the atmosphere

Temperature and humidity

Zonally-averaged T_a decreases upward and poleward

equator-pole contrast is about +40 °C at the ground

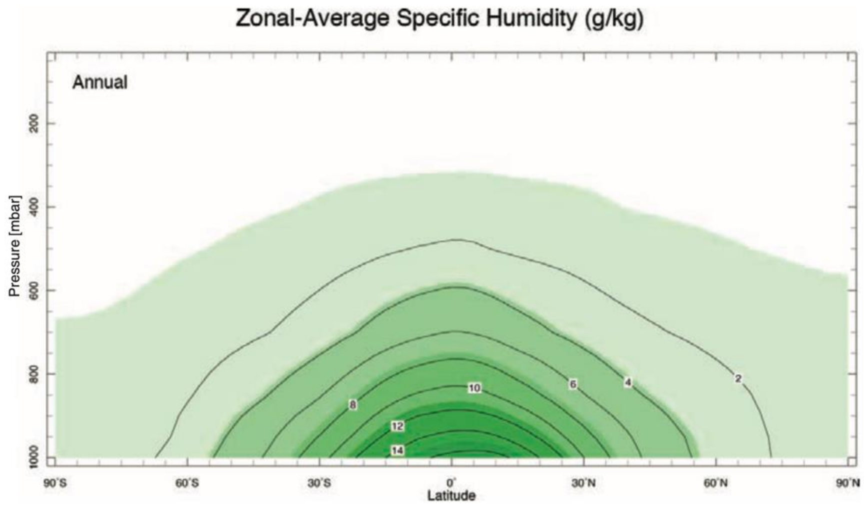
tropopause is high and cold in the tropics



[MP08] 5.7

moisture is strongly controlled by temperature, due to:

- Clausius-Clapeyron relation
- nearly constant relative humidity (70-80% at ground)



[MP08] 5.15

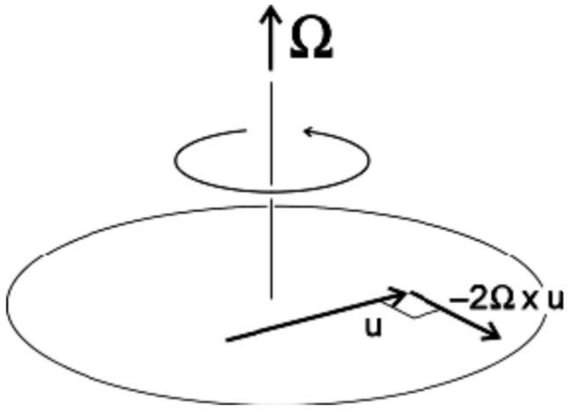
Coriolis force

A fluid parcel moving with velocity **u** in a rotating frame experiences a Coriolis acceleration.

Given the Earth's parameters (thinness of atmosphere and strength of gravity) its expression simplifies to

$$-2\boldsymbol{\Omega} \times \boldsymbol{u} \sim -f\,\hat{\boldsymbol{z}} \times \boldsymbol{u}$$

- with $f = 2\Omega \sin\varphi$ (Coriolis parameter, φ is latitude)
- directed to the right (left) of **u** in the northern (southern) hemisphere



[MP08] 6.10

4x tropical value

Latitude	$f\ (\times 10^{-4}\,s^{-1})$
90°	1.46
60°	1.26
45°	1.03
30°	0.73
10°	0.25
0°	0

Geophysical motions where Coriolis force is at play:

- cyclones and hurricanes
- trade winds
- ocean western boundary currents (e.g. Gulf Stream)
- Ekman transport

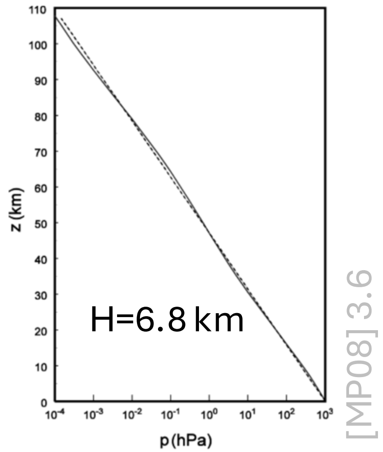
Meridional structure of the atmosphere

Geostrophic balance

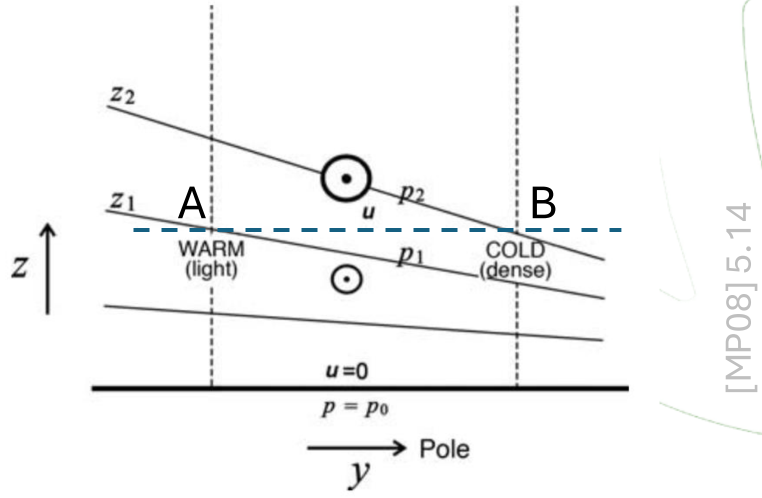
The *hydrostatic* balance and ideal gas equation lead to:

$$\frac{\partial z}{\partial \ln p} = -\frac{RT}{g} = -H,$$

vertical scale height *H* is proportional to the average temperature in the atmospheric layer.



Resulting exponential profile is strongly supported by observations



Consequences: $p_A > p_B$; isobaric surfaces are higher and more widely spaced in lower latitudes, where it is hotter.

→ poleward pressure gradient

Combined with Coriolis force → *geostrophic* flow,

$$\mathbf{u}_g = \frac{1}{f\rho}\hat{\mathbf{z}} \times \nabla p,$$

which is stronger aloft (wind shear) due to isobars spacing increasing with height

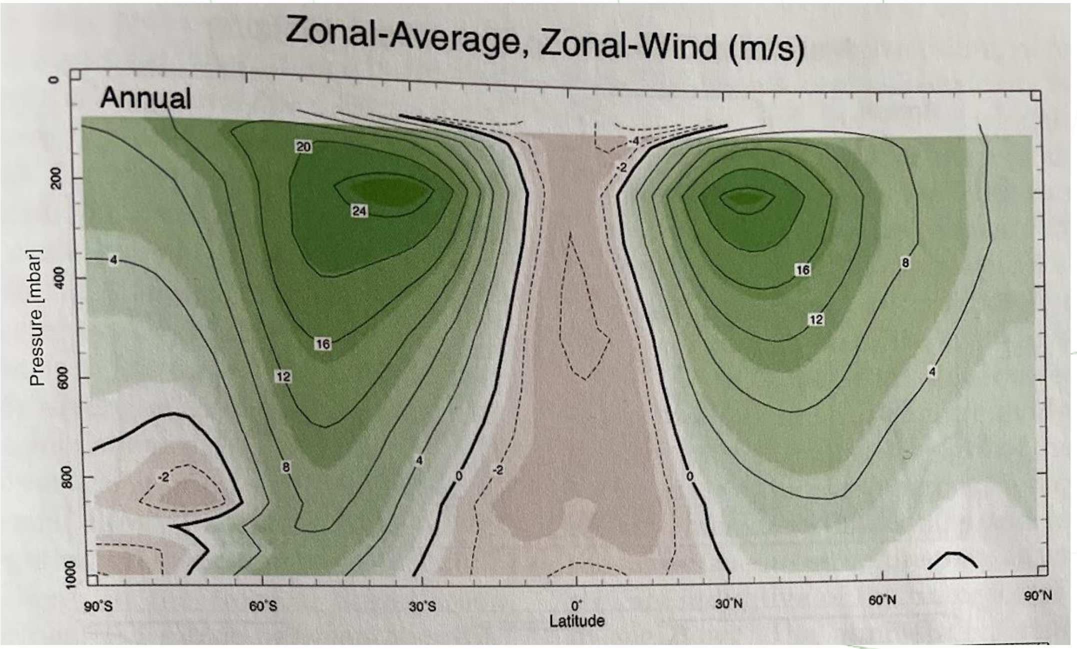
Meridional structure of the atmosphere

Zonal winds

Stronger winds are westerlies aloft (*subtropical jets*), $\bar{u}$ ~ 10 $m \cdot s^{-1}$

Weak sesonal variation, with jet intensifying and moving equatorward in the winter hemisphere

Near surface, easterlies prevail both in the tropics (contributing to the *trade winds*) and in the polar regions (surface air flowing equatorward) due to Coriolis



[MP08] 5.20

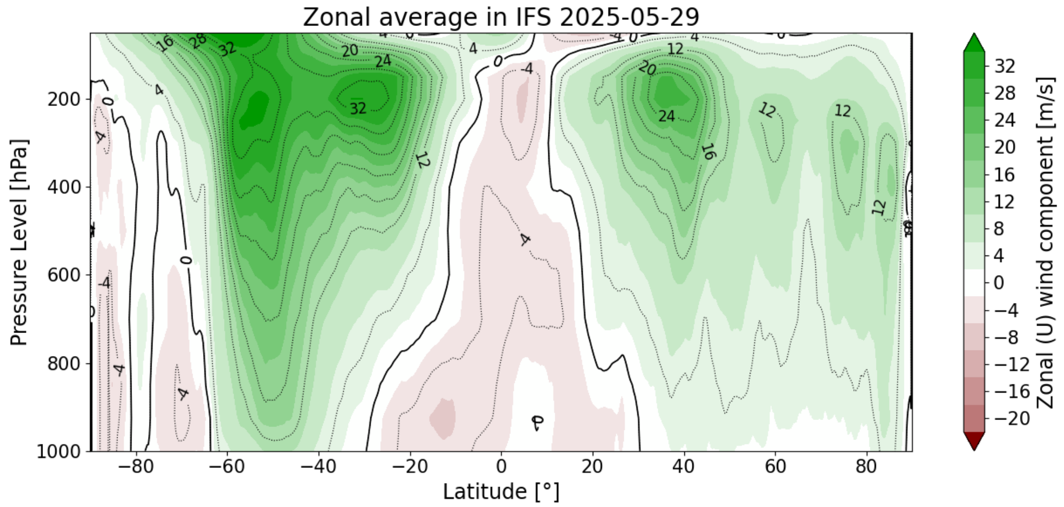
Meridional structure of the atmosphere

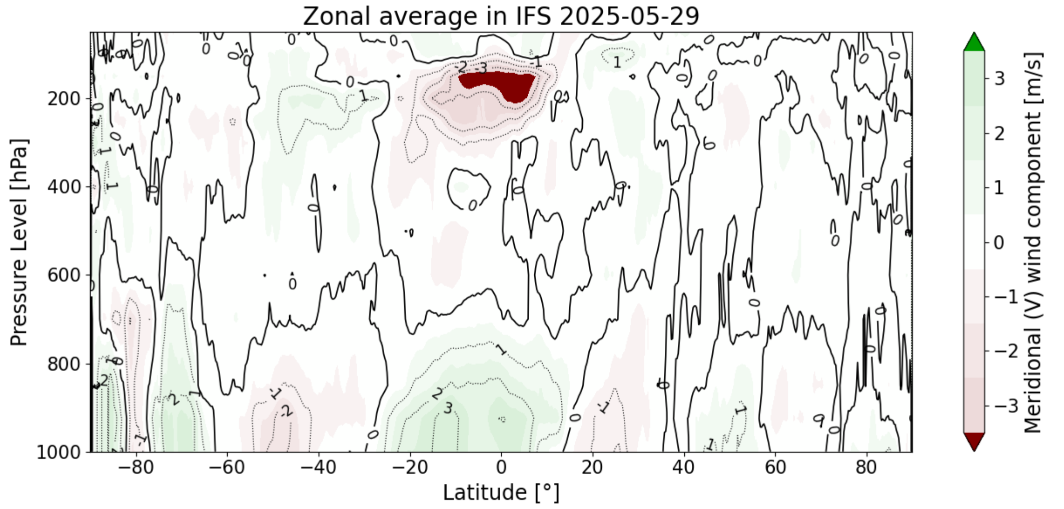
Zonally averaged wind

Single-day transect from a numerical weather prediction model

Data source: ECMWF IFS 0.25° latlon grid (86400 grid points/time step)

Zonal wind (u) is seen to be one order of magnitude stronger than meridional one (v)➔





https://www.ecmwf.int/en/forecasts/datasets/open-data

Mario L. Salinas

Meridional structure of the atmosphere

Overturning circulation

following subsolar point's migration, strong seasonal dependence

two tropical cells (*Hadley cells*), with air rising near equator (in the summer hemisphere) and sinking in the subtropics

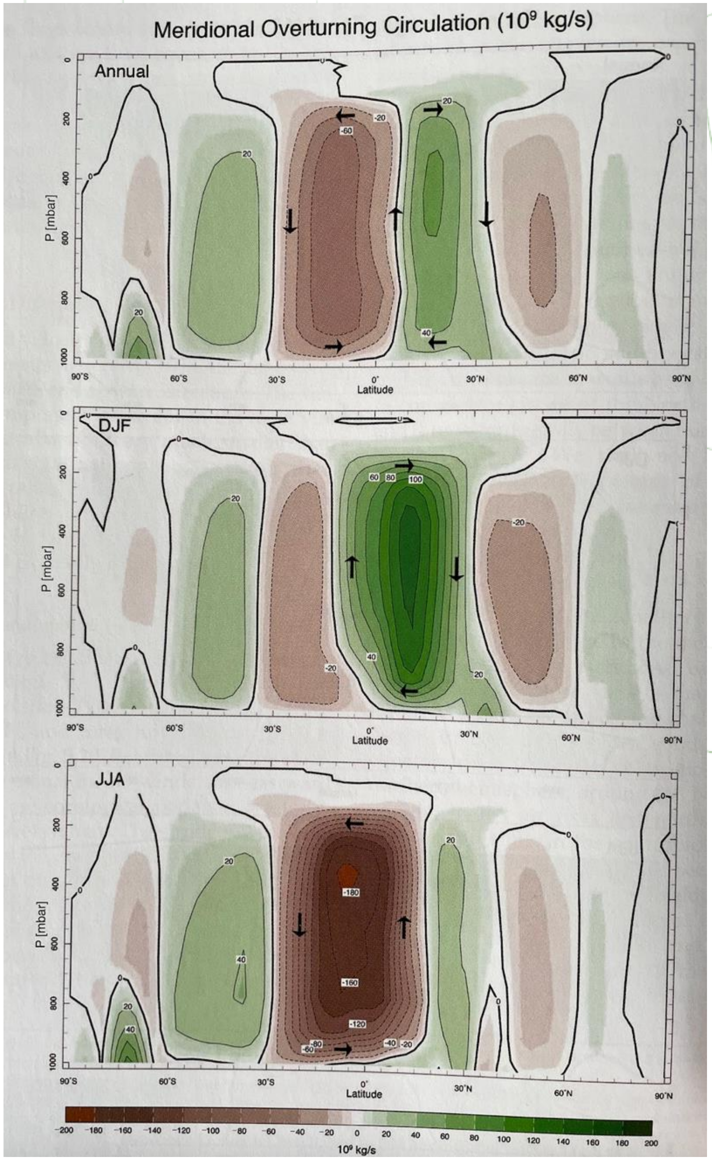
strong upward motion: deep convection leads to wet tropics

descending regions in the deserts belt

upper troposphere's winds towards winter pole at ~3 m/s

return flow in the lower troposphere provides the meridional component of the trade winds (which are north-easterlies)

circulation is the extratropics is dominated by eddies (s. after)



[MP08] 5.21

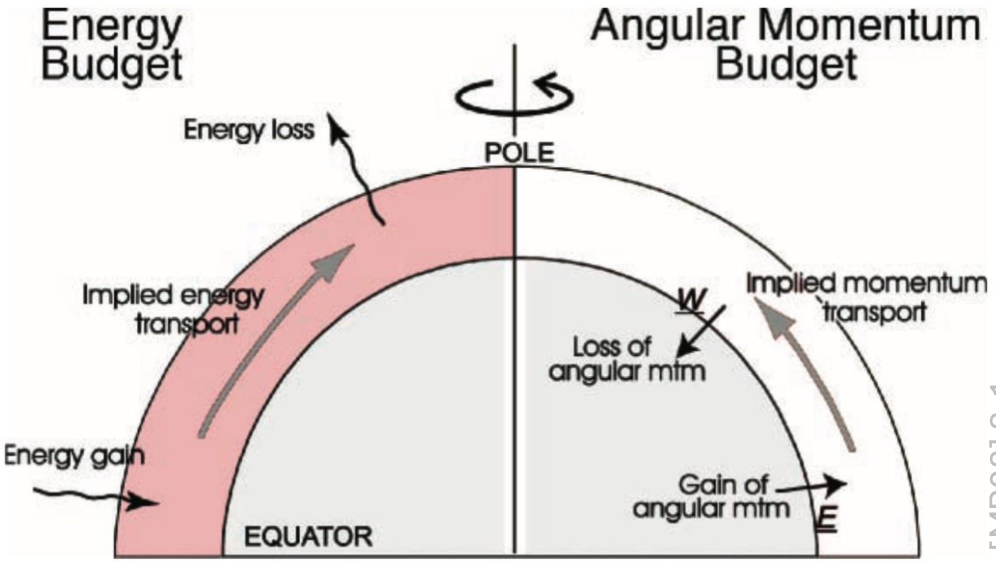
General circulation: atmosphere

Conservation of energy and angular momentum

- Net latitudinal unbalance of radiation: poleward transport is implied
- Earth angular momentum (counterclockwise) is transmitted to the atmosphere by friction and (in an axis-symmetric planet) must be conserved

The atmosphere (with a contribution by the ocean) circulates in a way to satisfy these constraints

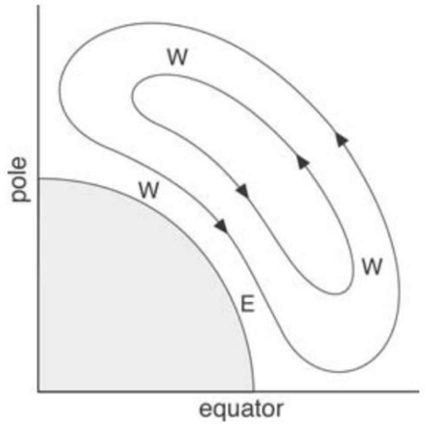
This is achieved via two distinct mechanisms, depending on relative importance of solar heating and speed of rotation



[MP08] 8.1

The (hypothetical) hemispheric Hadley cell

Differential latitudinal heating would lead to air rising in low latitudes, moving poleward (by pressure gradients), and sinking at higher latitudes. A surface equator flow closes the circuit.

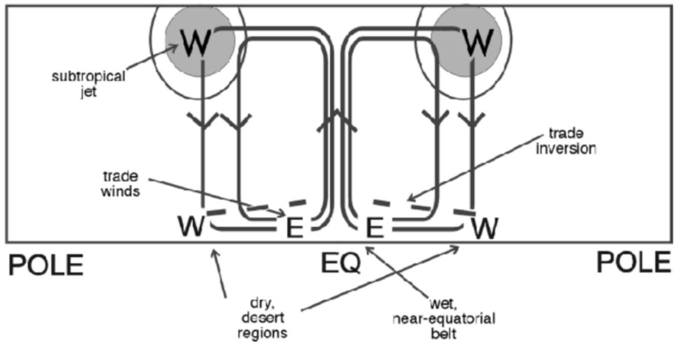


[MP08] 5.19

Along with Coriolis deflection, it would qualitatively explain the upper-level westerlies and the trade wind close to surface.
Surface-level subtropical westerlies would also occur for maintaning an overall null torque on the atmosphere.

However, conservation of angular momentum $A = \Omega r^2 + ur,$

would lead to unrealistically large zonal winds (130 m/s at 30° -- they are 1 order of magnitude smaller)



[MP08] 8.5

➔ Such a hemispheric Hadley cell is NOT realised.

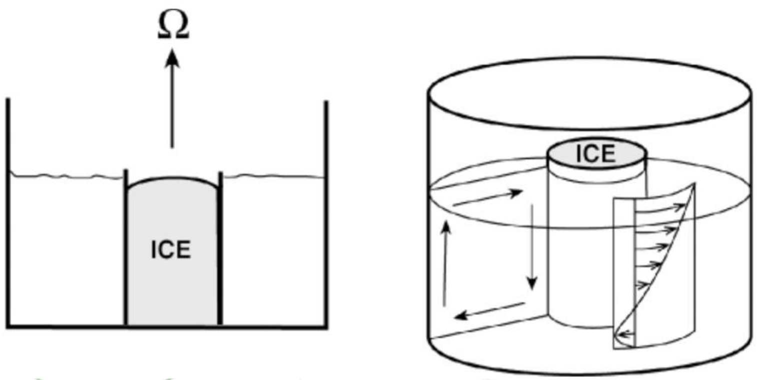
General circulation: atmosphere

Question: how will motions look like?

A tank filled with water contains an ice bucket placed at its center, creating a radial temperature gradient.

The entire setup is placed on a rotating table (Ω), with a camera mounted above, fixed to the table and looking downward.

Dye markers are introduced at specific locations in the tank, and their motion is recorded to observe flow patterns.



overturning circulation realized at low rotation speed

[MP08] 7.12

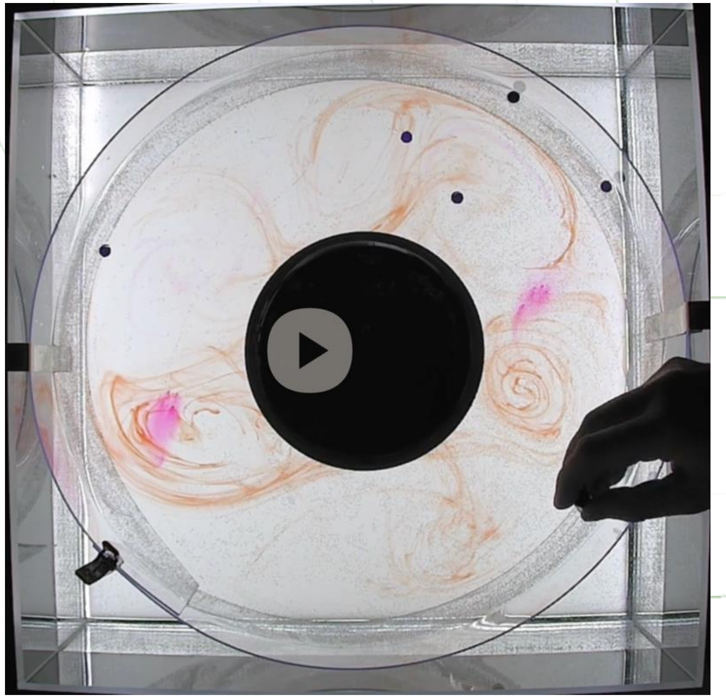
General circulation: atmosphere

Question: how will motions look like?

A tank filled with water contains an ice bucket placed at its center, creating a radial temperature gradient.

The entire setup is placed on a rotating table (Ω), with a camera mounted above, fixed to the table and looking downward.

Dye markers are introduced at specific locations in the tank, and their motion is recorded to observe flow patterns.



University of Gothemburg,
min. 3:25

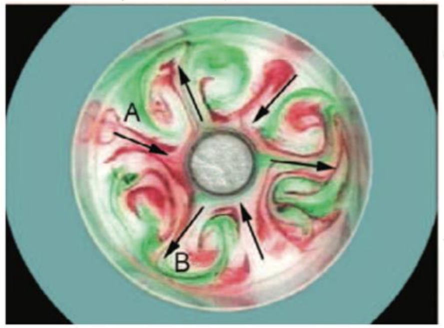
https://www.dropbox.com/scl/fi/umzzqi5cyj6ievnf10at6/baroclinic_wave.mp4?rlkey=3j967lqcg35z1m0weg53zntvp&e=3&dl=0

General circulation: atmosphere

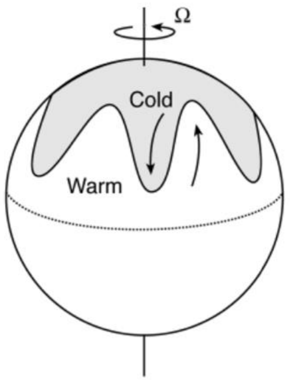
Baroclinic instabilities of a rotating fluid

Warm (A) and cool (B) fluids are exchanged radially by means of eddies

The fast rotation induces motions breaking the axisymmetry of the geostrophic circulation



[MP08] 8.4

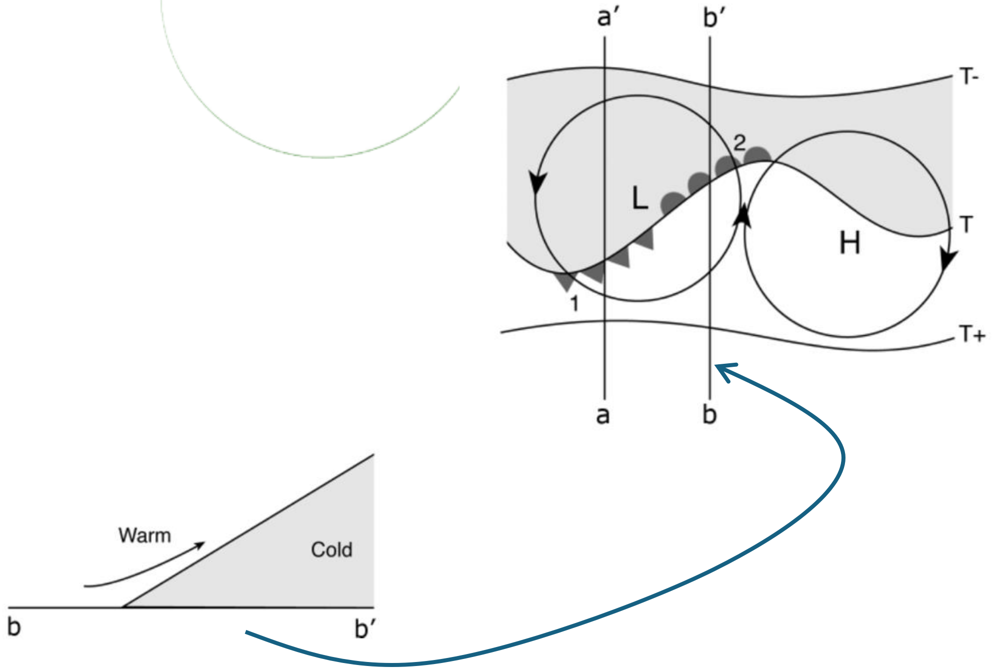


A similar behaviour is observed in the atmosphere, at the mid latitudes:

eddies stir the atmosphere zonally, exchanging heat meridionally

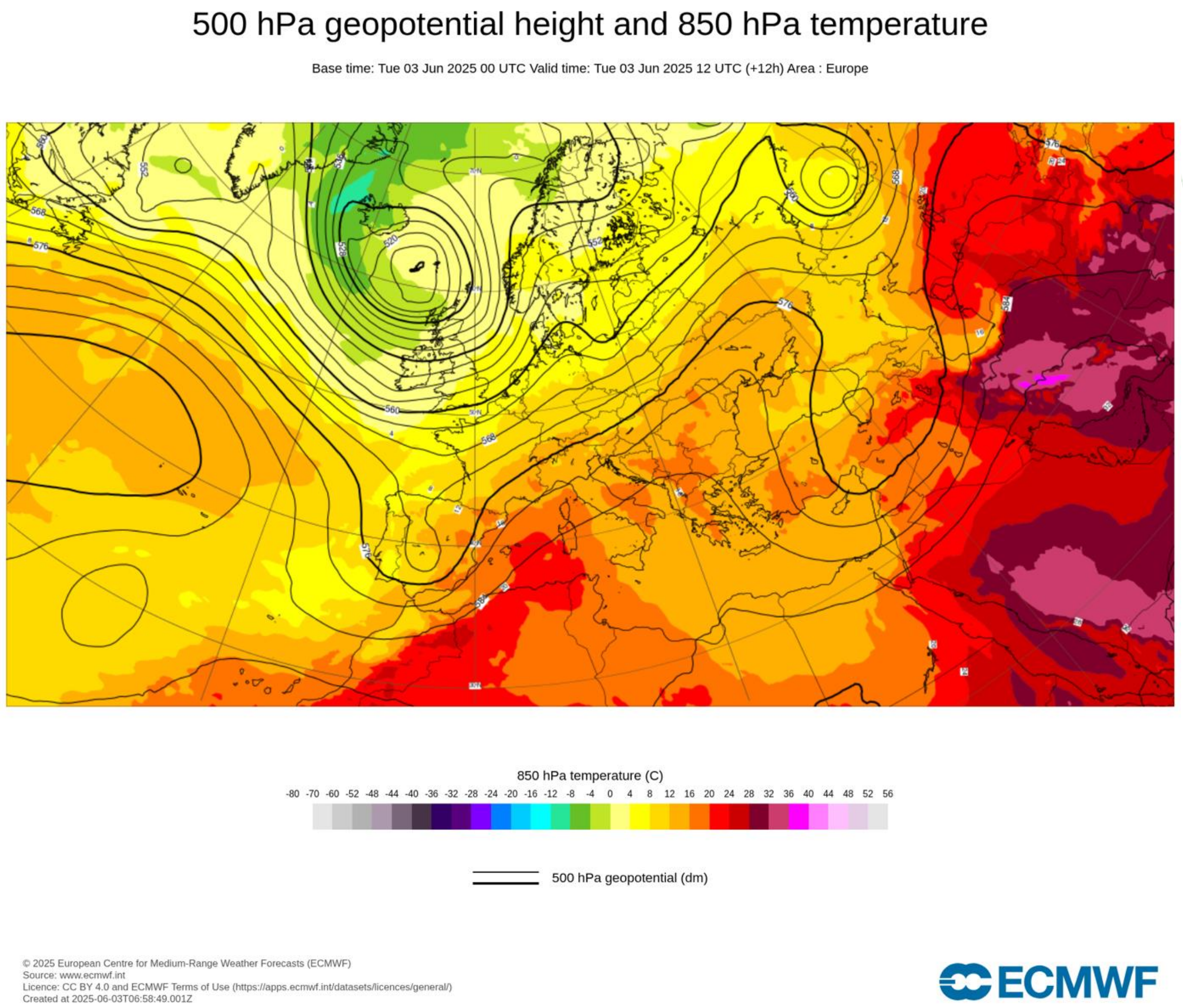
cold and warm fronts form at the boundary of fluids of different density (➔)

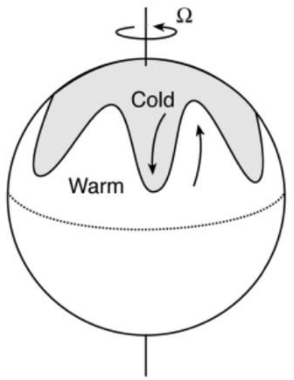
eddy size is proportional to Rossby radius of deformation (~1000 km in the troposphere, ~30 km in the ocean thermocline)



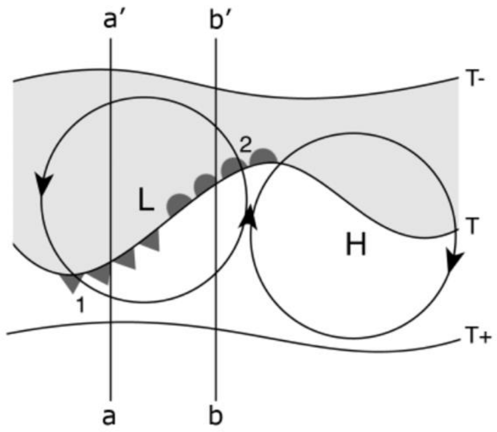
[MP08] 8.8

General circulation: atmosphere





[MP08] 8.4



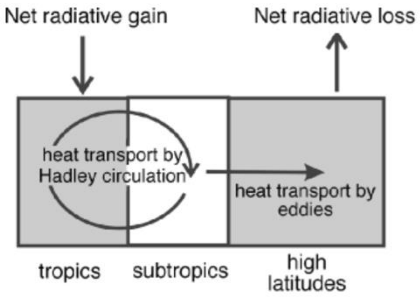
[MP08] 8.8

General circulation: atmosphere

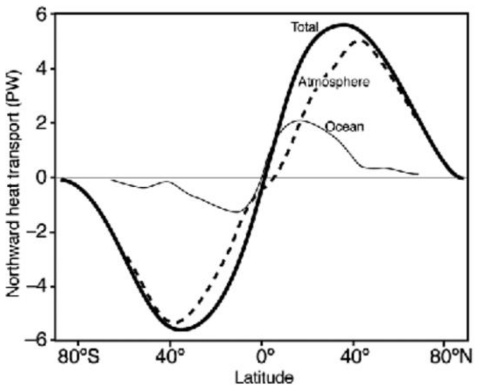
Key mechanisms

➔ Hadley cell at lower, eddies at higher latitudes

Heat transfer

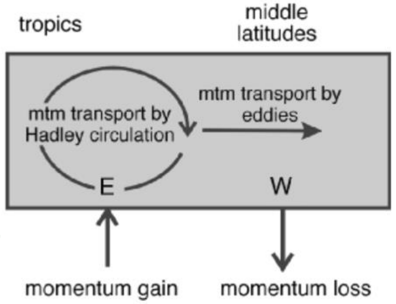


- radiation drives overturning atmospheric circulation from tropics to subtropics
- eddies at mid latitudes
- ocean contributing at the tropics



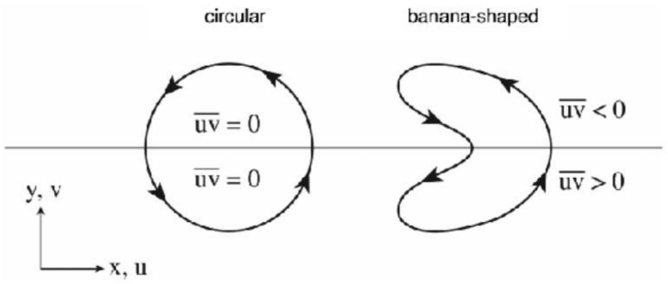
[MP08] 8.13

Momentum transfer



[MP08] 8.12

- surface provide westerly momentum at the tropics by braking (via friction) easterly winds
- momentum is transferred to upper air via convection and generates strong westerlies at midlatitudes
- there, friction-driven loss of westerly momentum near ground occurs, which is offset by momentum advection banana-shaped eddies:

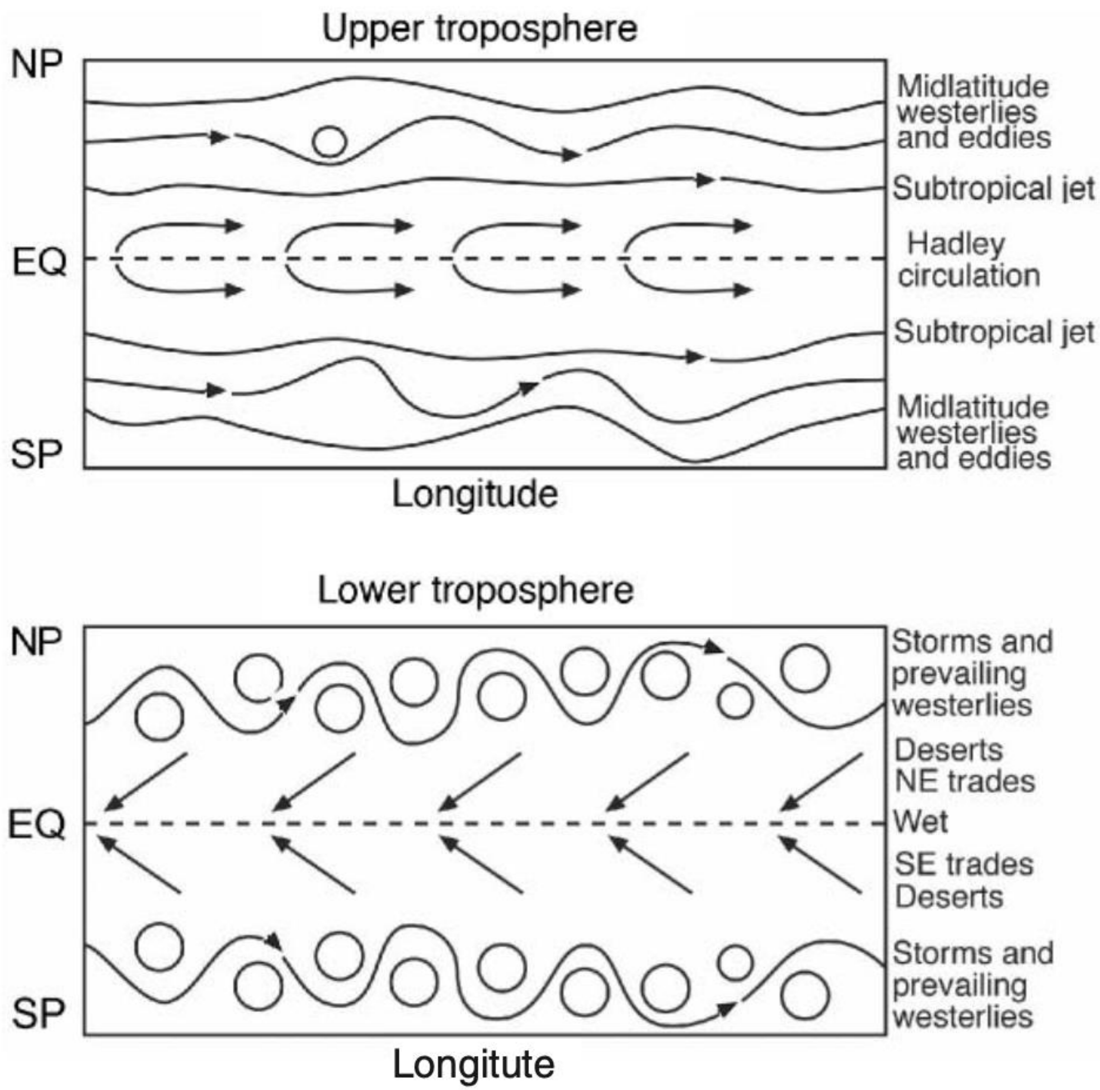


[MP08] 8.14

General circulation: atmosphere

Climatic zones

- Equatorial zone: convergence of trade wind➔ convection ➔ intense rainfall ➔ rainforests
- Subtropics: subsidence of warm, dry air ➔ deserts belt
- Poleward of ~30°: baroclinic eddies and weather variability (calm in anticyclones, wet and stormy during cyclones)



[MP08] 8.15

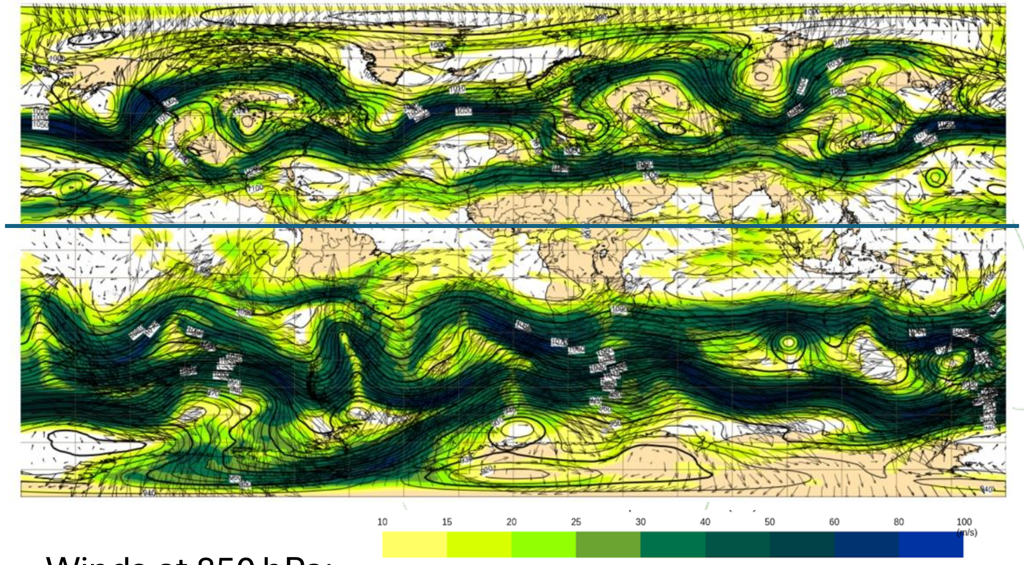
General circulation: atmosphere

Climatic zones

Numerical Earth System models can account (among many other things) for:

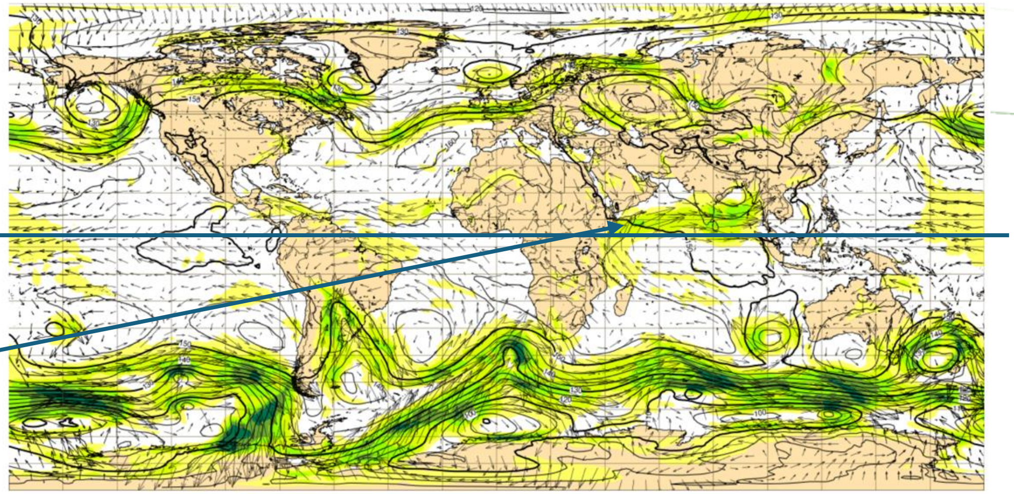
- Earth axis tilting: subsolar point migrates N or S, so the Hadley circulation, and the monsoons
- Landmass effects:
  - Heat capacity
  - Orography (boundary conditions for winds)
- Ocean-Atmosphere regional and seasonal coupling

Winds at 250 hPa:



equator

Winds at 850 hPa:



trade winds reversal due to summer Monsoon

https://charts.ecmwf.int/

General circulation: ocean

Comparison of two geophysical fluids

Atmosphere	Ocean water
compressible	almost incompressible
-	salinity as a key parameter
$\rho = \rho(p, T)$	$\rho = \rho(T, S)$
moisture as a source of latent heat	-
horizontally unbounded	oceans are laterally bounded by landmass
transparent to solar radiation	good absorber of light
heated from below	heated from above
they exchange heat, momentum, and moisture	
convection due to buoyancy gain	convection due to buoyancy loss
-	affected by wind stress

General circulation: ocean

Ocean basins: quick facts

71% of Earth surface

3.7 km average depth

1000x heat capacity of atmosphere

low albedo, ~10%

mean density: 1035 kg/m^3

Cryosphere: quick facts

It includes ice sheets, sea ice, snow, glaciers, permafost

represents 2% of Earth water

89% is made up of Antarctica ice

8% is made up of Greenland ice

high albedo (70%)

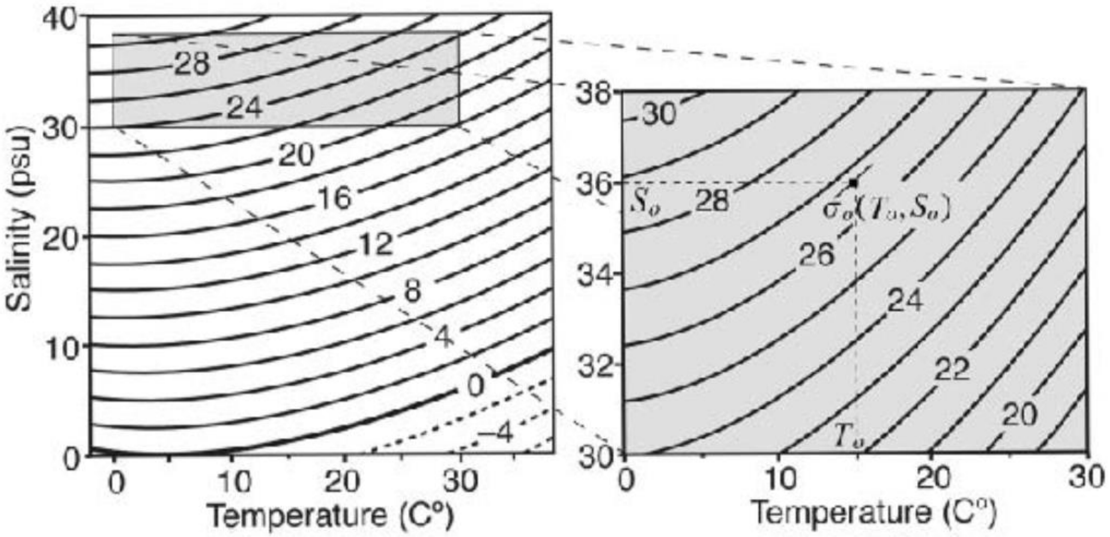
perennial ice covers 11% of land area and 7% of ocean

General circulation: ocean

Seawater equation of state

- salty water is denser than fresh water
- warmer water is (almost always) less dense than colder water
- fresh water has a peak density a 4 °C
- nearly linear dependence on both T and S in the range of ocean-relevant values

density anomaly $\sigma = \rho - \rho_{ref}$



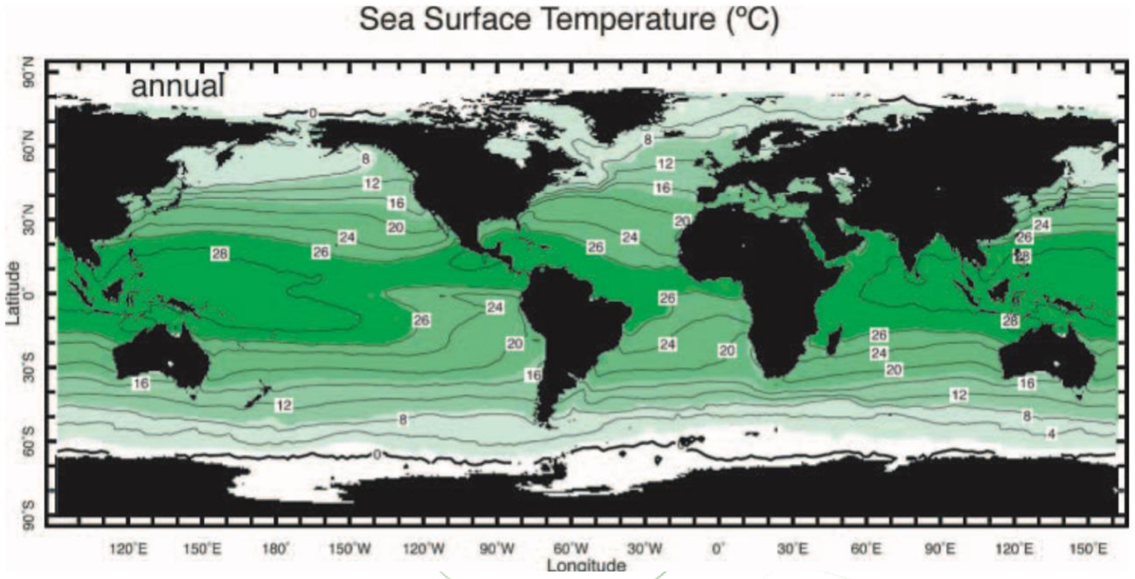
$(\rho_{ref} = 1000\ kg/m^3)$

[MP08] 9.2

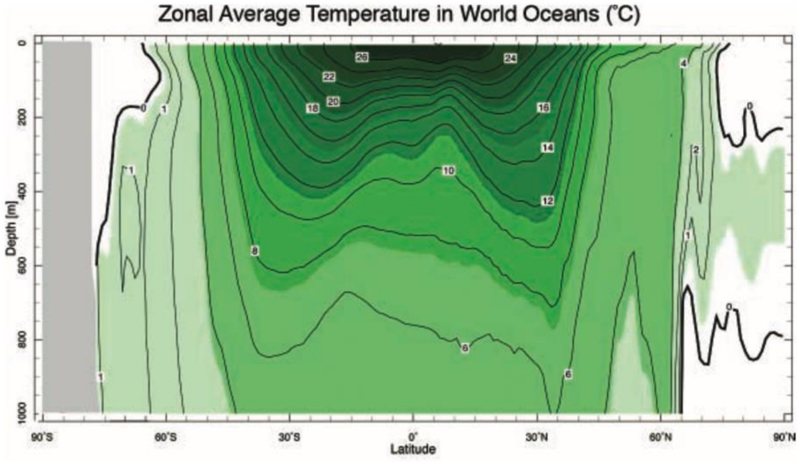
General circulation: ocean

Temperature structure - average

- pattern generally following insulation
- relevant zonal variations in the tropics (warmest in the west)
- in mid latidudes, impact of boundary currents (GulfStream, Kuroshio, ..)
- cold regions off California and Africa (upwelling)
- strong meridional gradient across the Antarctic Circumpolar Current



[MP08] 9.3

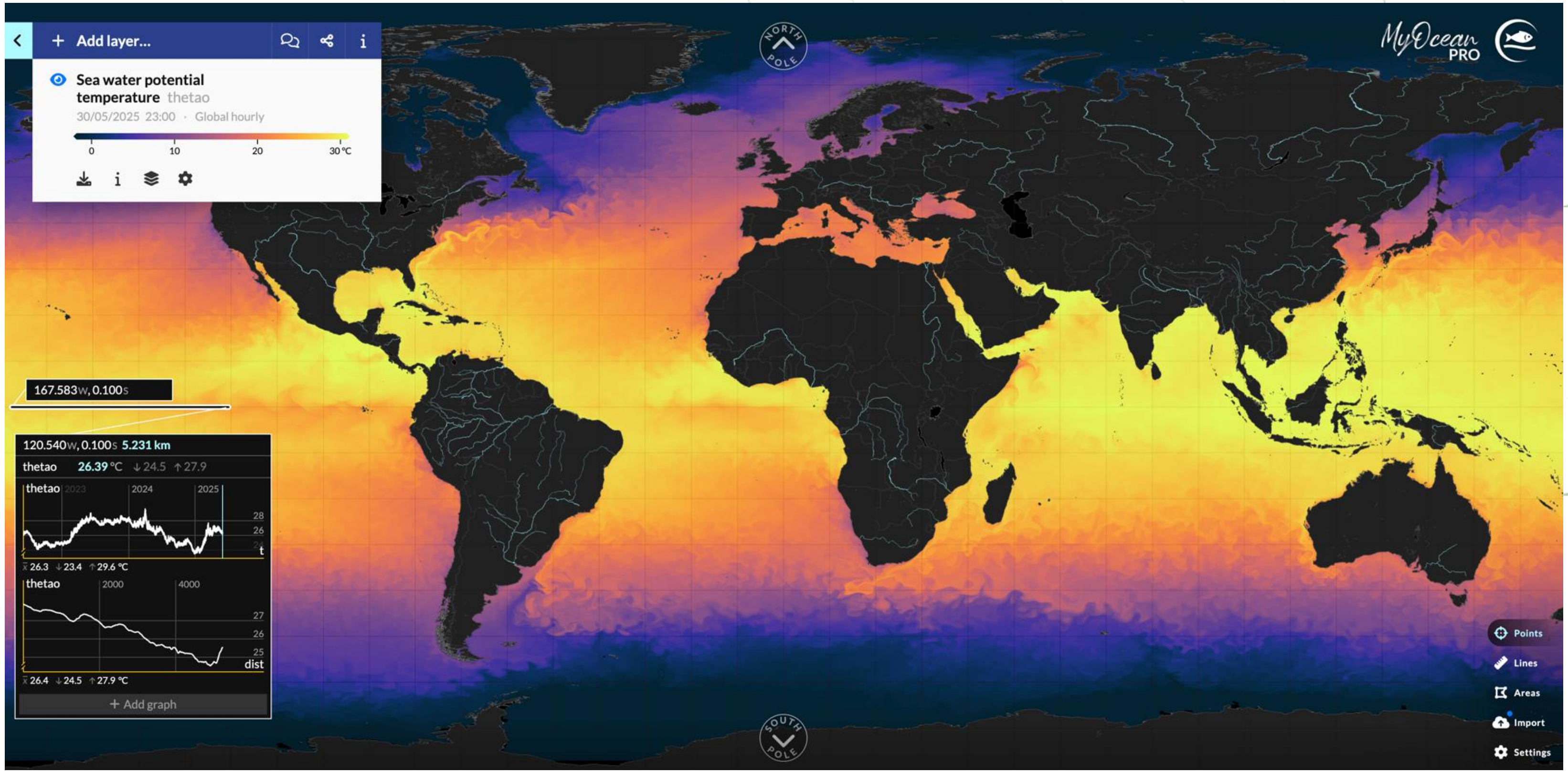


[MP08] 9.5

- strong vertical gradients in the upper 1 km
- *thermocline*: 600m at mid-latitudes, 100-200m in low lat

General circulation: ocean

Temperature structure – instantaneous picture



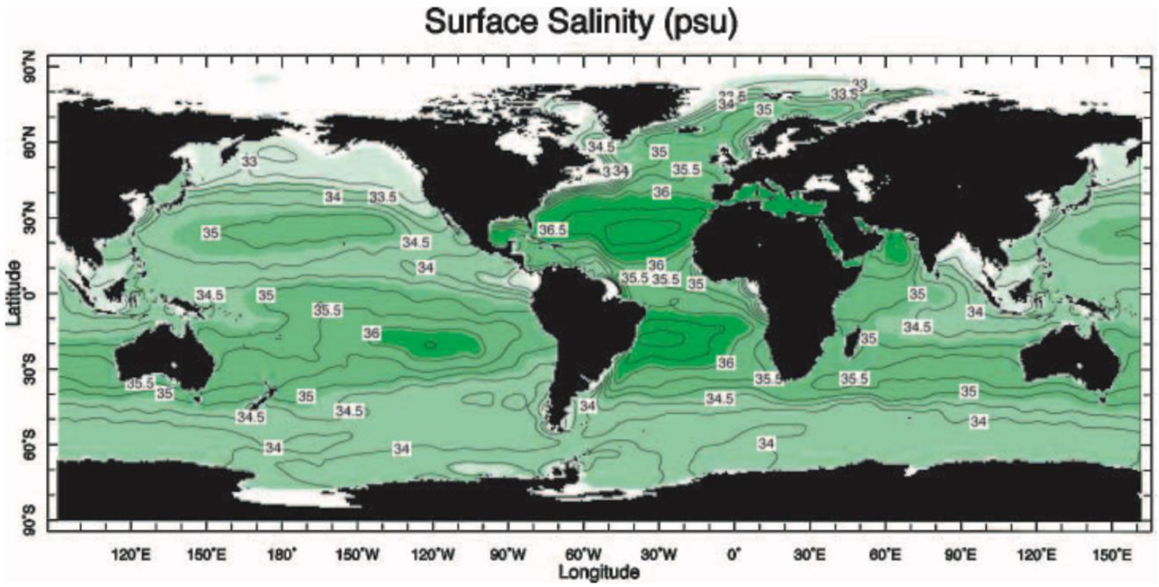
https://marine.copernicus.eu/
GLOBAL_ANALYSISFORECAST_PHY_001_024

- strong eddies in the vicinity of the boundary currents
- Nino3.4 region currently in weak LaNina mode (was ElNino in most of 2023 and half 2024): cooler in the east Pacific

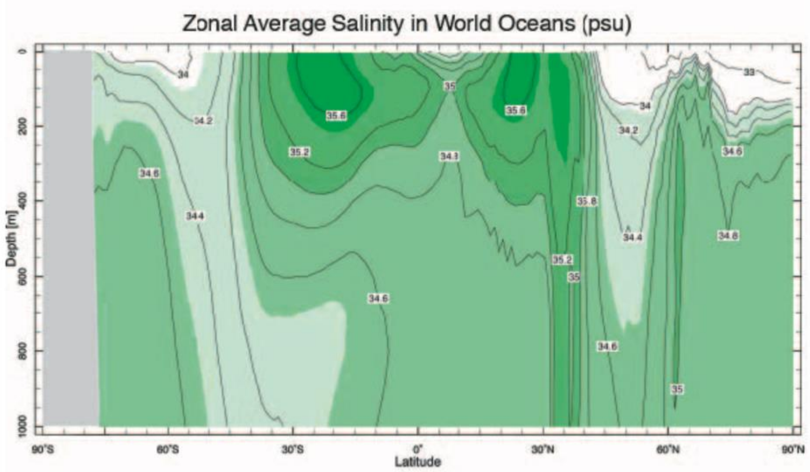
General circulation: ocean

Salinity structure - average

- subtropics: evaporation prevails on precipitation ➔ saltier waters
- equator & high latitudes: opposite trend ➔ fresher water
- high values of S (>38 psu) in the Mediterranean and Persian Gulf
- Northern Atlantic more saline than Pacific ➔ more susceptible to convection (→AMOC)



[MP08] 9.5

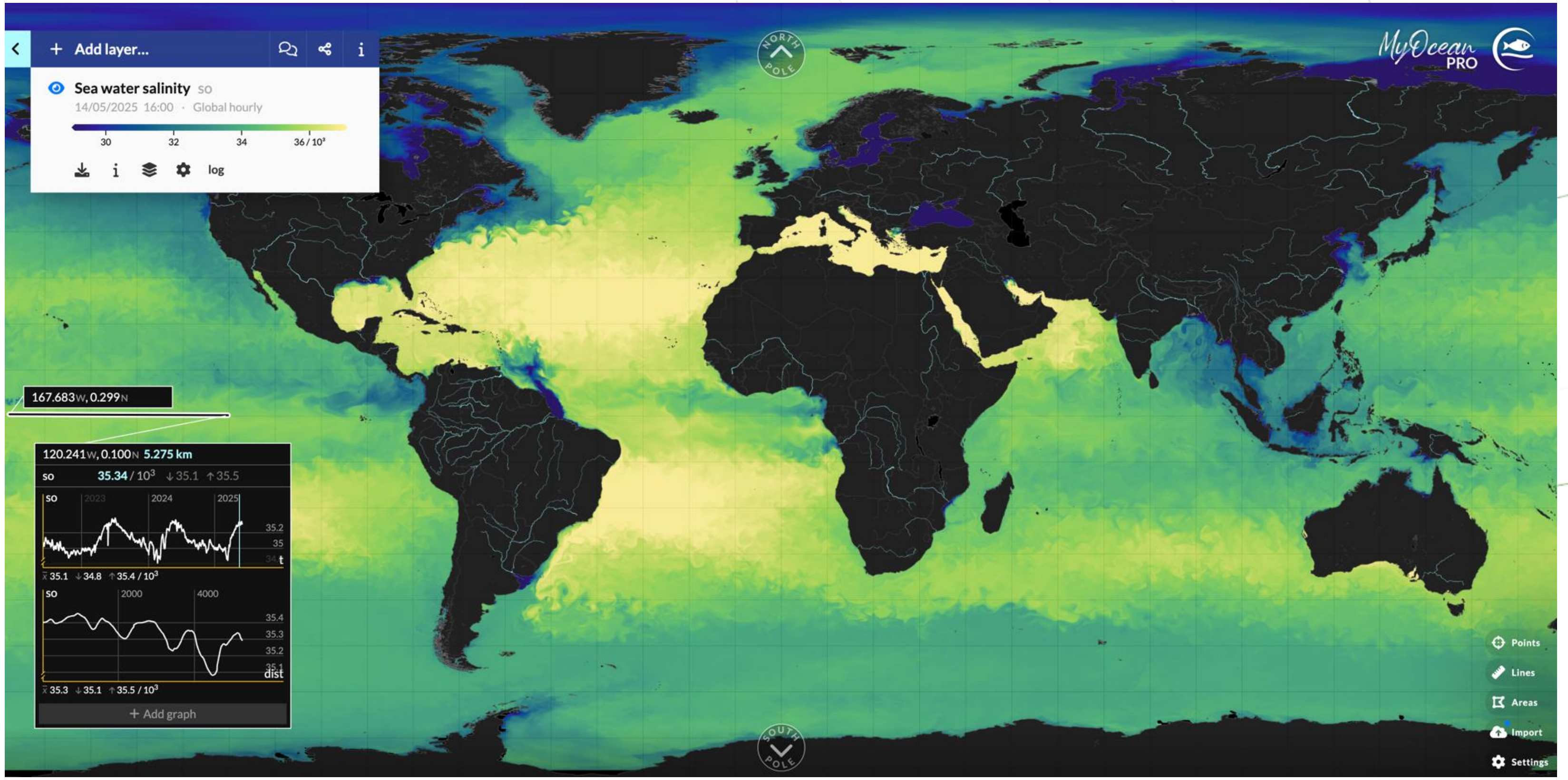


[MP08] 9.6

- two lenses of salty, warm water floating on fresher and colder water
- outcrops of the contours at high latitudes ➔ Indication of surface-to-abyss water transport
- around Antarctica, surface water can be colder yet still lighter than the underlying water because it is much fresher

General circulation: ocean

Salinity structure – instantaneous picture



https://marine.copernicus.eu/
GLOBAL_ANALYSISFORECAST_PHY_001_024

- plume of fresh water from greater rivers (e.g. Amazon River, Congo River)
- Mediterranean is a net source of salty water for the Atlantic
- Nino3.4 region displays just seasonal variations in salinity

General circulation: ocean

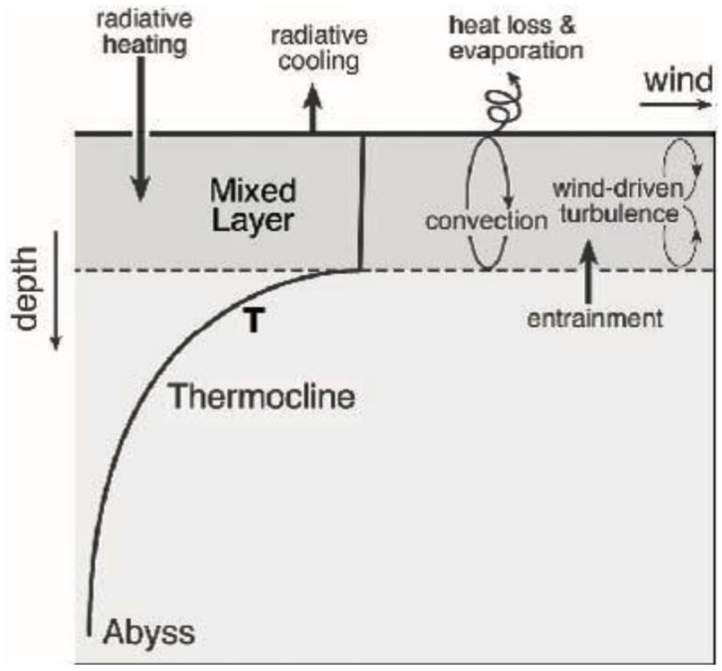
Mixed Layer (ML)

Layer at the surface is in contact with the atmosphere

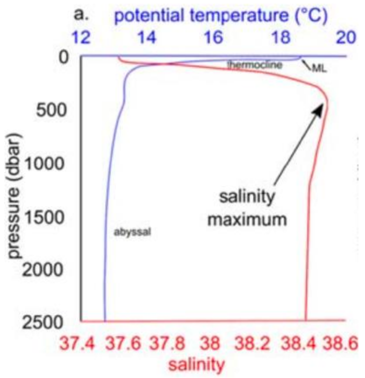
Its average depth is 50-100 m, but at high latitudes surface waters are in direct contact with the abyss (1 km depth)

Physical processes:

- radiation attenuated in ~ meters (IR: mm, blue/green: up to 100m)
- energy loss via black body radiation, sensible heat, and latent heat loss from evaporation
- buoyancy loss triggers convection
- wind stress drives further turbulence and may entrain into the ML cold water from the thermocline



[MP08] 9.11



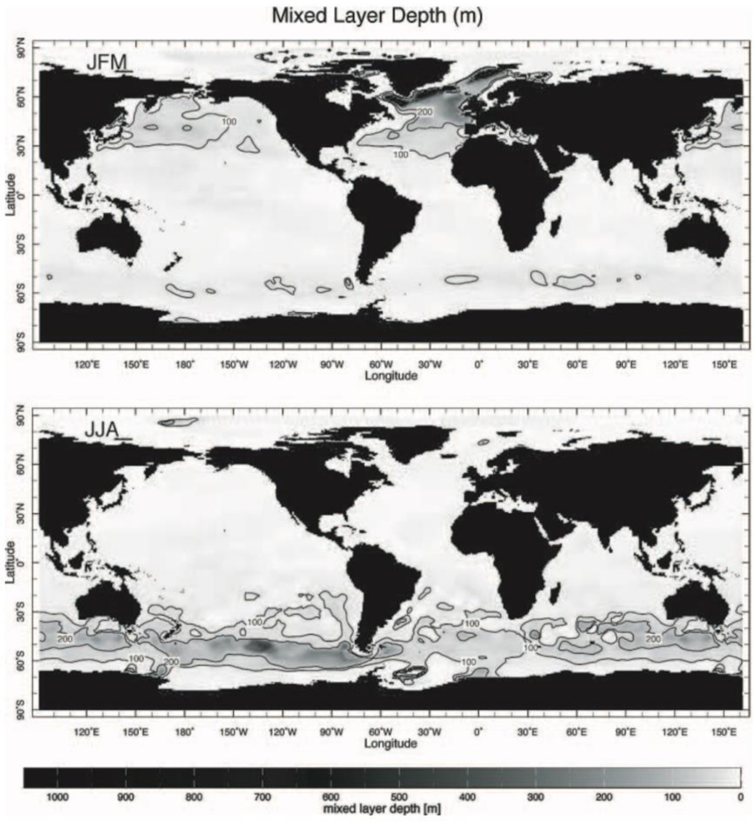
← In the Mediterranean Sea, the ML can be as shallow as 1-2 m in summer

Schoreder & Chiggiato (2023) Fig.4.13

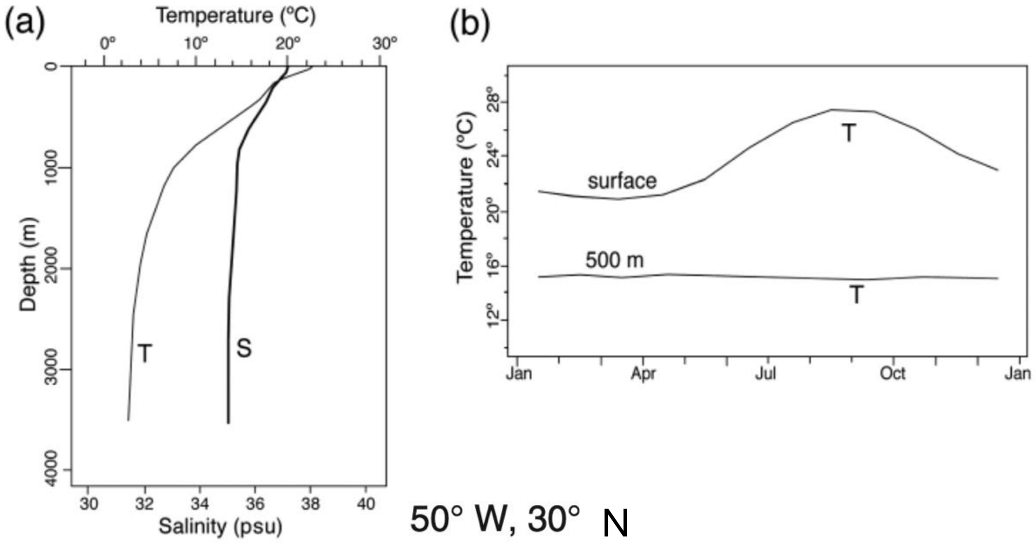
General circulation: ocean

Mixed Layer (ML)

Deepening in the highlatitudes of the winter hemisphere



[MP08] 9.10



50° W, 30° N

[MP08] 9.12

- diurnal, seasonal, inter-annual variations just in the ML
- deeper layer responds on longer timescales (decadal - centennial)

General circulation: ocean

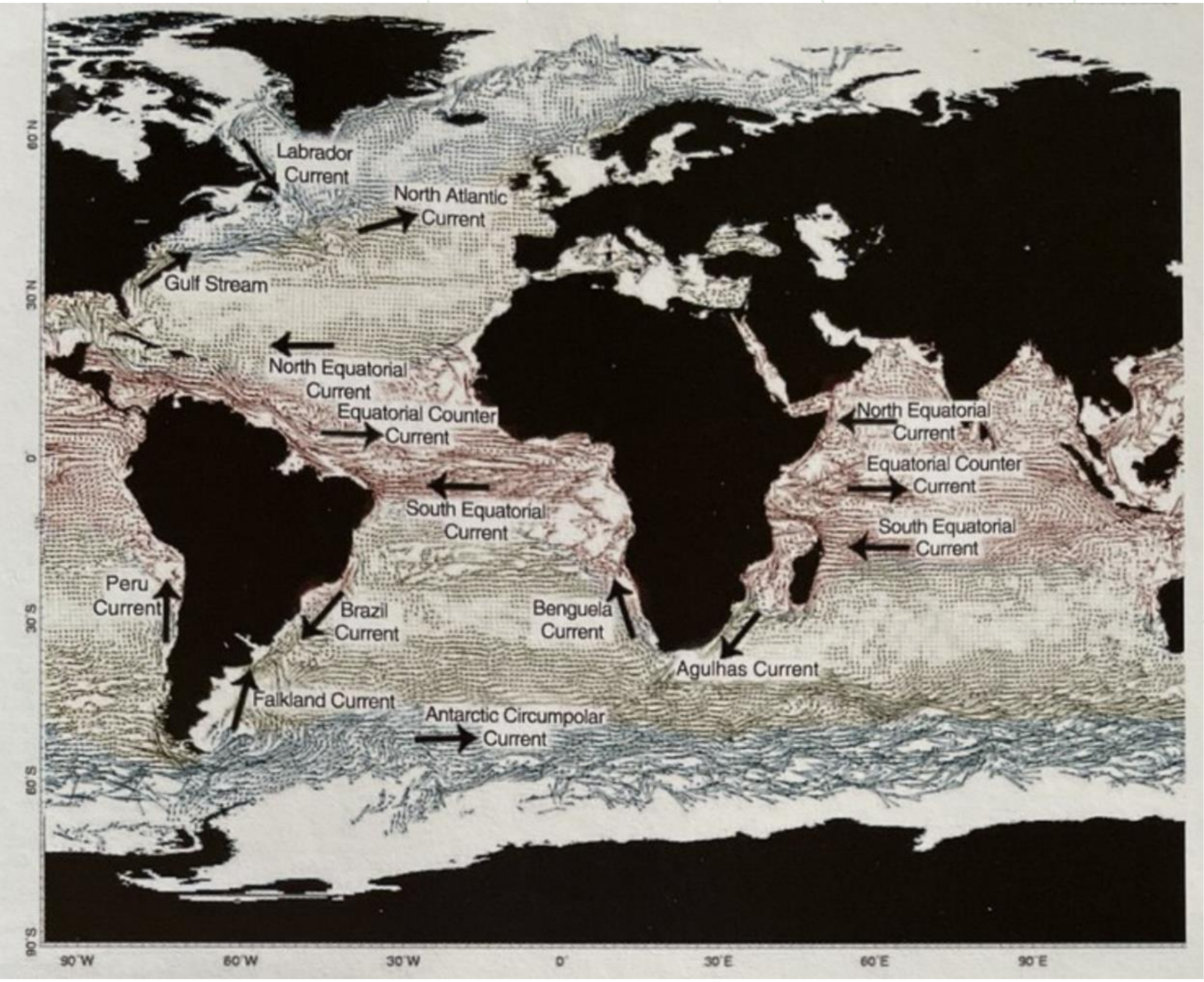
Mean circulation

average surface currents speed: ~10 $cm \cdot s^{-1}$(1/100 of atmospheric one) ➔ 2 years for transiting across the tropical Pacific

flow is dominated by *gyres*, especially in the northern hemisphere, due to continental confinement

in the subtropical gyres' western flank, currents up tp 100 $cm \cdot s^{-1}$ (Kuroshio and Gulf Stream)

subpolar cyclonic gyres with stronger currents on the West (Oyashio, Labrador)



[MP08] 9.13

General circulation: ocean

Mean circulation

In the tropics, strong zonal flows

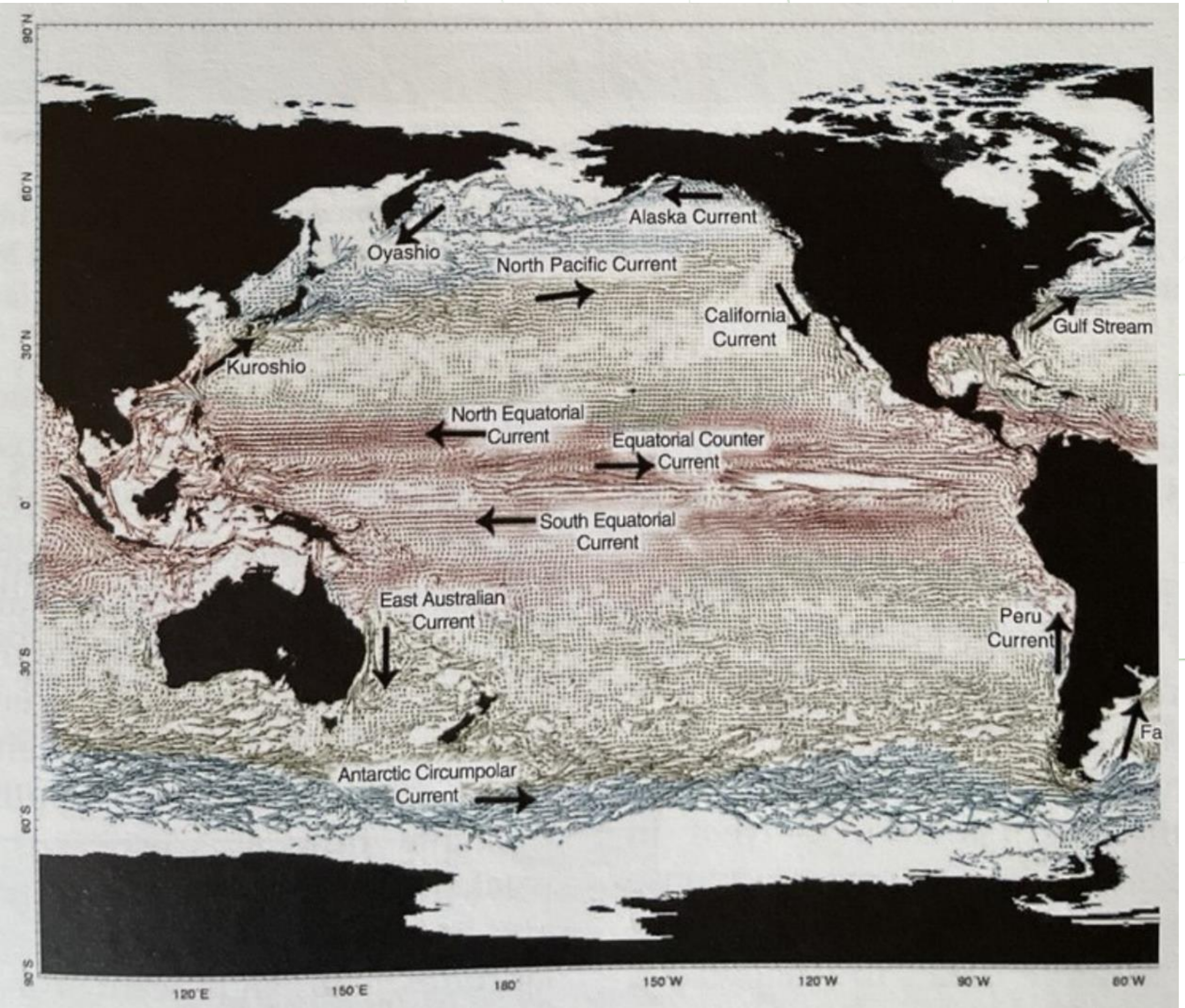
two currents aligned with trade winds with an equatorial countercurrent between them

countercurrent is located in the «Doldrums», near the Intertropical Convergence Zone (ITCZ), where winds are weak and variable

strong temperature gradients along the equator

they drive Walker-type circulations (ENSO, IOD)

southern ocean: Antarctic circumpolar current (similar to jet stream in the atmosphere)

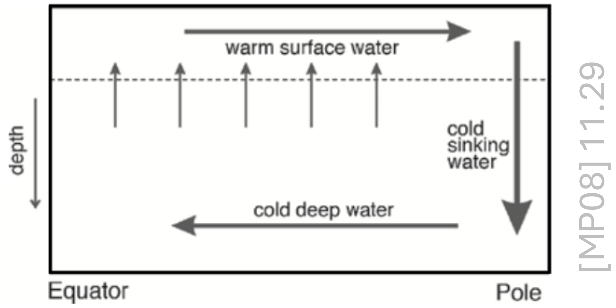


[MP08] 9.13

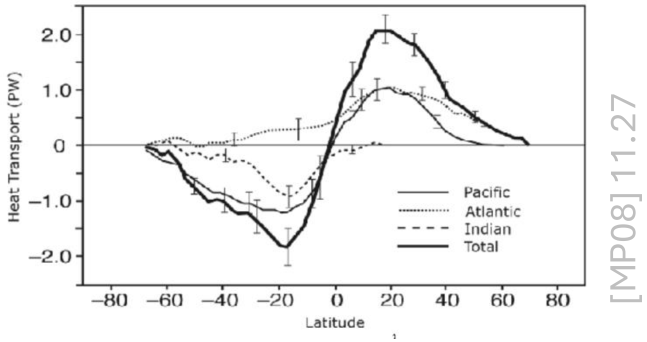
General circulation: ocean

AMOC

Atlantic Meridional Overturning Circulation

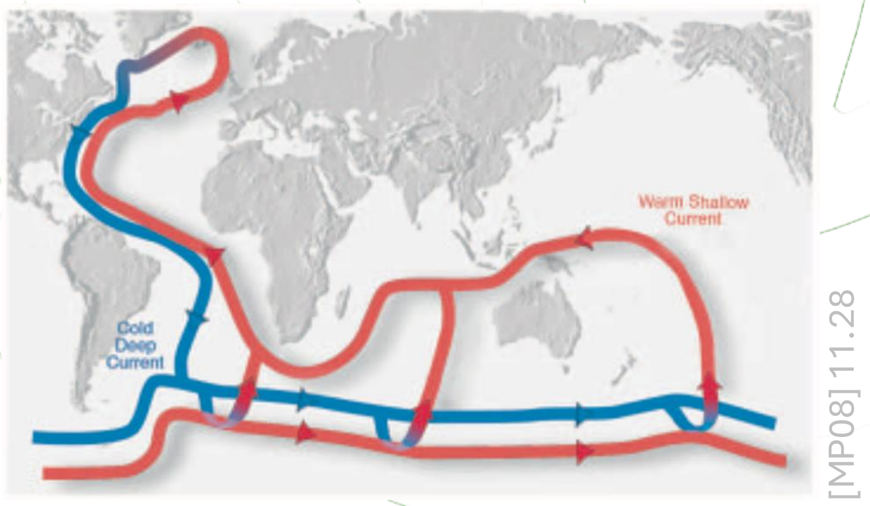


1) In polar latitudes, a cell driven by deep convective processes feeds the abyssal ocean



2) A net poleward flux of heat occurs if surface waters moving poleward are warmer than the equatorial return flow beneath

3) The AMOC could be disrupted by freshwater inflow from Greenland ice melt → regional cooling in north-western Europe, additional warming in the tropics



In the Pacific Ocean, the meridional overturning circulation is much weaker than the horizontal flow at the same depth → mainly wind-driven circulation along the gyres

General circulation: ocean

Ocean eddies

can be even faster than average flow

L ~ 100 km (due to weaker stratification of the ocean)

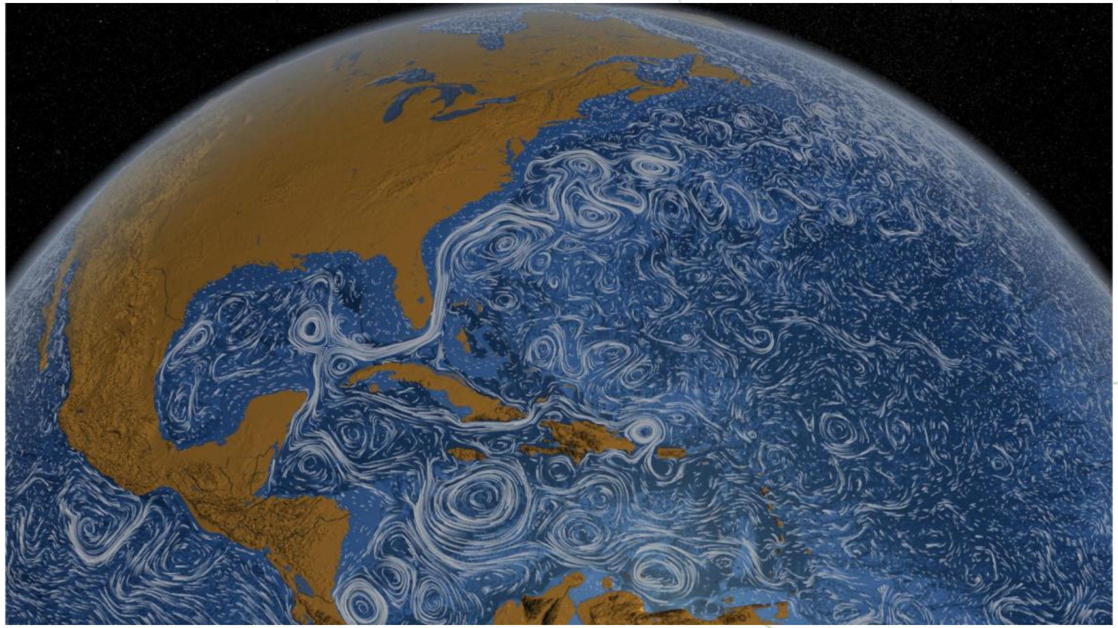
T ~ months

dynamical analogous of atmosphere baroclinic eddies

eddies are *ocean weather* systems

originate from available potential energies along sloping isopychnal surfaces

less crucial than atmospheric counterpart in heat transport (boundary currents are more effective) but along the Antarctica circumpolar current



https://oceans.mit.edu/JohnMarshall/research/ocean-dynamics/ocean-eddies/

General circulation: summary

A tale of dimensionality

0D: Estimate of blackbody-emission temperature

1D (vertical): Greenhouse models, convection

2D (vertical, meridional): Latitudinal heat transport, zonally-averaged winds, atmospheric overturning circulation

3D (vertical, meridional, zonal): Landmass effects (albedo, horography); western boundary currents and gyres in the ocean

Natural variability and teleconnections

Ocean as a buffer of change

Seasonal changes in surface temperature are much larger over land than over ocean (➔)

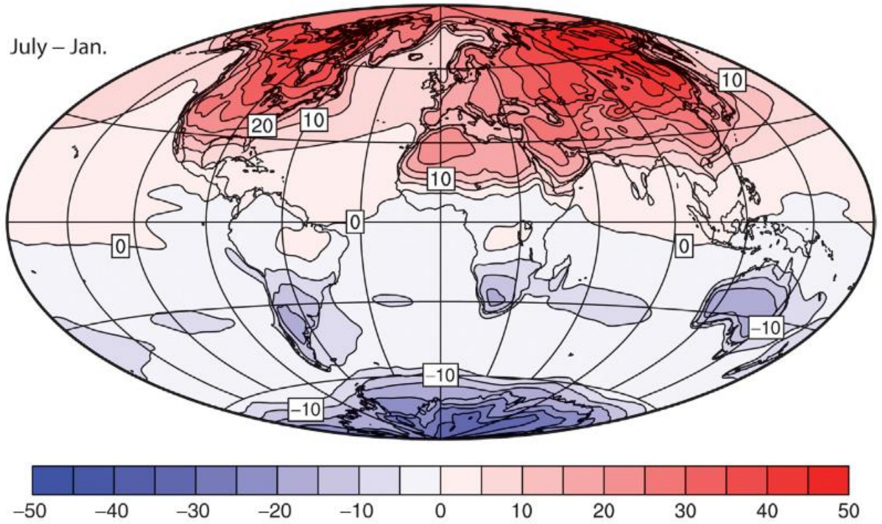
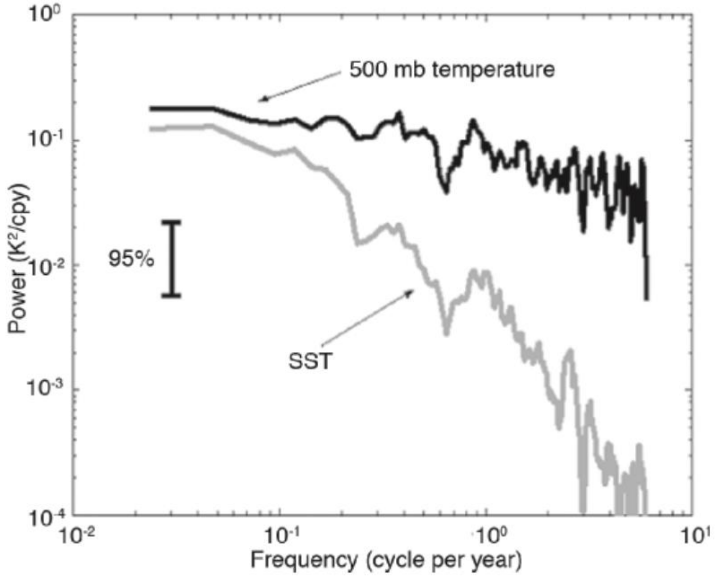


FIGURE 1.6 Global map of the surface temperature July minus January. *Data from ERA-Interim reanalysis.*

[H16] 1.6



[MP08] 12.3

(🡐) Ocean surface temperature responses to atmospheric forcing typically exhibit a time lag due to the ocean's large heat capacity (spectral *reddening*)

Natural variability and teleconnections

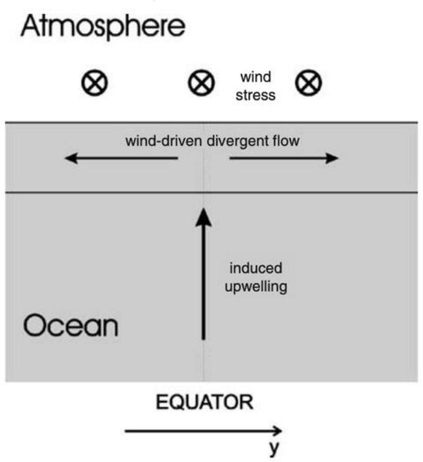
ENSO

In the tropical Pacific, moist convection leads to much stronger and faster coupling between the ocean and the atmosphere (*Bjerknes* feedback)

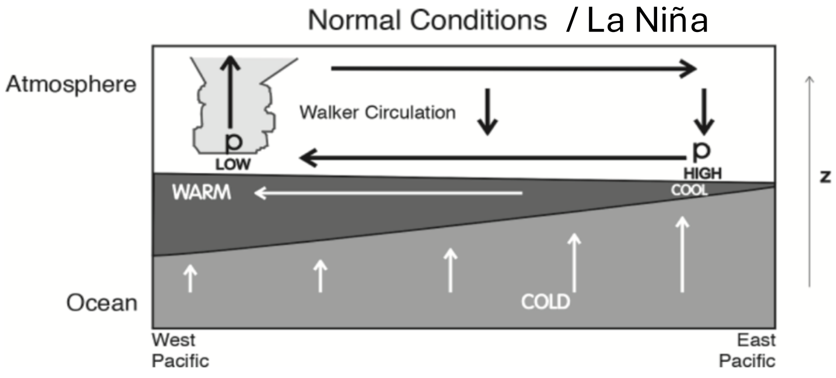
How it develops:

1. trade wind stress in the east induces surface divergence, which promotes upwelling of cold water
2. a SST gradient from east to west develops
3. it establishes a pressure gradient in the lower atmosphere (lower p. over the warmer west)
4. the west becomes instable to convection
5. a westerly flow aloft develops
6. subsidence occurs over the east
7. the overturning cell is closed by surface easterlies, reinforcing trade winds

positive feedback



[MP08] 12.5



[MP08] 12.5

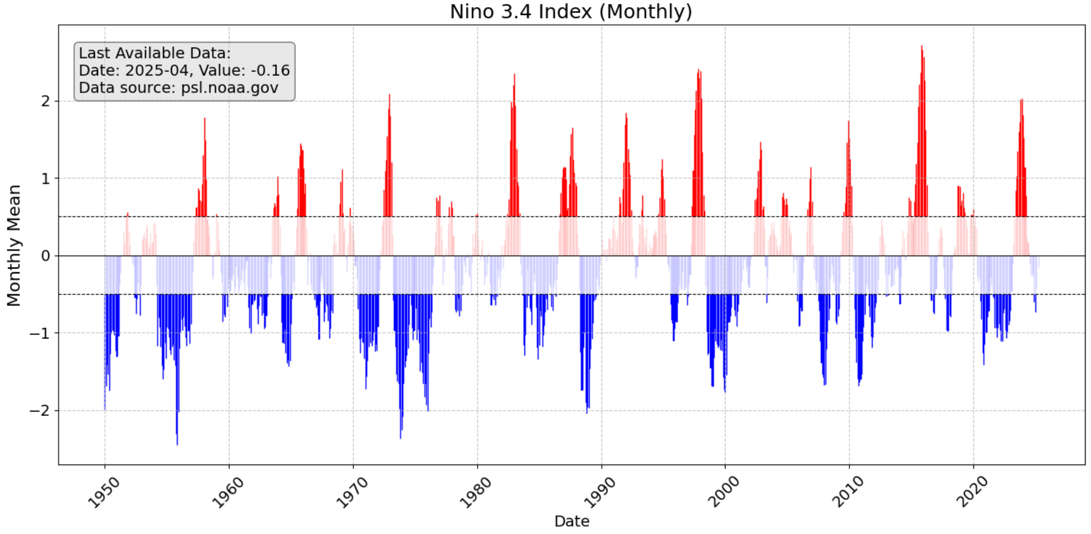
Natural variability and teleconnections

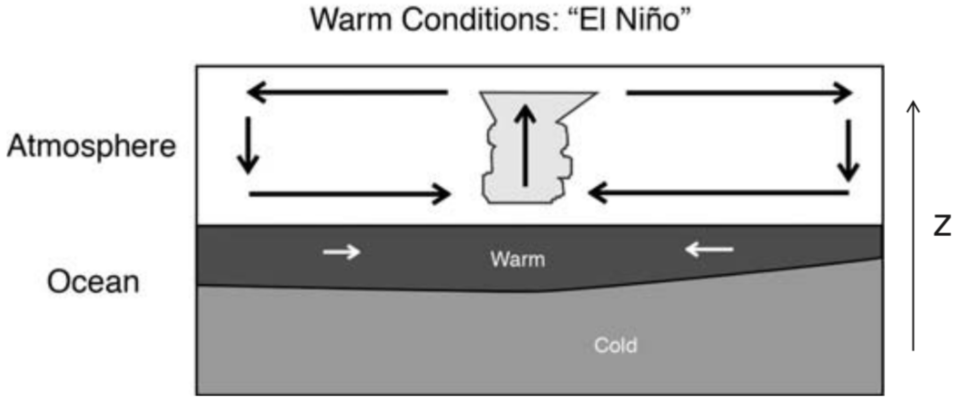
ENSO

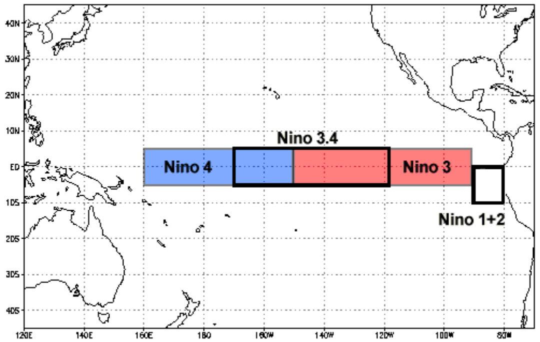
A perturbation (e.g. westerly wind burst) is amplified by the Bjerknes Feedback

How it develops:

- the warm pool in the west spread eastwards, flattening the zonal tilt of the thermocline and suppressing upwelling in the east
- atmospheric convection also shifts east, decreasing pressure in the mid ocean and increasing it in the west (Walker circ. weakens)
- a surface circulation opposite to the trade winds develops in the west (in a strong event, the trade winds collapse there)







[MP08] 12.11

Natural variability and teleconnection

ENSO

The phenomenon has teleconnections over most of the planet, both at oceanic and atmospheric level:

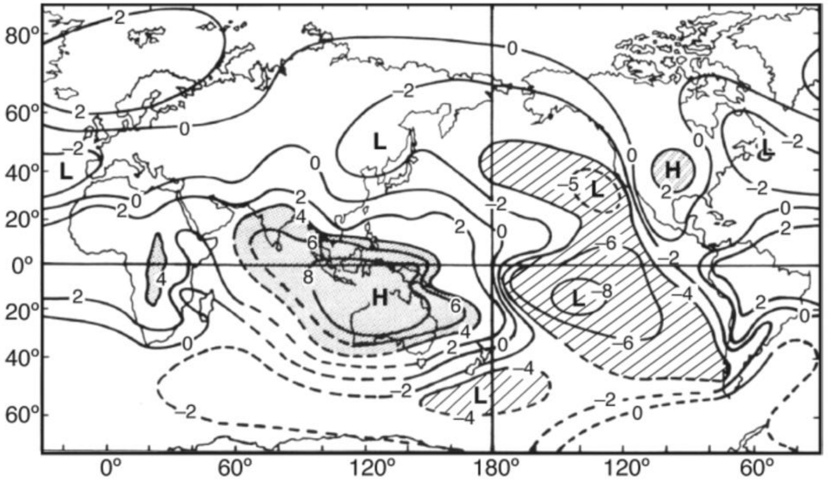
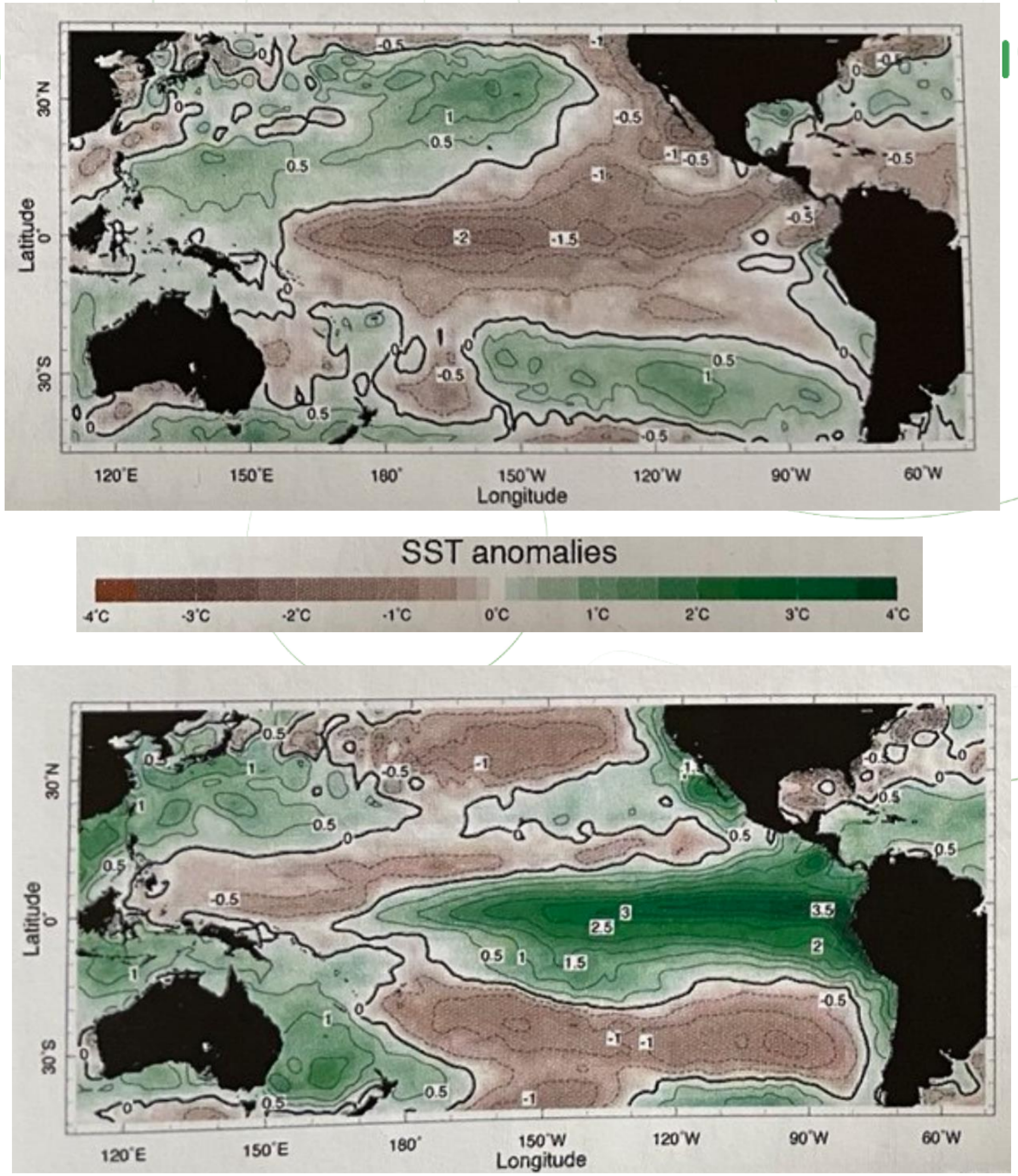


FIGURE 12.9. Correlations (×10) of the annual-mean sea level pressure with that of Darwin (north of Australia). The magnitude of the correlation exceeds 0.4 in the shaded regions. After Trenberth and Shea (1987).

The ocean dynamics is coupled to the atmospheric one (Southern Oscillation Index)

La Niña

El Niño



[MP08] 12.7

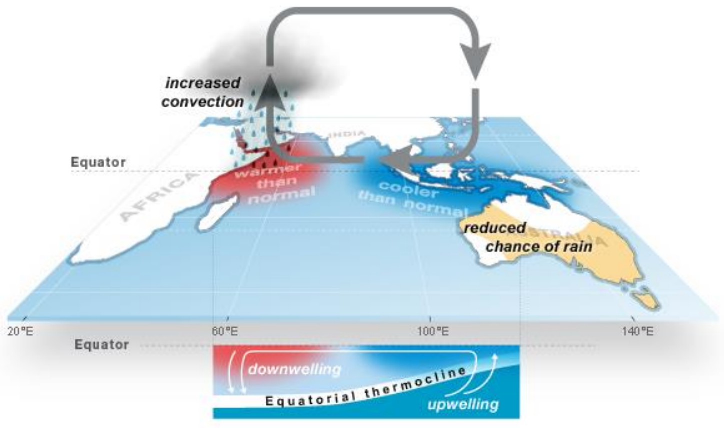
Natural variability and teleconnections

IOD

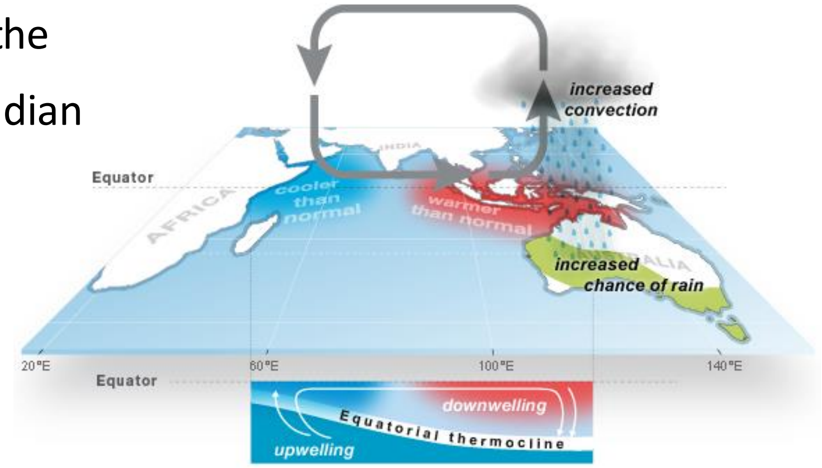
Indian Ocean Dipole

Often develops during boreal summer to autumn (June–November)

can interact with ENSO and can affect Indian monsoon (a strongly negative IOD – not the 2025's case – increases subsidence in the western Indian ocean, reducing rainfall)



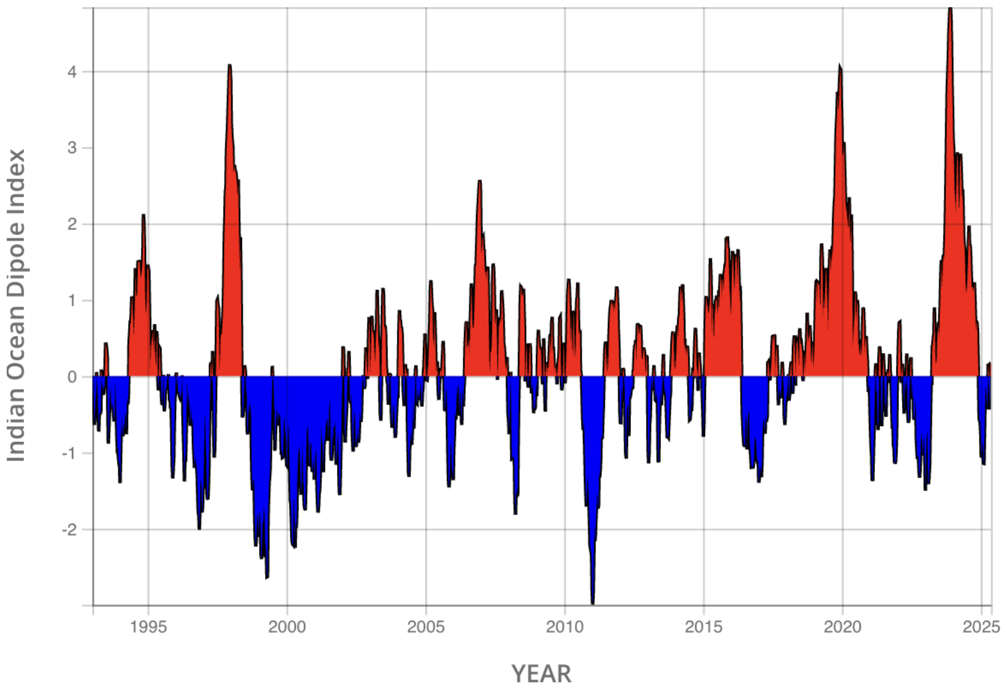
Indian Ocean Dipole (IOD): **Positive phase**



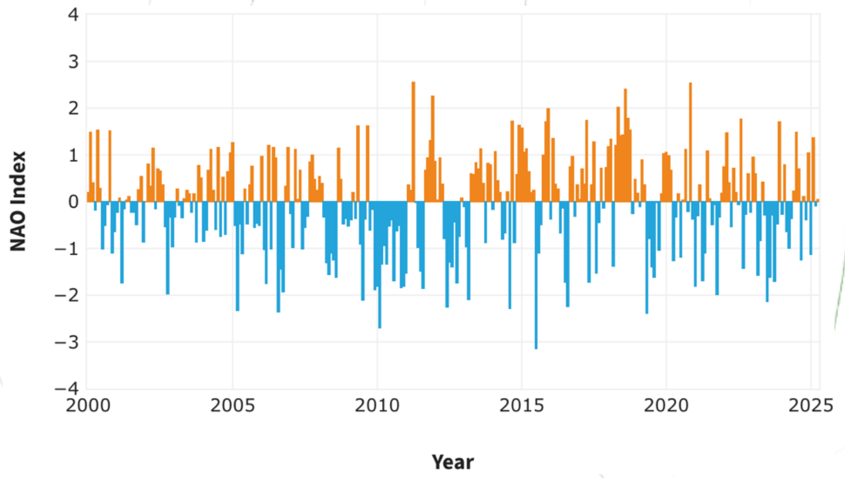
Indian Ocean Dipole (IOD): **Negative phase**

IOD INDEX: 1993-PRESENT

Data source: Satellite sea level observations.
Credit: NASA



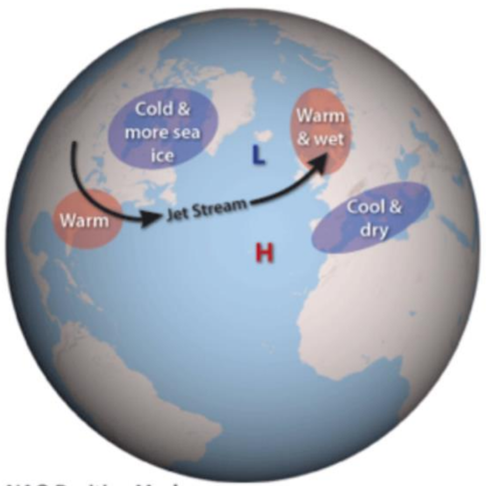
Natural variability and teleconnections



NAO

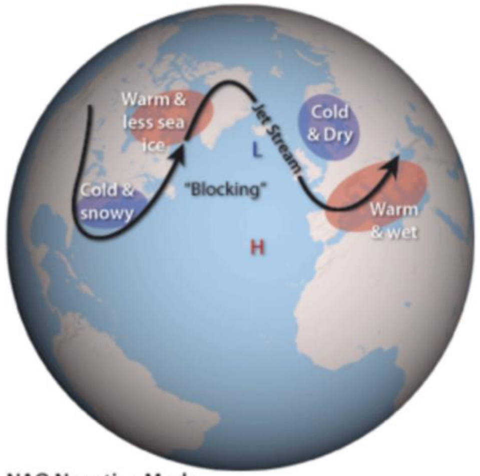
North Atlantic Oscillation

pressure difference between Azores High and Icelandic Low



NAO Positive Mode

[pictures from climate.gov]



NAO Negative Mode

Positive phase: stronger westerlies:
they push more mild, moist maritime air into northern Europe➔

- stormier and wetter in northern Europe
- colder, drier winters in southern Europe and the Mediterranean

Negative phase: meandering westerlies:
cold Arctic air moves south into Europe and eastern North America➔

- colder winters to Europe and the eastern US
- stormier and wetter in southern Europe

ITINERIS

THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

Finanziato dall'Unione europea NextGenerationEU

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